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Edited by

Matti Hellevaara
VTT Manufacturing Technology

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puh. vaihde (09) 4561, faksi (09) 456 4374

Statens tekniska forskningscentral (VTT), Bergsmansvägen 5, PB 2000, 02044 VTT
tel. växel (09) 4561, fax (09) 456 4374

Technical Research Centre of Finland (VTT), Vuorimiehentie 5, P.O.Box 2000, FIN–02044 VTT, Finland
phone internat. + 358 9 4561, fax + 358 9 456 4374

VTT Valmistustekniikka, Laiva- ja konetekniikka, Tietotie 1, PL 17051, 02044 VTT
puh. vaihde (09) 4561, faksi (09) 464 424

VTT Tillverkningsteknik, Skepps- och maskinteknik, Datavägen 1, PB 17051, 02044 VTT
tel. växel (09) 4561, fax (09) 464 424

VTT Manufacturing Technology, Maritime and Mechanical Engineering,
Tietotie 1, P.O.Box 17051, FIN–02044 VTT, Finland
phone internat. + 358 9 4561, fax + 358 9 464 424

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PREFACE

The symposium proceedings include ten papers given at the seminar 'Maritime Safety '97 on the March 19, 1997 in Otaniemi. This seminar is the first one on the ship safety questions organised by the Maritime Institute of Finland. However, research on this subject has been carried out in Otaniemi since the beginning of 70's, but during the last years the volume has increased substantially. The aim of the seminar is to present results of the research on ship safety carried out by the maritime community in Otaniemi during the last years and also to promote the Finnish dialogue between authorities, industry and researches.

Modern competitive shipping industry understands well that the safety issues form an essential part of the business where the new approaches to improve the safety by the authorities, such as the ISM (International Safety Management) Code are supported. The authorities have received new basic tools to develop of rules and guidelines for new technical innovations such as the formal safety assessment (FSA). The fast changing climate of the maritime safety requires deep understanding both about the structural safety problems but especially about the operational ones. There the crucial question is the human factor; how the modern technology is utilised onboard by the seafarers so that the safety level of the ship can be kept high.

The role of the Institute in developing the maritime safety is clear. We should produce new knowledge on this area by our research work; work which should base on keen co-operation with the industry. An outstanding example on this is the research project 'The Risks of the Finnish shipping' funded and organised by the Finnish Maritime Administration, which was started in 1996 and will last to the end of 1998. In this project we researches are forced from the office to the field to collect data for the risk assessment. First very preliminary results from this project are presented in this seminar.

The range of the topics covered by the papers in the seminar is broad. The reason for this is that besides the traditional subjects which are related to the structural safety of ship, the operational safety questions have received much attention at the Institute Especially the aids for the navigation both onboard and at the shore, where close connection exists to the teaching personal of the bridge simulator, are emphasized. We feel that it is important that the tradition of this multi-discipline research also in future stays at high priority.

The seminar was held at Innopoli. The number of participants was 75 people which is to be noted with satisfaction. The discussions during the seminar and the feedback on the contents of the seminar were very encouraging. We can conclude that after few years there is again the time to organise a new seminar on maritime safety, naturally with new research results. At last, but not the least, we want to thank Mr. Heikki Valkonen, the Councillor of Navigation, about his opening speech where he strongly subscribed for new profound knowledge on the operational safety issues. These he is personally willing to implement with the industry.

Otaniemi 7th October 1997
Petri Varsta

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CASUALTY INVESTIGATIONS AND STATISTICS

Juhani Sukselainen
VTT Manufacturing Technology
Espoo, Finland

1 GENERAL

Shipping casualties are the outcome of hazards involved in this industry. A precise knowledge of casualties is necessary in order to judge the influence of safety precautions and as a measure for risks involved in maritime traffic. There have been several problems in the way of fast and accurate analysis of casualties and in having well defined principles for generating useful statistical material.

Some years ago, also IMO recognised the need of suitable statistics to estimate the need for regulatory changes to abate certain causes of maritime accidents and, on the other hand, to estimate the possible positive effects brought by the new regulations. The problem is, however, that precise statistics require a good and well-defined investigation mechanism, as well as a suitable database structure to include a balanced amount of physical and causal data. Also, the more refined the database structure is, the more is required from the investigation. The IMO FSI 5 [1] last January reached a reasonable compromise in the question, and hopefully it can be adopted by MSC in May 1997.

2 CASUALTY TYPES

Casualties often consist of a chain of events, where the most spectacular phase may seem to define the type in question. But as pictures shown in the media in most cases present the final phase of the chain of events, they often give a wrong impression of the actual type of the accident, which is defined by the first phase. For example, the recent pictures of ro-ro ferry Seawind grounded in the Stockholm Archipelago showed the vessel after it had deliberately run in to shallow water to avoid possible loss of stability after having touched the rocky seabed a while earlier. A collision may be followed by fire etc.

The casualty types can be defined in many ways depending on the vessels and navigable waters in question. In some waters, grounding means only that the ship is stuck in mud, but in some waters a sharp rock may tear the hull very severely. Thus the statistics always have a localy characteristic profile, which differs from the global one. Despite these facts it is necessary to have casualty type definitions which are applied everywhere. Thus it is clear that the definitions in process of being finally adopted by IMO should be used [1]. As mentioned above, the initial event in the casualty determines its type, and in the following list the first type which is applicable is selected.

1 **Collision:** striking or being struck by another ship (regardless of whether under way, anchored or moored)

2 **Stranding or grounding:** being aground, or hitting/touching shore or sea bottom or underwater objects (wrecks, etc).

3 **Contact:** striking any fixed or floating object other than those Nos. 1 or 2.

4 **Fire or explosion**

5 **Hull failure or failure of watertight doors, ports, etc.:** not caused by Nos. 1 to 4.

6 **Machinery damage:** not caused by Nos. 1 to 5, and which necessitated towage or shore assistance.

7 **Damage to ship or equipment:** not caused or covered by Nos. 1 to 6.

8 **Capsizing or listing:** not caused by Nos. 1 to 7.

9 **Missing:** assumed lost

10 **Other:** all casualties which are not covered by Nos. 1 to 9.

3 COSTS CAUSED BY CASUALTIES

The costs caused by marine casualties per time unit, eg. a year, are by definition the measure for the risk involved in shipping. Thus it should be included in the recorded data of any casualty. Unfortunately, such information is only very seldom available. The underwriters, repair yards, and shipowners have a lot of data based on their actual casualty cases, but this is generally not available. And as an insurance policy is a commercial type of risk management, it hardly presents a neutral means of assessing the real cost of a casualty. The limitation of liability by some international conventions and many other factors make it still more difficult to assess actual casualty costs on the basis of insurance compensations. The distributions of different cost positions, published eg. by the London Underwriters [2], give an impression of the many cost factors involved in marine casualties.

Many statistics only use three categories describing the severity of a casualty damage: light, severe and total loss. In [3] there is some material giving direct monetary values on repair costs for different types and sizes of vessels only having the rough damage severity classification as starting point. Besides the actual repair, costs are caused by SAR, salvage, pollution abatement, lost revenues and replacement arrangements. The most important cost factor is the one due to injury and death, which are rather complicated to assess. Sometimes a definite value is given as a price for a human life [3,4], or an other value indicating the society's willingness to pay for arrangements to save a human life by reducing the number of fatal accidents.

To give an example of costs caused by marine casualties we may take as an example grounding casualty costs for dry cargo vessels [3]. Ships can be divided into 3 size classes: (S, M, & L) and the damage into 4 classes (Low, Moderate, Severe, and Total Loss). The amounts are in 1990 US$.

Table 1. Dry cargo vessel grounding casualty costs in USA in 1990 (1000$) [3].

Vessel size class	Damage severity	Damage cost	Ancillary cost	Social cost	Total cost
Small	L	12	7	94	113
	M	125	37	242	404
	S	1000	45	692	1737
	Total loss	3200	14	-	3214
Medium	L	25	7	125	157
	M	231	65	321	617
	S	1300	86	921	2407
	Total loss	8548	21	-	8569
Large	L	23	7	167	197
	M	345	133	426	904
	S	1800	280	1226	3306
	Total loss	18000	21	-	18021

The cost of environmental pollution is still rather difficult to assess, but for the estimation of cleanup costs The Port Needs Study [3] gives the following formula:

Ln(cleanup cost in $) = 4.8 + 0.72Ln(spill size in US gallons)
Standard error [Ln(cleanup cost in $)] = 1.37

4 CAUSAL FACTORS

It is generally accepted that the vast majority of casualties is caused by human errors or misjudgements. The following table shows the distribution of human errors and persons that made the errors in 100 accidents heard by the Dutch Shipping Council between 1982 and 1985 [5].

Table 2. Number of human errors and erring persons in 100 accidents at sea [5].

Number of people involved	Number of human errors											
	0	1	2	3	4	5	6	7	8	9	10	Total
0	4											4
1		3	18	14	6	4						45
2			4	11	16	7	2	1				41
3				1		3	2	1	1			8
4							1				1	2
Total	4	3	22	26	22	14	5	2	1	0	1	100

The authors of ref. [5] also performed a classification of the in total 345 human errors according to Feggeter's classification system [6].

Table 3. Classification of human errors in 100 accidents at sea [5].

Type	Feggeter's category	Overall frequency of errors	No. of accidents in which the errors occur
	Cognitive system		
1.1	Human information processing	44	35
1.2	Visual illusions	2	2
1.3	False hypothesis	60	51
1.4	Habits	50	46
1.5	Motivation	1	1
1.6	Training	41	35
1.7	Personality	43	35
1.8	Fear	0	0
Subtotal (%)		70 %	93 %
	Social system		
2.1	Social pressure	20	17
2.2	Role	2	2
2.3	Life stress	2	2
Subtotal (%)		7 %	21 %
	Situational system		
3.1	Physical stress	18	12
3.2	Environmental stress	22	17
3.3	Ergonomic aspects	39	34
Subtotal (%)		23 %	56 %

In ref. [1] a somewhat different grouping of human causal factors is made based on principles proposed by J. Reason [7].

Level 1 Human violations or errors

1. Human violation
2. Human error

Level 2 Violations and error types

1. Violation (deliberate decision to act against rule or plan)
2. Slip (unintentional action where failure involves attention)
3. Lapse (unintentional action where failure involves memory)
4. Mistake (an intentional action where there is an error in the planning process)

Level 3 Underlying factors

1. Physiological
2. Psychological
3. Physical
4. Others

Level 4 Latent factors

1. Physiological
2. Psychological
3. Physical
4. Others

It has become more and more evident, however, that the individual human errors or mistakes are not the only reason for maritime casualties, but the role of the whole company organisation must be studied in this context [7]. In IMO this has recently been recognised by introducing step by step in the regulations a quality magement system, called the ISM code [8].

5 INVESTIGATION OF CASUALTIES

The organisation which is used to investigate marine casualties varies from country to country. As the European Union is interested to harmonise the practices also in this area in its member countries, there is a so-called Concerted Action on

Casualty Analysis currently being carried out in DG VII(Transport). So far, the work has mainly been merely collecting of information on current practices in participating countries. Hopefully a more creative phase will follow in harmony with the IMO work mentioned above.

In Finland, an organisation under the Ministy of Justice, called Onnettomuus-tutkintakeskus (Accident Investigation Board), investigates all marine casualties where the ship is flying the Finnish flag or the casualty occurs within our territorial waters. Less severe casualties are investigated using the permanent staff of the organisation, but for severe cases a dedicated investigation commission is nominated by the Council of State and external experts are also engaged in the work. The investigation report is public and it may be criticised, but will not be revised.

The inherent problem in casualty investigation is the purpose for which it is made. In the present context the purpose should obviously be purely for the propagation of safety, eg. unveiling the causal factors and consequently learning as much as possible from casualties that have occured. This is, in principle, also the basis on which the statutes of Onnettomuustutkintakeskus are based. It works, however, in direct cooperation with the Central Criminal Police (KRP), which performs the questionings of people involved in the case. In Britain(MAIB) and Canada(TSB), for example, the casualty investigators work for pure safety goals under the Department of Transport, independently of police actions.

The importance of proper recognition and reporting of human factor aspects in the investigation process is underlined widely in IMO [1] as well as many of its member countries [9,10]. It generally suggests including suitable experts in investigation bodies.

Commissioned by the Finnish Maritime Administration, VTT and HUT have studied the reports of some 60 shipping casualties from several OECD countries which have a well established investigation system. The time range covered is 1979-95. The casualties are systematically described on specially developed forms in Excel Workbook format. Additionally, the recommendations made by the investigating bodies are reviewed and analysed [11].

6 AVAILABLE CASUALTY STATISTICS

There are many statistics available today, but none of them is comprehensive enough and they lack conformity. This has become apparent also at IMO. Therefore database work has been started. IMO requires information on very severe and severe casualties, but until conforming guidelines and reporting forms, the material is by far to superficial. Also an up-to-date database system must be introduced to manage the work properly. Unfortunately, IMO has very limited funds for any effective project work, and this may cause delays.

To have an overall view on casualty frequencies in the world, the authors of ref. [12]. have collected the results of several earlier studies. In Finland, the Finnish Maritime Administration collects annually our own national statistics, which are presented in ref. [13].

Table 4. Finnish casualties in 1968-95 according to FMA statistics.

Year	grounding	collision	cintact	failure	capsizee /leak	fire	cargo	other	total
1968	53	29			3	7	9	40	**141**
1969	41	40			5	6	1	22	**115**
1970	37	44			4	5	5	22	**117**
1971	33	25			1	6	3	22	**90**
1972	31	29			1	2	1	18	**82**
1973	28	20			2	5	5	19	**79**
1974	21	24			3	2	4	26	**80**
1975	35	13			0	5	5	25	**83**
1976	32	20			1	3	5	20	**81**
1977	32	17			2	4	8	33	**96**
1978	28	27	4	8	8	5	8	1	**89**
1979	32	18	1	9	8	4	7	2	**81**
1980	34	16	4	7	4	6	8	2	**81**
1981	26	22	5	4	6	7	3	0	**73**
1982	29	24	5	6	15	7	3	3	**92**
1983	29	10	6	3	5	3	7	2	**65**
1984	15	14	5	2	6	3	4	1	**50**
1985	28	21	7	5	6	4	6	1	**78**
1986	20	6	6	4	4	2	7	0	**49**
1987	28	20	4	4	10	5	2	3	**76**
1988	27	15	3	3	9	14	2	2	**75**
1989	30	13	3	2	4	2	1	0	**55**
1990	23	8	12	0	4	10	4	3	**64**
1991	25	13	3	1	6	8	0	0	**56**
1992	30	13	2	3	2	6	3	3	**62**
1993	21	8	6	3	2	2	2	4	**48**
1994	11	4	9	10	2	3	1	3	**43**
1995	10	10	6	0	2	4	2	0	**34**

7 CONCLUSIONS

The general picture of marine casualties show a number of lesser accidents, which are not too well reported and investigated. The severe casualties are in most countries investigated thoroughly, but conformity of the process should be improved along the lines under way at IMO. Then we have the well-known maritime disasters, which occur perhaps once per decade and are not easily accessible by any statistical or probability tools. And even many more spectacular casualties may be rather difficult to cover by the normal insurance methods, as certain ship types still tend to grow in size and liabilities involved [14].

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ASSESSMENT OF RISKS IN SEA TRANSPORTS BY THE SYSTEMATIC METHODS OF RISK ANALYSIS

Markku Reunanen & Risto Tuominen
VTT Manufacturing Technology
Tampere, Finland

Summary

This paper illustrates the risk assessment approach as it is seen to be applied in systematic examination of risks in the field of marine transportation. The need for proactive, systematic and auditable approach for managing maritime risks is explained. The main body of the paper is dedicated for illustrating practical aspects of the implementation of this approach.

1 INTRODUCTION

Successful management of risks is established on an agreed policy with respect to risks, an organised and planned approach to implement this policy, and, finally, on proper knowledge of the undesired system behaviours and outputs. Risk assessment is the part of the risk management process intended to provide the knowledge needed in order to make correct decisions on priorities, risk reduction or control measures, tradeoffs against financial resources available, etc.

Requirements that are placed on the processes to produce the risk knowledge can be seen to have shifted along the changes in technology and business environments. Increasing complexity of systems, rapidly evolving new technologies, low-risk and high-severity systems, increasing pressure for cost savings and cost-effective solutions, and reduced social tolerance to major losses are factors commonly accounted for the shifting requirements. When placed into the context of sea transports following types of needs in relation to successful implementation of the risk assessment process can be identified:

- need for proactive, systematic and auditable approach
- need for holistic approach
- need for informative system descriptions
- need for hierarchical approach
- need for quantitative assessment
- need for probabilistic data
- need for understandable risk communication
- need for dedicated risk analysis methods and tools
- need for crew participation

These identified needs are briefly discussed in the rest of this paper.

In this paper, the risk assessment procedure and the systematic risk analysis methods have been mainly considered as tools for designers and operators within the shipping industry to provide support in their risk management activities.

2 NEED FOR PROACTIVE, SYSTEMATIC AND AUDITABLE APPROACH

The traditional way of considering safety issues during the whole life cycle of technical systems is "adherence to good practice". This consists of observing the rules and regulations, meeting the requirements of the accepted standards, and following the practices that have been proven from years of experience with the same processes, the same hardware designs, and the same operating and maintenance procedures. "Adherence to good practice" is claimed to have been the principal way of addressing safety issues in the design and operation of ships, too (Bell 1995).

The aerospace and nuclear industries were among the first to develop and apply proactive systematic techniques for assessing the safety of their complex technical systems. The techniques then spread to other sectors involving high risks, especially to the chemical and petrochemical industries. Over the past few years there has been a growing awareness of the need to supplement the "adherence to good practice" approach by the application of proactive and systematic risk-based approaches within the maritime industry, too. The draft guidelines for application of formal safety assessment (FSA) to the IMO rule-making process (IMO 1996a) is one indication of the current progress within the maritime industry. According to Jenkins (1995) the leading marine operators are beginning to use risk assessment, too.

2.1 RISK ASSESSMENT PROCESS

Risk management is the process of weighing alternatives for controlling risks and selecting, implementing and monitoring of the most appropriate course of action. As illustrated in figure 1 (cf. IEC 300-3-9 1995) risk managers may base their decisions on the information provided by the risk assessment process.

Peachey (1995) makes a distinction between qualitative and quantitative risk assessment. Qualitatively, the risk is referred to situations or events associated with a potential loss, i.e. accident scenarios. Qualitative risk assessment is done by categorising the components of risk, frequency and consequences associated with a particular accident scenario, descriptively. The results of a qualitative risk assessment can be presented e.g. in the form of risk matrix that also contains the criteria for risk acceptance. Quantitative risk assessment is done by estimating the components of risk associated with a particular accident scenario by frequency analysis and consequence analysis methods, and by comparing the risk estimates against quantitative risk acceptance criteria. The analysis of risk management options may involve a quantitative cost benefit analysis.

Hazard identification involves a systematic review of the system under study to identify the hazards that are present together with the ways in which they could be realised. The essential question in hazard identification is what can go wrong in terms of accident scenarios. Identification of all hazards together with the relevant accident scenarios is a vital step in the risk assessment process due to the fact that what is not identified cannot be assessed and managed.

Various systematic methods of risk analysis are typically employed at different phases of the risk assessment process. These methods are briefly discussed elsewhere in this paper.

IMO prefers to call its new approach Formal Safety Assessment (FSA). The word "formal" is explained to reflect the structured and systematic nature of the FSA approach, wherein modern techniques of the safety assessment are used in a comprehensive and rigorous way, with the process being formally recorded and hence auditable (IMO 1996 b). The quantification of safety is typically carried out indirectly, by applying the concept of risk for that purpose. That is why e.g. the terms risk assessment and safety assessment can be considered interchangeable.

Process step	Hazard identification	Risk (or safety) analysis	Risk (or safety) assessment	Risk (or safety) management
1 Identification of hazards • Identification of hazards and the associated accident scenarios	Hazard identification			
2 Estimation of risks associated with the realisation of the hazards and accident scenarios identified • Frequency analysis • Consequence analysis • Risk calculations		Risk (or safety) analysis		
3 Evaluation of risks • Risk tolerability decisions • Analysis of risk management options (alternative ways of managing risks)			Risk (or safety) assessment	
4 Reduction and control of risks • Decision making between the risk management options • Implementation of the selected risk reducing measures • Monitoring of safety performance				Risk (or safety) management

Figure 1. Risk management process (c.f. IEC 300-3-9 1995).

3 NEED FOR HOLISTIC APPROACH

The systems of shipping to be considered in the risk assessment studies are complex including not only the ship hardware, the crew, and the potential passengers aboard, but also the route and the associated environmental conditions, the cargo, the harbour facilities and organisations, the traffic control/support systems and organisations, the shore-based fleet operations and management, etc. Instead of considering these components in isolation, it is necessary to pay attention also to the different types of interaction that take place between the components. The risk assessment approach to be used thus needs to adopt the concepts of socio-technical system and systems approach.

The need for a holistic approach in tracing the possibilities for shipping accidents is illustrated from one point of view in the etiology of the catastrophic accident of "Herald of Free Enterprise". The discussion by Rasmussen (1995) illustrates how operational decisions taken by individual decision makers in separate departments/organisations over time had interacting effects driving the system to the path of accidental events leading to capsizing of the vessel and to loss of 188 lives.

4 NEED FOR INFORMATIVE SYSTEM DESCRIPTIONS

Identification of hazards and assessment of risks are based on systematic examination of the structure and functions of the particular system of interest. Consequently, any risk assessment study has to begin by defining the system to be analysed and by preparing a systematic and comprehensive description of the system with reference to the analysis process it is supposed to serve.

The standard technical descriptions that are typically available on ships and ship elements are clearly insufficient alone to support any systematic and comprehensive consideration of safety. Instead, high level abstract descriptions that can capture the elements and complex interactions of the socio-technical system, such as a ship and its operating context as discussed above, would be needed. Such descriptions do not typically exist. Practical experience on risk assessment case studies will show the techniques that are most suitable for producing the descriptions of the socio-technical systems in shipping.

5 NEED FOR HIERARCHICAL APPROACH

Introduction of a hierarchical approach for risk assessments would be considered highly desirable in order to keep the resources and the effort needed in reasonable and cost-effective bounds without compromising the quality of the assessments. The aim of the hierarchical approach would be to ensure that enough attention, time and resources (i.e. optimal use of the available resources) are devoted to those issues that are the most important ones, risk wise. The basic strategy could be to start the assessment by system level examinations and to apply simple screening methods with easily accessible preliminary data in order to identify elements that due to their expected low risk contribution appear to deserve restricted additional attention. In the areas of significant risks the assessment is progressively carried on to the more detailed system elements.

6 NEED FOR QUANTITATIVE ASSESSMENT

Quantitative risk assessment provides the methods for probabilistic quantification of the accident scenarios found relevant in the hazard identification phase. For all of the accident event sequences (i.e. scenarios) frequency estimates of occurrence are assessed along with estimates of the potential loss (i.e. levels of undesired consequences). Explicit treatment of uncertainties associated with the risk model parameter inputs and propagation of these uncertainties is a fundamental feature of the probabilistic approach.

Quantitative assessments produce quantitative risk measures that can be used to support management and engineering decision-making during design, procurement or operational phases of the system life cycle. The quantitative risk measures whose uncertainties are properly defined should lead to increased risk awareness by management and an improved basis for making rational decisions. The analyses can typically provide:

- a quantitative assessment of risk, that is, a probabilistic estimate of the frequency of different undesired consequences of interest,
- an identification and prioritisation of the features of design and operations that contribute to risk (i.e. the main risk contributors),
- an identification and prioritisation of the features of design and operations that contribute to uncertainty with respect to risk (i.e. the main uncertainty contributors),
- a mechanism for risk-based evaluation of proposed modifications to the system.

By using the techniques and results of a quantitative assessment, such questions as "Which of the several candidate systems pose the largest (or smallest) risk?", "Which system elements are the main risk drivers?", "Are risk reduction modifications necessary?" and "What modifications would be most effective in reducing risk?" may be addressed. One can distinguish the main risk drivers from the less significant ones and subsequently concentrate the efforts of mitigation and control on these most important items at the cost of the less significant ones. One can use the risk measures as the basis of control and continuous improvement with respect to system performance. Also, with respect to system modifications, the analysis indicating whether a proposed modification reduces the cost-risk ratio sufficiently to justify implementation becomes available. Presumably same type of analysis could be used to support decision making in situations where, for example, new budget constraints request the decision maker to consider cost reductions in the existing (operational) risk control measures. The analysis could then provide advice on how to implement the requested reductions without compromising the current safety level, or the analysis could even prove such reductions impossible.

The quantitative approach clearly has certain benefits as discussed above when compared to the more traditional basically qualitative risk assessments. Influenced by these benefits and the methodology proven through its application especially in the nuclear industry, the formal safety assessment (FSA) approach proposed for application at IMO rule-making process emphasises the quantitative aspects of the assessments. The level of quantification needed in risk studies in general, however, appears to be dependent on the purpose that the assessment is serving. Fully quantitative assessment, although attractive from many points of view, is not necessarily always the one needed.

For example, in terms of providing a sufficient understanding of the possibilities for significant ship accidents, the accident scenarios arising from the qualitative analysis and describing the potential progression of postulated initiating events into the harmful consequences could very well establish the information needed. Also, when trying to demonstrate for a particular design that the residual risks are insignificant or reasonably low it may be possible to do it sometimes by qualitative arguments only. For some other cases, it could be that following an appropriate hazard identification process, the identified scenarios could be made subject to a screening process such that majority of the scenarios are qualitatively or semi-quantitatively adjudged to create insignificant or bounded level of risk, and that only a limited number of scenarios are required to be considered in more detail and assessed quantitatively. It could be just for the most severe consequences that the more sophisticated techniques would be required involving a detailed quantitative analysis including detailed modelling of accident scenarios with detailed estimation of consequences and occurrence frequencies.

7 NEED FOR PROBABILISTIC DATA

Lack of readily available probabilistic data could be seen as one of the main problems that could, in short-term at least, be limiting the use of quantitative risk assessment in the field of ship transportation. Considering the maritime applications it seems that very little operational experience data is systematically collected and will be directly applicable to support the data needs of the probabilistic assessments. This situation, which is often met in practice when a risk analysis is carried out, means that, at least in short-term, one must draw upon generic maritime data, data that might be available in manufacturers of ship equipment, and diverse data sources from related fields. The generic data sources for offshore, avionics, chemical process plants and military data handbooks are available for this purpose.

When statistically relevant data are not available for the events in the risk models expert judgements are typically used to capture the current state of knowledge with respect to the likelihood of the undesired events of interest. Quite a lot of effort has been put even in recent years in developing proper procedures for the elicitation and aggregation of expert judgements especially in the nuclear and space fields where quantification typically faces the problems of new novel technology and low-probability events. When expert judgements are applied, judgements elicited from a group of experts are preferred to judgements of a single expert. In order to avoid the various types of bias in the resulting data, well-defined, structured methods are recommended to be used when eliciting and combining expert judgements on probability distributions for the risk-significant items.

It needs to be stressed here that though the scarcity of directly relevant data is evident, it should not lead to a conclusion that one can not or should not perform probabilistic risk assessments for shipping applications as "the role of no or little data vis a vis good data" most certainly should be assessed. The role of expert judgements would presumably dominate in short run. In longer term, one may want to consider implementation of systematic data collection schemes and dedicated data banks. The needs of more systematic data could also warrant the creation of an international maritime data bank in addition to ship owner and ship specific data collection.

8 NEED FOR UNDERSTANDABLE RISK COMMUNICATION

In order to achieve credibility and acceptance among designers, managers and other possible parties expected to benefit from risk assessment results, it is necessary that considerable attention is paid on techniques that are applied in communicating the risk assessment results. This is important especially with respect of the probabilistic risk assessment approach. It could be recommended that also in risk assessment studies that are performed in the maritime sector, at least initially, fair amount of resources are allocated to the communication activities so that the information produced can emerge e.g. in the form of well planned Risk Summary Reports (c.f. Fragola 1995).

9 NEED FOR DEDICATED RISK ANALYSIS METHODS AND TOOLS

Various risk analysis methods exist for hazard identification and risk estimation (for an overview, see IEC 300-3-9 1995). Different types of methods have been developed to meet the requirements arising from the large variations in type of systems to be analysed, the nature of risks, the needs of and resources available for the analysis. Different hazard identification methods for example have different search patterns, resulting in the cumulation of information when several methods are used in combination and their results integrated. Hazard identification methods considered to be suitable for use in the shipping industry include (Peachey 1995, Spouge 1996, IMO 1996a):

- Failure modes, effects and criticality analysis (FMECA)
- Hazard and operability study (HAZOP)
- Brainstorming
- Human reliability analysis
- Structured what-if checklist (SWIFT)
- Fire hazard review
- Flooding hazard review
- Safety management audit

Most of these methods have been established and proven in other industries, and are considered to be readily transferable to shipping.

As with hazard identification, techniques for the estimation of risk are also well established and proven. They include for example fault tree analysis (FTA), event tree analysis (ETA), reliability block diagram, paired comparisons and category rating (IEC 300-3-9 1995, Peachey 1995, Spouge 1996, IMO 1996a).

Fair number of computer tools currently exist to support execution of the various risk assessment techniques. In the qualitative risk analysis the tools would typically provide help for documentation, routine clerical tasks, report generation, and configuration control. In the quantitative risk assessments software routines clearly are a necessity required to carry out the different types of risk calculations. Fairly simple PC tools already exist by which even reasonably large sets of scenarios can be quantified as fast as in tens of minutes time.

Most of the risk assessment tools tend to be more or less generic by nature though they have been evolved in specific fields of application. Many of them would be directly applicable in the maritime field, also. On the other hand improvements in performance, both time, cost and quality wise, could be expected by dedicated tools tailored to fill the specific needs of maritime risk assessments.

10 NEED FOR CREW PARTICIPATION

In many cases, it has been found very useful to have the system operators to participate directly the risk assessment process as experts having important knowledge about the risks. This is obviously true, in particular, when the assessment is directed on operational aspects of a specific system on which the operators have gained extensive hands-on experience.

On the other hand, in many cases, the operators can rather spontaneously also point out specific features in the technical equipment and facilities which they perceive as more or less important risk factors. Such features may be considered as symptoms of potential deficiencies in the technical design and/or its realisation, indicating perhaps a need for more detailed technical analysis on the particular item in order to be more certain whether the suspected risks are real. The use of operator experience would thus give advice on how to allocate the analysis resources and focus the analysis effort on the system. Of course, detailed technical analyses of the most critical equipment and subsystems would still be needed, irrespective of judgements of the operators, in order to verify that the designs are acceptable.

Furthermore, even when assessing the risks of completely new technologies or concepts, the previous practical experience of the operators on the application area in question, although on different hardware, can still be very helpful in providing insight into the variety of potential problematic situations and the criteria applicable for judging the performance, both needed to scrutinise the new system. Such assessments, typically performed via a close dialogue with system designers, could, in particular, reveal risks related to system behaviours that are found to be inconsistent with the expectations of the system operators. The findings could call for improvements in the technical system or they could prove it necessary to figure out the proper means that can be used to change the operator expectations as the new technology is introduced to use. One can try to improve anticipation of potentially catastrophic low-probability events which fall outside the experience of the operating personnel by including external specialists in the assessment team.

Using a ship crew, or a selected set of system operators in general, as a group of experts which is consulted in a risk assessment study places specific requirements on the analysis methods to be applied. Some of the common standard methods, such as, for example, FMECA, are found to fit rather poorly on assessments that are carried out in subject matter expert groups. Some other methods are found to better support the group processes. Along with some other things, success of the analysis approach appears to depend on how intensively the group members can find themselves to be able to participate the discussion and to influence the consensus output so that each of them can remain highly motivated throughout the analysis sessions. Along the analysis method and the protocols applied, selection of the members of the expert group, of course, plays an important role on the success. Typically, different experts would be needed depending on the depth and focus of the analysis. Diversity of backgrounds among the team members is desirable in system level assessments.

Participation of crew members in the risk assessment sessions can greatly improve their safety awareness and motivation towards safe operational practices leading to improved safety aboard.

11 CONCLUSIONS

A change of the paradigm to manage risks can be seen to evolve in the maritime sector. The traditional "adherence to good practice" approach is in the process of being supplemented by the application of proactive and systematic risk-based assessments. The two approaches can be seen to merge into a balanced and cost-effective regulatory activity.

Use of the risk assessment approach and the number of applications can be seen to increase both among ship operators and among ship builders as the benefits of the approach begin to be more widely realised.

More practical experience on the use of risk assessments in shipping is needed in order to see the potential problems and deficiences in their use and to tailor the methods and tools to better fit the special needes of shipping applications. Together with the development of individual methods, practical guidelines to support selection of analysis methods and development of proper analysis protocols would be needed.

Computerized tools that are simple and can support the execution of the risk assessment tasks are needed to be introduced to the shipping industry. Such tools would constitute one of the measures needed to ensure that the assessments will be cost-effective.

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FIRE PROOF ENGINE ROOM

Pentti Häkkinen
Helsinki University of Technology, Ship Laboratory
Espoo, Finland

Abstract

Fire safety in ships generally and in engine rooms is a result of good design and correct operations. All fires are widely different. All engine rooms are different. Quite small deviations between the sister ships may conduct identically started fires into totally different conclusions.

Fire resistant engine room is less likely to fire outburst than average one. It is more likely to remain navigable after a fire. It is definitely difficult to design, especially when economical factory are observed.

The paper describes the research project on engine room fire safety. The criteria, approach, and methods provide the designer with knowledge and tools for improved safety.

1 BACKGROUND

Ship fires are generally well known. The cases are investigated (with various accuracy) and reports submitted to IMO. IMO and classification societies issue statistical data and synthesis reports /1, 2/. Increased attention is currently paid to incidents and near miss cases that could have led to serious fires but fortunately do not.

Ship fires lead seldom into disasters. In most cases the number of fatalities is limited and losses are only economical. However, some 100 ... 200 fires are reported annually and about one third of them started in engine room.

Fire safety in engine rooms has been secured in multiple ways. IMO and other authorities have controlled the development by detailed regulations on ship structures and equipment. Specific regulations are applied to ship machinery and engine room.

The generally approved approach form sequential criteria:

1. Fire should not be ignited. If ignited, fire should be detected without delay.
2. The detection should cause an alarms of activate extinguishing of other appropriate action.
3. The extinguishing should be rapid and efficient.

4. Personnel should be evacuated without delay.
5. Fire should be spatially restricted in the zone of origin and spread-out prevented.

The classification societies' regulations specify the technical solutions needed to fulfil these criteria. Technical details are not repeated here.

The investigation of engine room fire reports raised new questions:
Should the a.m. traditional criteria be complemented with some others?
Is it possible to quantify the degree of engine room fire safety? If so, is it possible to find more economical solutions to meet pre-set safety level?
Do human aspects receive sufficient attention in the design of engine room?

Further processing of these questions and consequent research was the contents of Fire resistant engine room research project executed in 1995-7.

2 FIRE RESISTANT ENGINE ROOM

Fire safety can be defined in many ways:

Statistical rating is based on number of annually reported fires. This produces the *probability of fire*, a figure that can be processed to distribute engine room, specific ship age, specific flag and other items. Main drawbacks are: Incident are not included in statistics. Seriousness of engine room fire is not included. Statistical data does not reveal primary reasons nor other features that are important for improved design.

Number of fatalities or economical losses are reflecting the seriousness of ship fires. They are no delivering useful information for improved design.

Engine room fires must be analysed as processes starting long before the ignition, when fuel oil spray from a fracture pipe joint enters a hot surface.

2.1 OBJECTIVES

Objectives for the completed research project were to (1) design engine room that has significantly higher fire safety than concurrent designs and (2) reach alternatively an equivalent fire safety with significantly reduced cost.

Fire safety here included the established criteria:

- Low probability of ignition
- Early detection
- Efficient extinguishing

- Safe evacuation of personnel
- Prevention of fire spread-out to adjacent compartments

And those which were formulated during the first phase of research:

- Avoiding the fire hazard in normal and in abnormal conditions
- Securing essential functions during a typical fire
- Limited repair costs after the fire

2.2 FIRE SAFETY CRITERIA

'Normal conditions' refer to cases where fire is typically ignited by mechanical damage. Common example is diesel engine crank case explosion when heavy engine piece hits equipment containing oil causing both leakage and ignition of the combustible liquid. We wish to describe these fires as completely *unexpected.* More profound approach may reveal dimensioning error in engine, prolonged operation with worn-out piston rings, overloading etc.

'Abnormal conditions' refer to conditions where unexpected, rather harmless incident leads to outburst of fire. Compared with the previous chapter cases, here are designer's errors, operator's errors, ignorance or negligence included. Typical examples: Combustible material is temporarily stowed where oil leak or spray is most probable, thermal insulation cover has been removed during service operations and left uninstalled just for a coffee break, piping has been installed so that ruptures are caused but in an invisible location. Some equipment has been temporarily repaired violating safety rules but the repair was not mentioned to anybody else. It is only operational standard than can systematically prevent serious designer's and operator's errors. They cannot be prevented by general occupational safety campaigns. Systematical safety planning and involvement of the entire organisation is required to prevent the errors and accidents.

There is no such equipment that can resist heat and remain operative during hours in burning engine room. Such equipment would in any case be too expensive. In respect to structures, this is also admitted when bulkhead insulation class notations include time indication 15, 30 or 60 minutes. But improvements are possible, causing various cost increase.

Temperature during engine room fire rises above 500 °C, up to 900 °C. In principle, the amount of combustible material is limited and oil supply can rapidly be disconnected. In practice, the fire duration has been 15 ... 120 minutes until final extinguishing or consuming all the combustible material. It is necessary to specify the time of fire duration that the essential equipment should withstand. Likewise the essential equipment should be specified.

Repair costs after fire is a criterion that is seldom applied. Engine rooms in merchant ships are simply not analysed in respect to easy repair nor low cost repair. Nevertheless, many limited engine room fires have caused 3 ... 12 week off hire time. Cablework and other equipment that are most probable to damage in fire, have not been designed for swift replacement. Even the removal of scrap and debris from engine room is difficult. It should be investigated if significant improvement in this respect could be achieved with low or moderate costs.

Another feature of reparability has strong connections to the engine room fire safety. Some of the essential functions may be lost during the first minutes of fire. This is possible even if the equipment would be of improved, 'fire resistant' type. In normal conditions the function and performance could be restored in a short time but during fire it may be impossible to approach the equipment. As it is not possible to install parallel systems for every function. The reparability of essential equipment - still during the fire and even temporarily - should be investigated.

Tools to recognise the condition of vital systems during the fire and especially to predict how long time they will remain operable, would be very useful for decision making.

2.3 SCOPE OF RESEARCH

The design project concentrated in the engine rooms of diesel engine driven ships. Both mechanical and electrical power transmission systems were studied. Propulsion power. electric energy and heat generation systems were analysed. Auxiliary machinery supporting these systems, fire and bilge systems were also included. Selected passive structures were included.

In general, other types of propulsion machinery, dry and liquid cargo handling were left outside the scope. Gas turbine plants have inherently high fire safety, mainly due to the modular enclosure. Oil tanker cargo area and cargo handling equipment have been involved in serious fire accidents. They are not investigated here.

2.4 METHOD

Important part of the research was thorough investigation of engine room fires. Many fire cases described in detailed and excellent reports. Direct contacts were used in many cases to give additional information and parallel reports obtained in some cases.

Expert interviews were systematically used to predict ht probability of fires and various incidents in the engine room. The population was limited but resulted in rather similar frequency rate of the asked incidents.

The research was organised into sub projects that are listed below in the end of chapter 2. This division was based on the working organisation.

The expert interrogation results were used as input figures in NFPA - type probability tree /3/. The fire and hazard risks were calculated.

As the properties of all engine room components were systematically analysed, technical data was requested form several manufacturers. The harvested data amount was modest, as expected. Most manufacturers were willing to contribute but did not possess the required product knowledge.

Engine room components were investigated in respect to construction, materials, vulnerable bearings and gaskets, content of combustible material and ignition energy. No mathematical methods were applied here; the analysis was mainly comparison, based on empirical facts.

The approach can be visualised in Table 1. Every component and structure was given various roles. Contents of the table are not accurate nor complete, and should be regard and guidance only.

One of the investigated methods was numerical simulation of engine room fire. Several methods for fire simulation have been utilised in stationary plants. Great differences between the modelling accuracy and consequently the input data and results can be found. The target was to test how efficient and user-friendly the simulation methods can be. There is a need for temperature rise and smoke flow prediction tool. Such tool would indicate the efficiency of compared fire safety improvement actions. In most simple case those actions would be relocation of a single component, new enclosure, intensive cooling in case of fire, modified structure or heat resistant materials etc.

The sub projects were:

1. Risk analysis and performance of fire simulation tools
2. New extinguishing and fire detection systems
3. Investigation of normal and improved materials
4. Analysis of single components and passive structures
5. Man in engine room
6. Engine room concept: summary of fire safety improvement methods and designer's guide.
7. Reparability

3 RESULTS

The details are not discussed here in detail. They can be found in the 290 page project report /3/. The statement in several chapters is that more profound research is needed. This is an important result while in some other items it was found that the solutions have very limited influence on the engine room performance during fire.

Risk analysis indicates that incidents are frequent and fire risks cannot be neglected in any circumstances. Maybe the maintenance operations at sea have the highest risk levels.

Fires are highly different in respect to origin and the whole process. The use of 'average type fire' is pointless.

Simulation calculations with *two-layer model* and two separate fire power levels indicate that further research and designer's instructions cannot be based on numerical simulation. The models cannot find any difference if e.g. a single component is moved 2 meter distance. In real engine room such relocation may bring decisive improvement.

Water mist as extinguishing system eliminates most of the disadvantages of carbon dioxide, various foams, fire water or halon systems. In some cases a combination of two extinguishing systems has more benefits than water mist alone. The accurate analysis has been based on manufacturer's recommended systems and their cost comparison. No reliable and universal data is available to compare their fire extinguishing efficiency. Even if such data were available, assumption of the fire would bring uncertainties.

Rapid release of total flooding extinguishing system is very important. Delays should be minimised. Carbon dioxide system suffers from delays when all openings must be closed and personnel evacuation confirmed before the gas is released in the compartment of fire.

Fire detection system should include both smoke detectors and flame detectors. Half of smoke detectors should be of optical model, half of ion type detectors. Flame detectors in engine room are preferably of IR (Infra Red) type that is more reliable in open and well ventilated spaces than the smoke detectors. Flame detectors are less suitable for smouldering fires than such fires where clear flames and rapid heat generation a typical. When fuel spray is efficiently mixed with surrounding air, less smoke is generated.

Most detection systems utilise standard point detector units. Alternative sampling system has been installed in stationary plants with good results.

Gas analysers can be used for early detection of increased fire risks. There is no practical experience available. Explosive and generally abnormal gas can be detected and alarm given before explosive or dangerous pyrolytic gas content.

Unfortunately too many gas compounds should be detected in the alarm sensors. Efficient ventilation also dilute the atmosphere that enters to the sensor unit.

Traditional portable extinguishing units and sight, hear and smell observations have been valuable in several engine rooms. If engine room round tours are further reduced, significant improvement in remote controlled fire detection and extinguishing systems is required.

Cable insulation materials and plastic pipes are investigated among engine room materials. Further research is required in new fire insulation materials and insulation paints. The additives that improve fire resistance of plastics should also be investigated in detail.

Engine room components differ greatly in fire safety. Significant improvement, mainly voluntary has been made in diesel engines. For other components, there is great variation between different makes and models. Improvement can be proposed for several detail cases.

Engine room structures in fire have not earlier been systematically analysed. Hull strength members are not in danger. (Only exemption are the aluminium hull high speed craft.) Also the platforms and pillars have kept their load carrying capacity in typical engine room fires. Gangways, stairs, platform grids etc. should be designed in respect to fire and smoke propagation.

Man in engine room investigation shows that fire safety can significantly be promoted by improved design of various components and engine room layout. Man is analysed in various roles which gives tools to detect the unsatisfactory solutions. Almost all fire reports prove that improved design would have greatly restricted the fatalities or damages. However, only few of those items have been recognised in the final report chapter; *recommendation.*

Most engine rooms were not designed for easy cleaning. Neither were systems designed for easy detection of wear or leak. Escape routes were are compromises that were primarily designed to meet the regulations. Such conclusions are frequent results of the analysis.

When engine room fire is started, rapid countermeasures are in general required. Surprisingly many fires show that at later stage immediate decisions and actions are not crucial. The correct decisions are more important than urgent actions. Time can be spend for situation evaluation and information search.

Engine room concept summarised the fire safety improvement methods by evaluating the two remaining: parallel safeguarding systems and rational layout. Further research items for smoke control are proposed. Smoke is highly toxic and accelerates the fire spread-out. Active smoke control in engine rooms has not been developed. The chapter proposes numerous construction ideas that would prevent the start or propagation of fire.

Reparability gives guidelines and includes proposals that facilitate the engine room system restoration at sea and repair yard. Further work can be done on general level, without the need to focus on a specific ship.

4 CONCLUSION

All fires are different, already from the origin. The wide difference of shops and engine rooms dictate that fire spread-out and consequences are widely deviating. Designer's guide book is indeed an extremely difficult opus to compose.

Engine room fire safety has been efficiently promoted in many parallel ways. However the fire resistance of components and other vital questions have been studied only sporadically. The need for efficient utilisation of design tools is apparent and has been surprisingly neglected.

Fire resistant engine room is the first documented attempt to improve fire safety by engine room design. Great share of the work has been problem analysis. Formation of new questions and proposing further research is the core result. In addition, the results include directly applicable solutions.

Engine room fire safety can be and must be improved. The generally satisfactory status that is shown in statistics, is not achieved by safety engineering. It is worrying to state that important cofactors have been engineering art, improvisation, and - good luck.

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3 Häkkinen P. et al, Fire resistant engine room - project report (in Finnish) Helsinki University of Technology, Ship laboratory report M-215, Espoo 1996, 290 p. *This report contains references to 50 various papers on engine room fires. They will not be repeated here.*

Table 1: Engine room components in various roles. Safeguarding *denotes various ways of raising system safety: parallel functions, stand by units etc.*

Role Item	**Igniter (fierce/slow)**	**Propagating ignited fire**	**Requiring protection**	**Obstacle or shadower**	**Vital unit /Remark**
Diesel engine	fierce, many ignit. patterns	generally no	difficult full enclosing	obstacle for escaping	vital, stand-by unit?
Turbocharg.	hot surface	generally no	difficult	no obstacle	stops engine
Reduct. gear	generally no	no combustible	not required	minor	vital
Elastic coupling	practically no	practically no	if enclosed, ventilation!	*cul de sac*	safeguarding
Friction clutch	may become hot if slipping	practically no	practically no	in some cases	safeguarding!
Shaft line	no	no, bulkhead penetrations?	enclos. poss. if needed	in some cases	vital
Support bearing	no	no	enclosure or add. cooling	no	not vital
Hydraulic power pack	leak, oil spray	generally no	enclosure or add. cooling	no	safeguarding
Steam boiler	no	no	enclosed	some cases	not vital
Oil burner	yes, leakage or spray	yes	improved enclosure	no	not vital
Exhaust gas piping	in some cases	generally no	enclosed	no	no cause of engine stop
Exhaust boiler	yes, intensive soot fire!	generally no	enclosed, add. cooling	no	not vital
Cooling syst	no	no	add.cooling	big cooler?	vital
HFO unit	yes, oil spray	combust. oil	enclosing?	some cases	important
LO unit	yes, oil spray	combust. oil	enclosing?	some cases	vital
Oil purifier	seldom, spray	combust. oil	separ. room	no	not vital
Valves actuators	no	no	enclosure or add. cooling	no	some may be duplicated
Generator	seldom	no	enclosure?	some cases	safeguarded
Electr.motor	seldom	no	possible	no	some duplic.
Switchboard	short circuit	sparking	safe location	some cases	safeguarding
Power cabls	no	in some cases	var.methods	no	safeguarding?
Instrument cables	no	in some cases	many ways to protect	no	safeguarding
Transformer	when failured	short circuit	separ. room	no	safeguarding
Sensors	no	no	enclosure?	no	manual oper
Fans, ducts	no	smoke route!	enclosed?	no	not vital?
Oil tanks	generally no	practically no	enclosed (?)	no, integral	safeguarded
Air system	generally no	some risks	enclosure	small units	duplicated
Hydraulic oil pipes	cold oil is not major risk	in some cases	enclosure	no	some vital
Stairs, floors	no	no	add cooling?	some cases	parall.routes
Insulation	no	when oil soakd	normal encl.	some cases	reinstallation
Cable ducts	no	smoke route	add cooling?	no	safeguarding
Oily rags etc.	self ignition	fierce propagat.	metal pin	no	safety rules

HUMAN FACTORS IN THE BRIDGE ENVIRONMENT

Antti Haapio
Maritime Safety Training Centre
The Ship Simulation Unit
Espoo, Finland

Abstract

The human element has been seriously discussed in conjunction with marine operations for only a few years. Some companies and institutions have considered the defence mechanisms against this factor economically so valuable that management models and methods have been created to a large extent on the basis of protecting the system with carefully designed procedures, training, selection methods and incident reporting systems against the Human Element. The maritime management environment has changed a lot during the past twenty years. Today, the complexity in this branch is very high and possibly it is the pluralism in the management system which adds some unpredictability into the system. Some management experts have named the maritime industry to be the only existing industry where the name "Error Inducing System" is valid.

The ISM code was adopted some four years ago and will be fully mandatory during 1998. The STCW -95 takes effect between 01 02 1997 - 01 02 2002 and sets demands for the education and training of seafarers. Both the education and training shall follow the requirements defined by a quality system. Through implementing quality demands for the operation of the fleets, it is believed that the intricacy of the industry will diminish.

1 HUMAN ERRORS

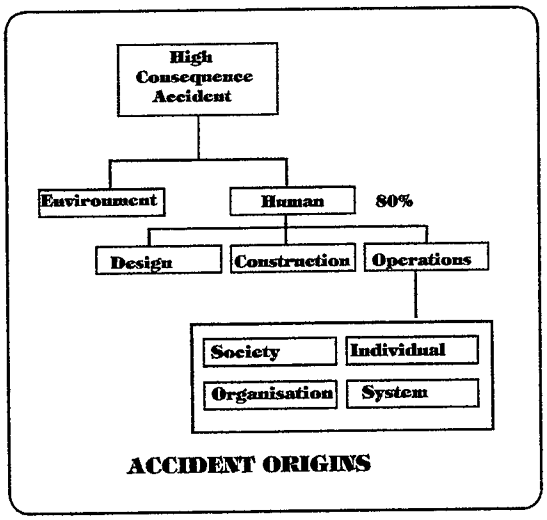
1.1 HUMAN AND ORGANISATIONAL ERRORS

Ship accident analyses have shown that the majority of accidents, about 80%, can be traced to human or organisational errors. 20% of the catastrophic accidents are caused by structural or mechanical failures under extreme environmental conditions' i.e. design loads have been exceeded. [2]

High consequence accidents resulting from human errors can be divided into three groups:

- design,
- construction,
- operation.

In many recent accidents the error chain has included items from each individual group. Accidents resulting from operations may have several origins: this may refer to the society with cultural effects, to the individual and his or her qualities, to the organisation or to technical systems, which should be sufficiently designed and documented. [2]



Picture 1.

1.2 HUMAN ERRORS

Human errors are well known to everyone. In many cases we tend to "explain" the causes for accidents as being of human nature, through blaming the controllers of their faulty operation. The actual items below describe the complexity of the human nature operating in an organisation. Human errors:

Fatigue	Wishful Thinking	Misjudgement
Negligence	Mischief	Sloppiness
Ignorance	Lazyness	Physical limits
Greed	Alcohol / Drugs	Boredom
Folly	Lack of Seriousness	Inadequate Training

The likelihood of errors are intensified under excessive stress and panic. [2]

1.3 ORGANISATIONAL ERRORS

Organisational errors refer to situations where actually no individual can be blamed for a malfunction but the organisation deficiencies have been the dominating factors, such as:

Time Pressure	Language Problems	Incentives
Cost/Proft	Moral	Communication
Rules & Regul.	Appreciation/promotion	Production Orientation
Management Style [2]		

It should be noted that the higher a person's position within the decision-making organisation, the greater is his or her potential to breed pathogens.

1.4 SYSTEM ERRORS

Systems with numerous functions and data presentations are often the source of errors and mistakes. The complexity of modern control systems is high and would require sufficient anticipation of the system operability under variable conditions before final implementation in order to identify the latent errors built into the system. Below is a list of some system errors:

Complexity	Latent Flaws	Excessive Demands
Close Coupling		
Lack of Redundancy	Small Tolerances	False Alarms [2]

2 TECHNICAL DEVELOPMENT OF THE SHIP ENVIRONMENT

2.1 NATIONAL DEVELOPMENT

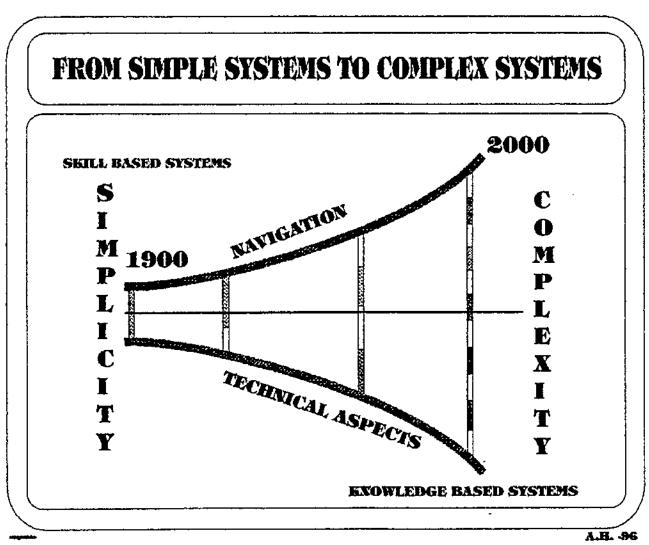
The maritime development during 1900 - 1960 was rather slow with respect of to technical progression. In the early 1900's one could still find persons who claimed that they were fully capable of it all, and it is indeed easy to say that they were probably right in saying so. During the '50s, the radars and autopilots were introduced. Radar brought visibility in darkness and in fog. Traditional ways of managing traffic and navigational situations altered; officers had to learn the utilisation of a relative motion "bird's eye" display, a rather large change in behaviour. In some cases the radar was not readily accepted and in some cases it was misused. The Rule of the Road noted the radar's existence in the early '70s. The first autopilots were also introduced during the late '50s. Helmsmen were not needed during open sea voyages. In many cases, however, people were still kept at the wheel during night time in order to avoid too long periods of inactivity. The most common vessels during the '50s were general cargo, tanker and passenger vessels. The average crew size was large. IMCO had over 30 members.

2.2 HARDWARE DEVELOPMENT AND SYSTEM DEVELOPMENT

The period from 1960 to 1980 brought about specialised vessels. Collision Avoidance Systems (CAS) and Automatic Radar Plotting Aids (ARPA), smaller crews ship's beam increase, blunt bows, controllable pitch propellers, bow thrusters, rate - and radius of turn autopilots, fin stabilisers, stabilizer tanks, heeling tanks, cargo handling systems, RORO ships, container ships, lash ships, heavy lift vessels, fairway marking systems etc. were introduced. IMO had over 110 members and over 35 consultative organisations.

2.3 ELECTRONIC AND SOFTWARE ERA AND THE COMPLEXITY BOOM

During the period 1980 - 1996, development advanced with accelerating speed, certain ship sizes increased, navigation systems were integrated, engine control systems were computerised, voyage preplanning demands set, voyage management systems were introduced, autopilots grew even more sophisticated, the positioning systems' accuracy developed into something one could only have dreamed of ten years earlier, Resource Management methods were introduced in the marine environment, International Safety Management Code adopted and implemented, as were separately driven twin rudders, rotatable propulsion systems, "black box" -type recording systems, DP systems, PC-based ship path simulators for analysis purposes, control system development on board ships etc. Today the most advanced bridges have nearly 20 control-oriented data systems and screens on the bridge.



Picture 2. The complexity today is manyfold compared to the beginning of the century, where one person was possibly competent in it all.

The increase in complexity has been enormous. This is well illustrated by the number of different sensors installed into the engine control systems, which may today exceed the number of 10.000 compared to the few hundred of the early '70s. In 1995 IMO had over 150 member states and over 50 consultative organisations. The various organisations affecting the maritime safety now number thousands. Nowhere in other industrie branches do we have such a scattered management model. Charles Perrow calls the maritime industry as an "error inducing system" in his book Normal Accidents. [1]

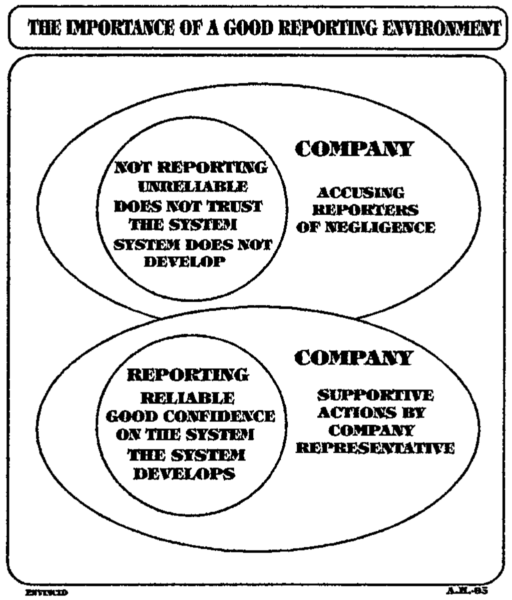
3 HUMAN (NATURAL) ERROR AND INCIDENT REPORTING ENVIRONMENT

The bridge and the engine control room are the extreme ends of maritime management: everything culminates here, i.e. all the various mistakes and misjudgements made by the organisations above materialise here. Many of them are so-called Human Mistakes (Natural Mistakes) made either in the organisations above the ship, onboard the ship or in both environments. In most cases recovery is made from these erroneous situations. The relation between accidents and serious incidents is something like one to a few hundred.

The so-called "Human Error" would be more naturally understood and more easily accepted if we talked about natural mistakes. There is nothing human about the mistakes but they are fully natural as part of life. Had there not been any errors or mistakes attached to living, the whole world would have been ready-made right from the start.

Why is it so difficult for the individual to admit that also he makes mistakes? This must be partly because the system of growing and education "punishes" us for the mistakes we make. This is just like in the nature, those animals who make more mistakes than average do not survive. However one should remember that we are no longer just beasts, but occasionally live in peace with our neighbours and colleagues. One should also remember that no human or beast shows its weakest capabilities first, but tends to hide these as long as possible. We humans resemble animals. It is difficult for us to confess that we made a mistake or that this is our weak part. It seems to be more normal that we give good grounds why we did what we did, in order to cope with ourselves.

The surroundings of any sophisticated control environment today so complex that **misbehaviour and malfunctions need to be well documented.** It should also be remembered that this has also a positive impact on the economical aspects. A reporting system can be seen also as a last stage warning and correction indicator. There are about 400 - 600 incidents between serious accidents allowing sufficient time and amount of warning between accidents. Effective reporting means that **we must confess and record our own errors as well as the malfunctions of the control equipment.**



Picture 3. The closest atmosphere is vital for a successful reporting system.

How well such a recording system functions can easily be estimated by the number of incoming reports, and through comparing the amounts of technical deficiencies with the amount of human errors. **A well running incident reporting system on board any ship indicates good relationships amongst the employees and also a mindful management.** One can also state that caring for a well functioning reporting system is wise and allows a good base for a sound business.

It should be noted that even if an active incident reporting system is important and needed, it does not replace good and sound anticipation of ship daily operation, including preplanning and effective support methods.

A reporting system is also an important part of the ISM management. However, any new complex control system takes its time before the implementation phase is completed. A well documented incident reporting system forms the correct basis for the development of technical systems, personal capabilities and economics evaluations. A company's education and training contents benefit a lot from this kind of reports, keeping them up-to-date along the years. Aviation has a lot to give to the maritime environment both in reporting development and also in education and training. Many of the aviation reporting systems are accessible through WWW pages.

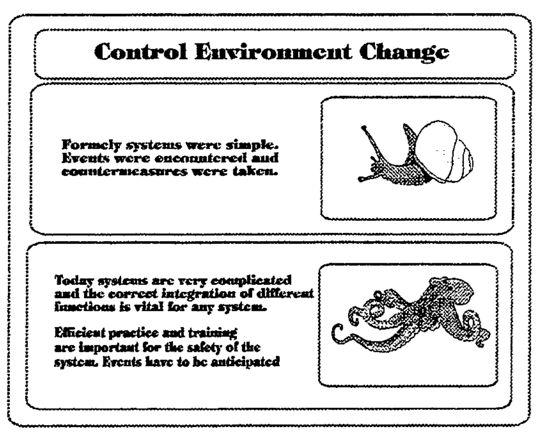
Confidence and trust within any organisation is the base for honest communication. In any control environment with high risks this trust forms the vital base for sound and safe operation, system development and management of high cost errors. The systems reflecting this openness or distortion well are incident reporting systems. Maritime magazines have published voluntary reports for some years. The reporters are all (100%) persons who have managed to prevent the situation from developing into a misshap. A sounder basis for reporting would be if the ones causing the situation had reported. This is an indication of mistrust to the whole higher maritime system. Is a reporting system running well if there are 30 reported technical faults and no human (natural) based ones?

3.1 HOW TO AVOID THE HUMAN ERROR

At present the maritime community has accepted the ISM Code as a management method for companies and ships. This management systems recognies the present rules and regulations and creates a Safety Management System, the task of which is mainly to define:

- safety (part of economical operation) and environmental policies,
- create instructions and procedures,
- define authority levels and communication channels, create an incident reporting system,
- prepare procedures for and respond to emergency systems and also procedures for audits and management reviews.

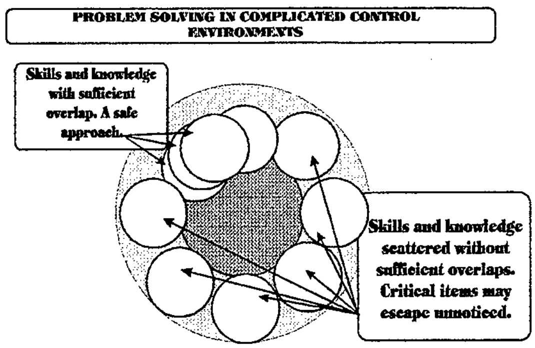
Anticipation or preplanning is actually the word that should be used in connection with ISM.



Picture 4. Anticipation of events is vital for any system today.

Some three years ago Scandinavian Airlines System completed a Crew Resource Management package for mariners called the Bridge Resource Management. This multimedia-based training package has been adopted very widely by the maritime control environment. The aim of this training is to create an atmosphere where all those involved in the control participate in the decision making and monitor the progress. The methods introduced by this course increase safety on the bridges and engine rooms. One could also say that BRM decreases complexity and uncertainty among those responsible, by allowing more efficient teamwork through easier communication. The training method and model have been adopted from aviation.

Ship management has accepted the management methods readily, but the implementation seems to suffer from initial problems. This has its effect on the behaviour of the teams, and in the worst cases still creates situations where only one of the team is active and the others are passive partners. It is often believed that the BRM management method is something for ships only, but the modern management methods for any company are very similar to the resource management course. It may well be that it is not understood that the effective utilisation of the BRM methods calls for a cultural change, which can only start from a carefully controlled and guided attitude change within the whole company. Similar difficulties have been met in aviation [9,10]



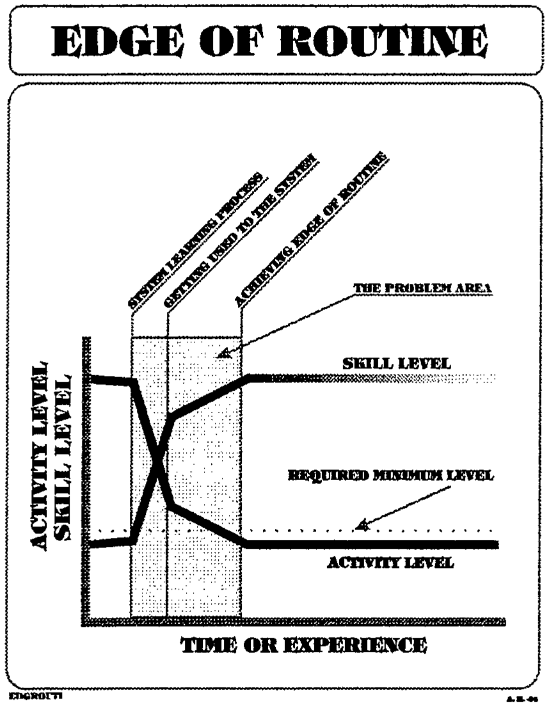
Picture 5. Only sufficient knowledge of any topic can create a real discussion.

The importance of backup skills and knowledge in a control team are not appreciated well enough. Any complex system where resource management methods are used should include multiple skill and knowledge overlaps to enable efficient decision making in a team. These overlaps form the basis of a mutual "language".

The resource management methods should be utilised throughout the whole education and training processes in order to create a demanding and favourable environment for a sound cultural change in control behaviour. Aviation started the CRM training in the early '80s and their experiences of implementing the behaviour show that the RM methods should be used throughout in training and education, thus indicating that it is always present and demanded. It should also be noted that **the company can use the same management model** in their daily action. [10]

3.2 EDGE OF ROUTINE

The edge of routine is one of major enemies in an automated control environment. To overcome the negative effects of "dangerous" routines **anticipating training** should be available at suitable intervals. The operating personnel should define what he suitable intervals are according to their experiences.



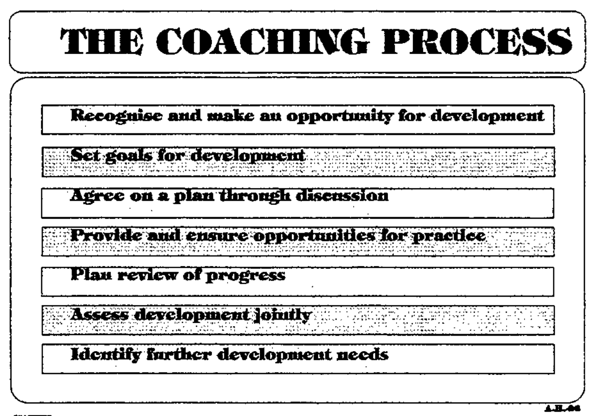
Picture 6. The Edge of Routine's effects should be systematically anticipated.

The main problems today in the bridge working environment are the numerous various bridge and system designs in use. This, combined with high or very high complexity, produces situations which are difficult or impossible to predict. However, a comparison with aviation and readiness to deal with exceptional situations shows a vast difference between these two industries. The aviation checks and tests such situations and creates procedures, i.e. tries to **anticipate** such situations, and also rehearses these abnormal circumstances using simulators at least twice a year. Aviation companies utilise standardised cockpits on similar aeroplanes, which makes it easy and efficient to licence pilots on certain types of aeroplanes. In aviation one is certified only for one type of aeroplane at one any time. (Changes to this practice are at hand with the new AIRBUS types of different sizes.) This should be part of the licensing process with the various control systems on board vessels as well.

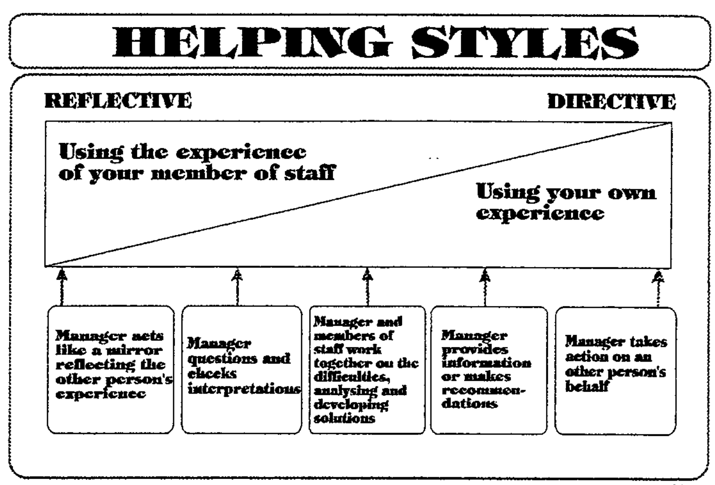
The maritime world is possibly the most scattered management environment of all the different industries.[l] Its complexity is very high and it seems that this tangled environment continues with its distributed and scattered responsibilities where connections and continuous communication tends to be a random ordeal. The number of maritime organisations is somethingwell over a thousand. Hopefully the introduction and implementation of the ISM code simplifies decision making in this unpredictable network. Scepticism has, however, a natural and fundamental place, since the QM system has first been assigned to the furthest and lowest level of management in the maritime hierarchy. QM-sertified organisations should basically deal only with organisations already possessing this certification. This may present problems. There may be a danger that the whole environment grows even more diverse.

3.3 THE IMPORTANCE OF COACHING

Training and education onboard vessels still presents a major safety role. The broad variance of control systems on bridges is a cost increasing factor especially if one ship owner has several differently equipped bridges. Most of the additional costs are invisible, since the education and training on board a vessel very seldom has a debet or credit item in the book-keeping. This disharmony of systems can also be considered as a negative safety factor; the transfer of people between different systems allows too short unlearning time for the operators and the negative end results may be totally unpredictable.



Picture 7. Items connected to coaching.

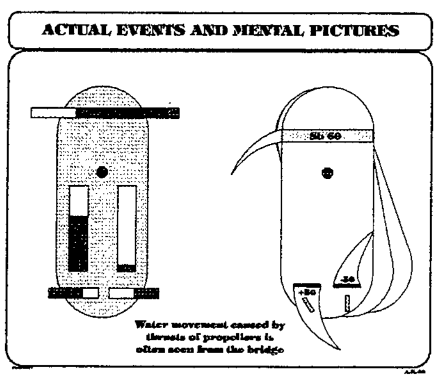


Picture 8. Coaching means capability to let others carry out challenging duties. [4]

4 THE TECHNICAL KNOWLEDGE AND SYSTEM LEARNING ENVIRONMENT

Some of the man-machine user interfaces require complicated interpretation and mistakes are readily available. In too many cases communication with high technology systems seems to be on a level similar to that of a beginner. This is partly due to insufficient testing, education and training on such systems and also lack of human centred equipment design. The economical impacts have in some cases been extensive.

The training arrangements are too often such that the actual "hands-on" training is given during the operation of the vessel, which will limit the practice of various system modes to what is considered safe. Exceptional situation training practice tends to be low, resulting in insufficient skills and knowledge of the systems. Aviation values exceptional situation training very high, rehearsing these skills at least every six months. A slogan used by aviation states: "If you think safety is expensive, try an accident". Another notable approach difference is that when new aircraft type training starts, flying with the previous aircraft stops, allowing time for the pilots to "unlearn" the previous aircraft.



Picture 9. Presentations should be developed!

This approach is totally missing from the maritime culture. Standardisation of control equipment has started within shipping companies.

In the maritime world, different system-oriented training is normally arranged and given by importers of different systems. Training commences mainly in ports under static conditions. Training lasts only a few hours, resembling a demonstration and those on leave are guided into the system secrets by trained colleagues. A few weeks after the training some 25% of the total training contents is still remembered. If this 25% is the basis for the training of those who were on leave while training was given by the importer, the end result of the training transfer is about 8 %. The effectiveness of such a familiarisation / demonstration period is low. System salesmen are often the same people carrying out the training. It may be difficult for them to reveal system deficiencies already known to them during the training period. A safer approach would be to follow the training models of aviation.

During simulator training it has been noted that insufficient technical knowledge is rather common. Similar results have been identified in the paper " Evaluating Shipboard Automation: Application to Mariner Training, Certification and Equipment Design." [4] This paper identifies even major shortages in the IMO ARPA model course, proposing fourteen additional learning objectives for the model course.

Control system development tends to be so rapid that the efficient training, education and control responses drag a few years behind this progress resulting in situations where learning system utilisation occurs in a real control environment.

Pilots are the group who control vessels with unfamiliar and variable systems. Ships, on the other hand, are normally operated in open sea conditions with automated systems resulting in diminished manual skills, which are often the operation method of pilots. "Mr Pilot, we do not have any capable helmsmen" is a rather common statement. Today some of the high-technology vessels are navigated into harbours using automated systems the pilot's role being that of a monitor. Are the pilot and ship's officers still capable of accurate communication with each other? Do they still speak the same language? What will happen to the communication when DGPS-based transponder systems link the control of vessels to VTS operations?

Communication between pilots and ship's officers tends to become one way communication in uncommon situations, for example, in ice covered areas where navigation differs a lot from normal. An unexperienced crew may easily overload the pilot through ignorance, and incapability especially in situations where the ship's control systems are unfamiliar to the pilot. [5,6,7]

The communication environment rapid change is a fact and the negative effects should be anticipated and remedies sought. Sufficient skill and knowledge overlap between the controller and the monitor helps them to understand each other better, i.e. brings them more or less to the same level increasing the likelihood of right decisions. Communication is very difficult in the case of a knowledge gap on either side. [7]

New control system installations totally lack anticipation of the forthcoming changes in the control capabilities of the personnel. The installation and implementation procedures should include an analysis of the changes in the controllers capabilities during the forthcoming months. This would pinpoint the skills which will be lost while using the new system, and also include an evaluation of the need to maintain old and still relevant capabilities. This could form the basis of the practical training.

5 THE WORK ENVIRONMENT CHANGE AND CREW TRAINING

A major part of navigation today is monitoring. Is an efficient monitor still of the same person type as a seasoned sailor of the old days? Are we still seeking for executors for the officer posts and should we? One of the selection criteria for VTS operators in the Netherlands is that the operator should be satisfied with carrying out monotonuous and tedious tasks and maintain his or her attention! Do the people selected for the control jobs on board fullfill this criteria and should they?

Active participation in navigation is diminishing. Passiveness pushes us further from active participation. The threshold to interfere rises if the system has worked well during the past months. "Hey! Look what is she doing now?"

The ability and desire to interfere in automated systems functions gets worse. The controllers become more dangerous. Training at suitable intervals is needed to re-awaken these skills. [8]

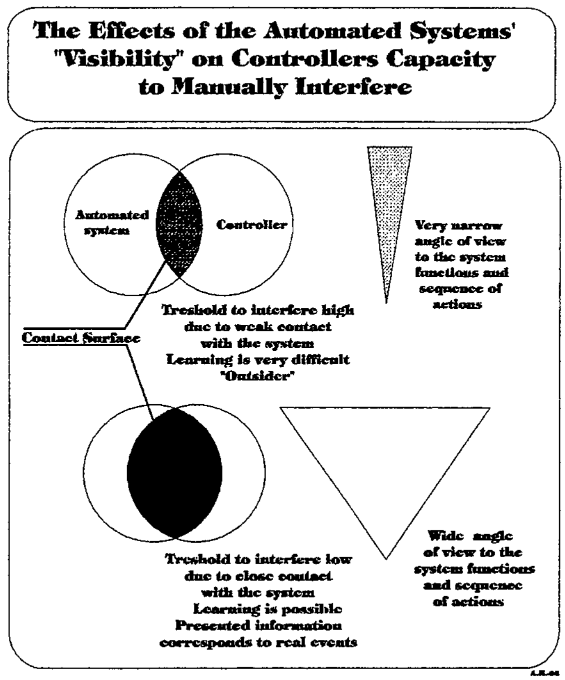
Training in different industry branches is increasing heavily with systems complexity. In the future, companies will mainly be themselves responsible for the specific and system-oriented training of their employees. This situation will possibly be very close to the aviation training models where also the manufacturers play a major role.

When using an automated control system, error situations are often dealt with using the following lower-level automated system, rather than the low-level manual control systems. **One could say that we have learnt to play with computerised automated systems.**

Automated systems have to be used for a certain amount of times in a timespan or the alternative is additional training. Some manual functions should have same criteria.

System displays and also situation interpretations are difficult to perceive and yet one should constantly follow up the functions of an automated system. Exceptional situations are rather rare and thus practice in handling these situations is random. Man-machine interfaces are complex to interpret. In aviation there are several accident and incident cases where this has been a major causal factor. The angle of visibility into automated systems is too often very narrow, i.e. the controller sees only the end results of its decision making. This has a vital effect on the controller's ability to interfere in the process.

The 'Angle of View" into any system should be so wide that we can see intermediate results of the system's decisionmaking process rather than only the end results or the actions taken by such a system. The presentations should be interesting to follow up rather than tedious and frustrating. Control system presentations should not require lengthy learning nor complicated interpreting.



Picture 10. The effects of clear presentations.

Modern computer technology allows the fulfilment of the above criteria. Most of the so-called ship manoeuvring skills are actually skills related to information interpretation and integration and secondly, making accurate adjustments through experience and anticipation. The time scale of the adjustments is **normally** rather slow in the marine world.

6 FROM SYSTEM REQUIREMENTS TO EMPLOYMENT, FEEDBACK, EDUCATION AND TRAINING

Frequent practice of exceptional situation management is considered to be very important for the controllers of complex systems. This kind of training is needed both for the engineers and for the deck officers. It is likely that the trainers will be the company's own personnel; audited trainers within a company. There is also a severe need to test systems properly before installation on board vessels. Efficient testing and documentation forms the only sound base for the system user education, training and efficient practice before user certification. This testing and system design evaluation could follow the same principles as in other high risk industries. Ship owners are facing a new period in the training of their own personnel. What is the present status of system-oriented training for the various control systems?

In order to create a reliable and sound basis for system education and training, methods and instructions should be created for the assessment of system requirements down to system employment and feedback. Corresponding methods within other industries, i.e. aviation, nuclear power stations, the oil industry and other process industries might give insight to this problem. Assessment of the present status of system procurement for ships might give a good starting point for the development of safe and controlled methods for the whole process. The procurement, education and training process could be the following:

- Assessment of requirements for the system
- System performance specification
- System order
- System construction
- System installation
- Education for the system
- System training
- System testing
- System implementation
- Final system training and practice
- Follow up and documentation
- Feed back
- Etc.

7 CONCLUSIONS

The maritime world has grown in complexity during the past twenty years to a level where it is correct to suspect whether this intricacy is still manageable. The scattered pluralism creates situations where it is difficult to choose whom to believe. Situations where shortcomings have been found are normally compared to national and international requirements, but in case these criteria are imprecise or even vague who will have the final say? A good example of a rule which is very difficult to obey can be found in the Rule of the Road in chapter 17 a and b, where the undefinable has been defined.

The situations described above contain the Human Element which normally refers to control situations, i.e. situations met on the furthest level of maritime control. However it should be recognised that this Element has an influence anywhere where people carry out their duties. The Element exists also in the recommendations, rules and regulations, model courses, inspections etc. It is a part of life. The negative effects of the Human Element culminate on the bridges and in the engine control rooms of ships. Simplification of the total management system has possibly started with the ISM implementation. Future actions and audits will show if this has been achieved or not.

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SHIP NAVIGATION AND TELEMATICS - TRANSPONDER TRIALS IN FINNISH VTS'S

Martti Heikkilä
Göran Granholm
VTT Manufacturing Technology
Espoo, Finland

Abstract

During the last years there has been significant development in several technologies which can contribute to the efficiency and safety of maritime traffic. The most important of these are *accurate positioning systems* (DGPS), *digital data transmission/transponder technology*, *electronic chart systems* (ECDIS), *control of ships using electronic passage plans*, and *ship path prediction*. With a widespread implementation of these new techniques combined with advanced ship-shore and ship-ship data transfer, significant improvements can be achieved in traffic situation awareness both in a VTS and onboard.

1 INTRODUCTION

Due to the increasing traffic density and the decreasing response and reaction times allowed there, new mechanisms have to be found for both ship-ship and ship-shore communications, especially between vessels and VTS centres ashore.

New navigational technologies, contributing to the efficiency and safety of maritime traffic when implemented both onboard and in VTSs are: electronic chart systems (ECDIS), accurate positioning systems (DGPS), digital data transmission technology (e.g. GSM, 4S transponder), the control of the ships using electronic passage plans, track autopilots and ship motion prediction. This type of ship control contains all pilotage information in electronic form.

A general aim of the ongoing development work is to improve traffic situation awareness both onboard and in the VTS, enabling more accurate ship control and monitoring in both grounding and collision avoidance and offering practical solutions for shore-based pilotage. The use of AIS (Automatic Identification systems, i.e. transponders) will resolve identification problems and reduce the need for routine voice communications, providing automatic position updates, without the need for action by either the VTS or the vessel. It also extends the capabilities of VTS/VTMIS to areas not covered by radar. In areas where the traffic density is low it can be argued that careful assessment should be made of the balance between investments in onboard systems or shore-based VTS.

This paper describes the research carried out at VTT on VTS development, and gives especially an outline on which functions the VTS should have in ship-shore and ship-ship data transfer. The research is funded by the EU, Finnish Maritime Administration and VTT. The VTT research in this field includes previous work in the COST 301 (1, 2) and EURET TAIE (3) projects. The ongoing research in this subject takes place in the EU 4FP projects POSEIDON and COMFORTABLE.

2 VTS TRANSPONDER DEVELOPMENTS IN FINLAND

2.1 FINNISH BACKGROUND

The research and development to be carried out within the POSEIDON project by VTT in the transponder technology has special reference to VTS systems in the large archipelago areas of Finland. Two thousand nautical miles of restricted waterways, shadowing due to islands and the large area to be covered with a VTS place special requirements for it. This structure of the Finnish coastal waterway network calls for new solutions and functions to be integrated into the VTS. A VTS relying solely on tracking based on radar coverage is not viable. An additional characteristic for this area is low traffic density. For these reasons the VTS area should be covered with a combination of radar and onboard transponder.

The Finnish development will concentrate on applying and enhancing transponder technology to VTS and ship-to-ship interaction. In this development work VTT will concentrate on the *concept of passage plan sharing between ship and VTS,* as well as on the *application of ship path prediction displays in VTS.* Also *ship to ship transmission of prediction data* will be tested.

The so-called 4S transponder (ship-shore, ship- ship) developed in Sweden has been chosen as the AIS, to be used in this development work,. There is also close cooperation with the Swedish Maritime Administration in the project. This AIS operates in broadcast mode, providing navigation, communication and surveillance information. It is able to automatically broadcast full ship reporting data and short messages, in addition to basic ship identification, position, course and speed, at high data and repetition rates.

The information which can be provided by transponders in a ship-shore and ship-ship data transfer can be divided into four types: navigation, voyage-related, ship-related and traffic management. The primary purpose of such information is to assist in the safe navigation and efficient management of the vessel. Information within different data types can be:

- <u>Navigation</u> Ship's position, course and speed over ground, heading, rate of turn, angles of heel, roll and pitch.
- <u>Voyage-related</u> Ship's draft, hazardous cargo, ETA, destination and passage plan.
- <u>Ship-related</u> Identification, type and dimensions of vessel, type of positioning sensor and location of positioning system antenna.

- Traffic management GNSS integrity warning, availability of track surveillance, routing advice, pilotage information, navigational warnings, meteorological data and tidal information.

It is important to distinguish between tactical (safety-related) and strategic (commercial) information in ship-shore and ship-ship data transfer in order not to block the channels available. The transponder data should be clearly restricted to that of tactical nature. For the transmission of strategic information, possibly of large magnitude, more broadband transmission techniques should be used.

The improved traffic situation awareness can be realised by applying advanced AIS technology to VTS and ship-to-ship interaction, especially with the application of the concepts of passage plan sharing between ships and VTSs, as well as the application of ship path prediction displays for all vessels in ship and VTS displays. The functions of the Finnish development are shown in Figure 1.

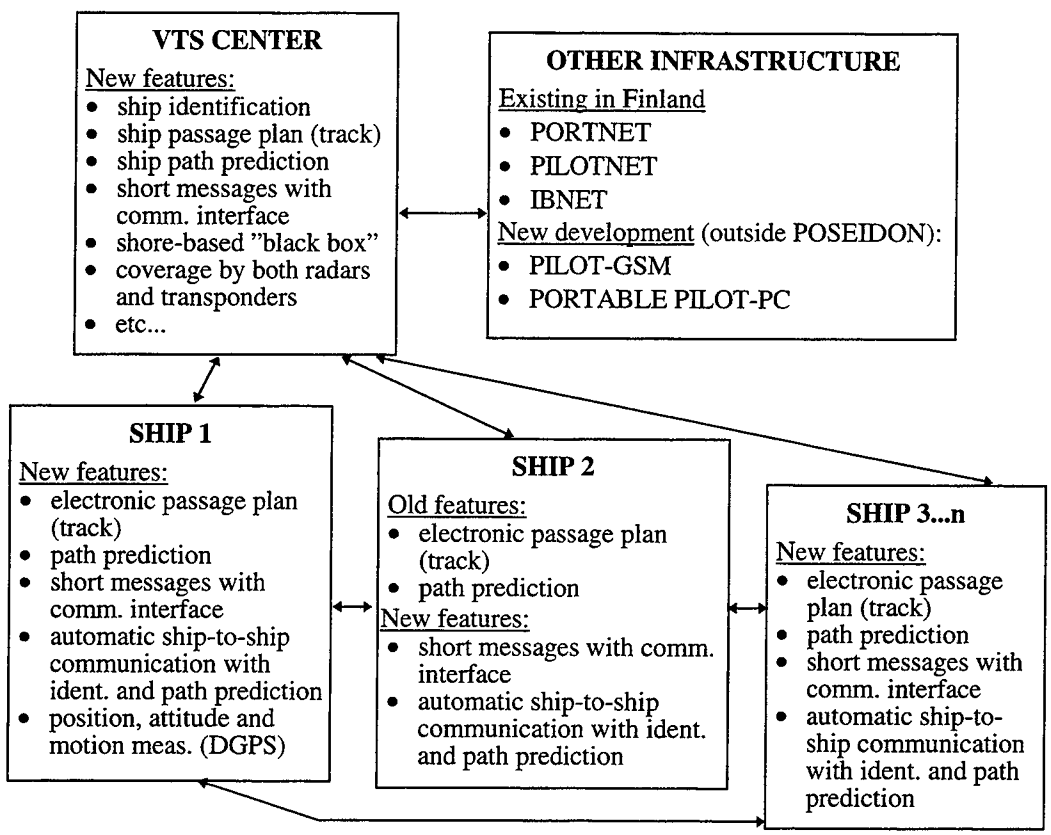


Figure 1. Functions of the Finnish development.

2.2 TECHNOLOGIES TO BE IMPLEMENTED

Technologies contributing to the efficiency and safety of maritime traffic when implemented in VTS are: electronic chart systems (ECDIS), accurate positioning systems (DGPS), digital data transmission/transponder technology (e.g. GSM), the control of the ships using electronic passage plans, track autopilots and ship motion prediction. This type of ship control contains all pilotage information in electronic form.

The system development by VTT has been divided into *Chart Display Subsystem (CDS), Message Handling Subsystem(MHS), Transponder Subsystem (TS) and Attitude and Motion Measurement Subsystem (AMMS).* The technologies described below are used in the subsystems.

2.2.1 Chart Display Subsystem (CDS) and Message Handling Subsystem(MHS)

Electronic passage plan and ECDIS

In present day ship control systems, a detailed passage plan (pilot data) is stored in the integrated navigation system on the bridge. All the waypoints are tied to geographical coordinates and include information such as the speed, course when approaching a turn, the radius of turn to be used and the next course. Also the wheel-over points are included in the information which can be displayed either on the radar or an ECDIS display. The pilotage with this information can be performed either manually with the help of proper prediction displays or using autopilots of different levels of sophistication.

Ship path prediction

A new display to improve the control situation awareness is ship path prediction developed at VTT and tested onboard SILJA LINE's cruise ferries. In a research project the performance of the navigators with the path prediction and another one with a lower in level of information for comparison, has been evaluated using a full-bridge shiphandling simulator. Path prediction improves steering accuracy and also the abilities of the pilots to monitor the functioning of the autopilot.

The display format for ship path prediction is basically a ship's outline presented continuously on a digital chart on the correct scale, with information on the history of the motion and a new method for displaying a prediction of the ship's future sweep. The paths of the extreme points of the vessel both starboard and port, from the present position to the predicted position, are also displayed. The prediction also shows the turning motion, which has not been possible to do in current displays. The path prediction format is shown in Figure 2. The accurate observation of motion parameters and position is very important in narrow fairways due to the small time and space margins. The manoeuvring characteristics of ships change according to the loading conditions, and the wind especially has a great effect on vessels with large windage areas. Because this is a kinematic prediction of ship motion, the prediction has an inherent capability to adjust for presentation of wind effect.

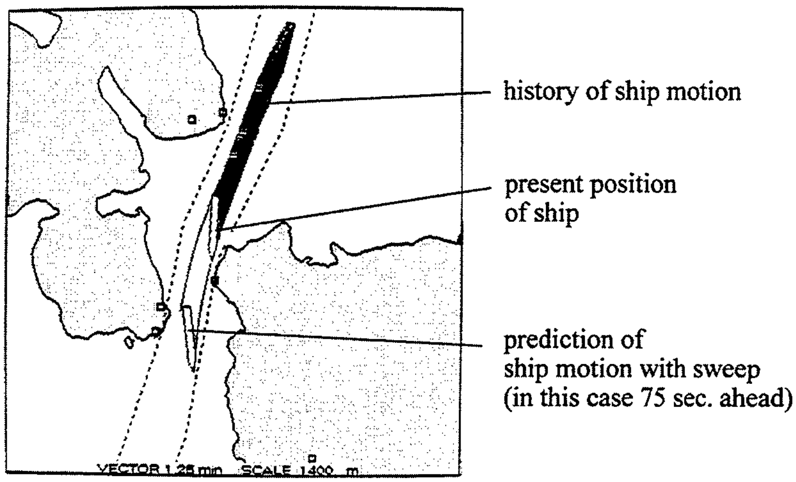


Figure 2. Ship path prediction.

2.2.2 Message Handling Subsystem (MHS)

The 4S transponder is equipped with an internal GPS receiver and can operate as a stand-alone, unit broadcasting its own position information over the radio link. In order to transmit more detailed information and to process received messages, there is a serial port for communication with external equipment. Messages read by the transponder, as well as messages to be transmitted, are accessed through this port. The message format is in accordance with the NMEA-0183 standard, but due to the high information flow, bit rates can be set to 9600 or 19200 bit/s.

The transponder interface programme developed within the project is designed to handle the information exchange between the transponder, the ship's control system interface, chart displays and the user. This programme will undergo continuous development during the project. Currently supported functions include:

- collecting data from ship interfaces to compose standard position report
- receiving and displaying (listing) information from other transponders
- interacting with a chart display program to display and identify received targets.

The standard position report includes identification (MMSI number), navigation status, position, speed, course, heading, time and position accuracy information. The listing presenting information of other received transponder targets will include, except the above information, also information passed through non-scheduled standard messages.

The interface programme is also designed to interact with a connected chart display application running on the same or a separate connected computer. Targets received by the transponder are shown on the chart and can be focused in to by selecting from the list view. Targets selected on the chart display are highlighted in the list. If ship dimensions are received or can be read from a database based on the identification number, the actual size of the ship can be displayed. If, in addition to this, the ship provides speed, heading, course and rotational data through the transponder, an indication of the target's current motion (path prediction) can be displayed.

Functions still to be implemented include:

- sending and receiving addressed and broadcast text messages
- function to enable radar-followed targets to be transmitted over the radio link (mainly for VTS use)
- function to enable sending and receiving of binary messages, e.g. for passage plan sharing.

2.2.3 Transponder Subsystem (TS)

The 4S transponder system The 4S transponder system was developed in Sweden, initially for aviation use, and it employs Self-organising Time division Multiple Access (STDMA) to maximise channel capacity. STDMA relies on the use of a single, common time standard by shore stations and all transponders, to arrange time-slot allocations. Existing implementations use GPS time. The transponder operates in broadcast mode, providing navigation, communication and surveillance information. The 4S transponder system requires allocation of one or two dedicated VHF channels within the Maritime Mobile Band, or somewhere else where a 25kHz channel can be made available. The 4S is able to automatically broadcast full ship reporting data and short messages, in addition to basic ship identification, position, course and speed, at high data and repetition rates. The 4S transponder has the potential to provide much more information about a ship, and perform other functions. The ship-shore and ship-ship data transfer capability of the 4S transponder will be tested and the messages will be developed in the forthcoming Finnish projects.

2.2.4 Attitude and Motion Measurement Subsystem (AMMS)

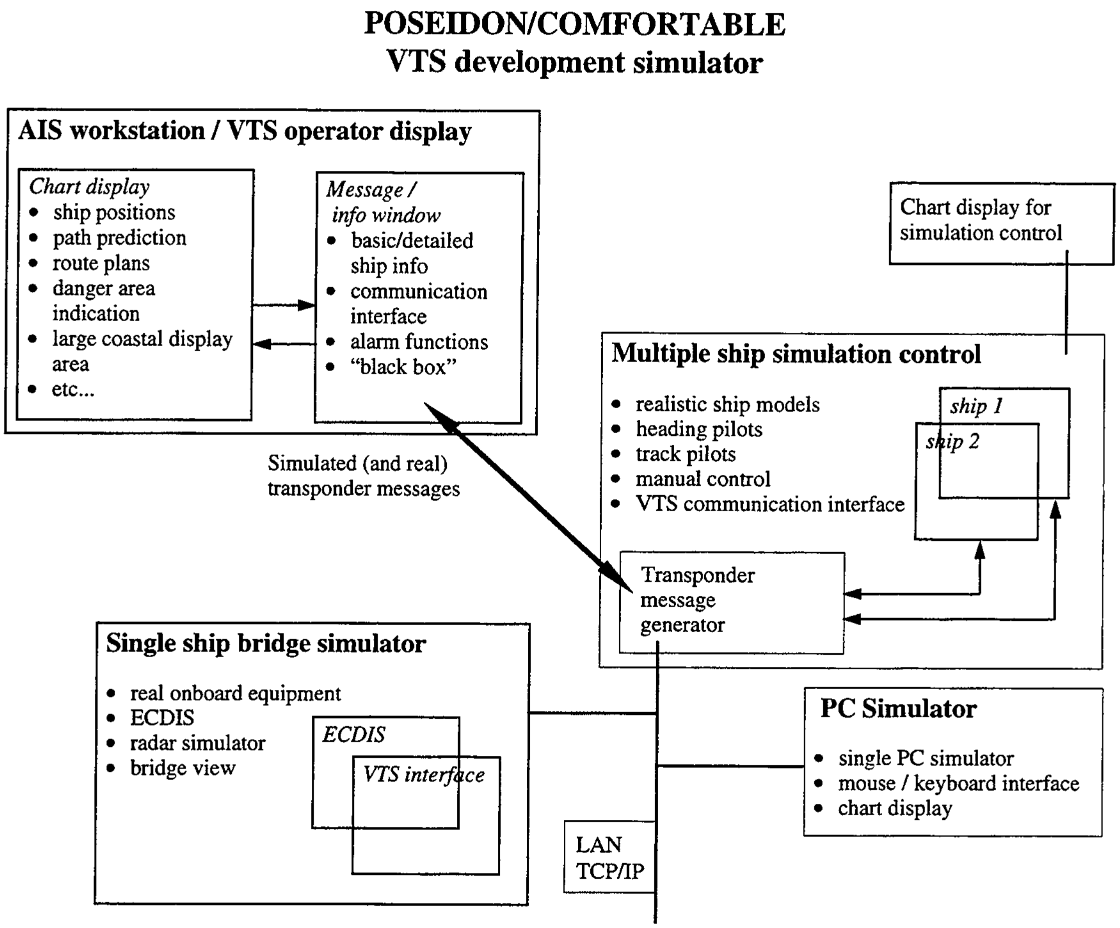
Ship position and motion measurement technology

DGPS has been successfully tested in Finland and Sweden with a long-term accuracy of 2 metres. A six degree-of-freedom (6 DOF) motion measurement capability added to the concept improves it further. All 6 DOF motions of a vessel, including translational speed components, rates of turn and attitude angles (heading, pitch and roll), can be measured with a satellite positioning system using three or four antennae (or receivers). In principle, it is possible with this kind of receiver to extract all motion parameters from one source onboard. This simplification of the instrumentation can lead to inexpensive installations affordable for practically all ships.

2.2.5 Development system

Engineering simulator

A decision has been made to build an engineering VTS simulator identical to the VTT test system. The engineering simulator principles are presented in Figure 3.



To be evaluated:

- VTS operator display layout and functionality
- VTS messages
- transponder performance
- route plan sharing between ship and VTS
- multiple antenna GPS equipment for ship motion measurement
- motion based path prediction on VTS display
- ship-to-ship data exchange

Figure 3. The engineering simulator principles.

3 TRANSPONDER TRIALS

3.1 DEMONSTRATION INFRASTRUCTURE

In the POSEIDON project, five national demonstrations are planned for summer '98. The technical infrastructure at the Finnish test site will consist of a VTT developed VTS test system to be used both in simulator-based development and in transponder field trials (ship-shore and ship-ship data transfer). The new VTSs and their personnel, both in Helsinki and in the Turku area, will be available for user feedback and technical backup as needed. STN-ATLAS will use their mobile VTS in the Finnish demonstration in conjunction with the VTT developed transponder application.

Participating organisation in the demonstration the is VTT Manufacturing Technology as site co-ordinator and system developer. The authorities involved are Swedish Maritime Administration (Associate Partner), Finnish Maritime Administration (Sponsoring Partner) and two Finnish Maritime districts. Also the Port of Helsinki and two ship owners, SILJA LINE (Sponsoring Partner) and VIKING LINE, participate in the demonstration. The German VTS manufacturer STN-ATLAS will use their mobile VTS in the Finnish demonstration in conjunction with the VTT developed transponder application (ship-shore and ship-ship data transfer).

Two SILJA LINE passenger ferries (m/s SILJA SERENADE Helsinki - Stockholm and m/s SILJA EUROPA on the Turku - Stockholm route) have been selected as initial transponder test installation platforms. One VIKING LINE passenger ferry (m/s MARIELLA on the Helsinki - Stockholm route) will also be included in the trials. This will facilitate especially ship-ship data transfer, because Silja and Viking ships depart at the same time from Helsinki and Stockholm so that their distance during the trip will allow a continuous test of this feature for the whole 15-hour trip. They will also be simultaneously within the reach of the shore based transponder. A small communication vessel belonging to the south-western Sea District in the Turku area will also be used as test ship.

Two transponder shore stations will be installed, one in Helsinki and the other in the Turku VTS area.

3.2 FIRST EXPERIENCES WITH THE TRANSPONDER AND MOTION MEASUREMENT SUBSYSTEMS

Preliminary transponder tests were performed at an early stage of the development. Transponders and computers for message handling and interacting with the transponder were installed onboard the two cruise ferries Silja Serenade and Viking Mariella. Dedicated GPS and VHF antennas were installed for each transponder.

Some modifications were made to the transponders' system software so that externally provided position data could be transmitted as own ship position. Originally the transponders were designed to connect to their own VHF and GPS antennas and optionally to an external differential correction receiver. After this modification, the transponders can now be configured to use either their own GPS antenna or an external position source. The GPS time, used for synchronizing transmission and time stamping of reports, must still be provided through its own antenna. Speed, heading, course and rotational information, as well as the differentially corrected position were read from the ship's interface and sent out to the transponder for transmission over the radio link.

The 6 degree-of-freedom GPS receiver equipment has not yet been tested onboard. First laboratory tests have been made and have given encouraging results.

4 CONCLUSIONS

This paper describes the research on VTS development, and, in particular gives an outline on new VTS functions using ship-shore and ship-ship data transfer. The possibilities of enhancing traffic situation displays both in a VTS and onboard have also been described. New development work will concentrate on applying and enhancing transponder technology to VTS. The development by VTT in Finland will concentrate on the concept of passage plan sharing between ship and VTS as well as on the application of ship path prediction displays in VTS. Also ship to ship transmission of prediction data will be tested. These improvements in the VTS functions enable more accurate ship control in both grounding and collision avoidance and offer practical solutions for shore-based pilotage. A general aim with this development work is to improve traffic situation awareness both in the VTS and onboard.

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PREDICTION OF WAVE LOADS ON A BOW VISOR

Tuomo Karppinen
Antti Rantanen
Sakari Rintala
VTT Manufacturing Technology
Espoo, Finland

Abstract

The main features of a numerical method used for predicting the vertical wave load on the bow visor of MV Estonia in irregular head and bow seas are described. The wave-induced motions of the vessel are simulated by applying the linear superposition principle, while the vertical load on the visor is computed at each time step up to the instantaneous waterline. The forces acting on the visor are in accordance with the non-linear strip method. The non-linear impact force has been included in the form derived by a momentum consideration. Illustrative examples of results are given and the accuracy of the method in comparison with experimental data is discussed.

1 INTRODUCTION

The Estonian flagged passenger ferry MV Estonia encountered on 28 September 1994 heavy bow seas on a scheduled voyage from Tallinn to Stockholm in the northern part of the Baltic. The lockings of the bow visor of the vessel broke and the visor plunged to the sea. Water flooded the car deck, the vessel lost stability and sank shortly before 2 a.m. Finnish time.

As part of the accident investigation, wave loads on the bow visor of MV Estonia on the accident voyage have been estimated both by a numerical method and model experiments. The long numerical simulations carried out by VTT (Karppinen et al. 1995) complete the experiments made at the SSPA in Gothenburg (Trägårdh, 1995) where the measurement times, due to practical limitations, have been much shorter than the simulation times. The main features of the simulation method, with some illustrative results, are presented here. The correlation of the simulated data with experimental data is discussed.

2 SIMULATION METHOD

Several fairly accurate methods, for instance the linear strip method (Raff, 1972), are available for predicting linear wave loads and wave-induced motions of ships in bow waves. The linear strip method, however, cannot be used for evaluating wave loads on parts of ship hull which are above the waterplane, since only the underwater hull up to the mean waterline is considered in the computations. There is no general, exact numerical method for solving the flow around a body entering water (Trosch & Kang, 1988). Due to the very complicated non-linear free surface and body boundary conditions, the calculation of the impact forces on a body entering water requires simplification. Von Karman (1929) presented the first solution for this problem in two dimensions and since then several methods have been developed. A review of the solutions for circular cylinders and wedges is given by Greenhow & Yanbao (1987) and Greenhow (1987), respectively.

A practical method applied quite often for estimating the flare impact loads on ships is the non-linear strip method (e.g. Yamamoto et al. 1980 and Chiu & Fujino, 1991). A variant of this method, based on the work of Matusiak & Rantanen (1986), has been used for simulating the vertical component of the visor load. Unfortunately, the method does not give the pressure distribution on the surface of the visor and thus determination of the opening moment of the visor around the hinges must be based on quite rough estimates. However, the method is not very demanding on computer time so that it has been possible to run long simulations to find out statistics of high visor loads.

A main difference between the linear strip method and the non-linear strip method is that in the linear theory the equations of motion are solved for the mean waterline in the frequency domain, while in the non-linear version the motions are simulated in the time domain and the non-linearities of the hydrodynamic forces arising from the variation of the submerged portion of the hull are taken into account. Here the formulas of the non-linear strip-method have been applied to simulating the vertical force on the bow visor in long-crested, irregular waves. However, the rigid body wave-induced motions of the ship have been determined by the linear strip method (Raff, 1972) and simulated by applying the linear superposition principle. The non-linearities in the hydrodynamic forces affect the heave and pitch only slightly (Yamamoto et al. 1980).

The non-linear hydrodynamic forces on a heaving ship section may be determined by a momentum consideration, as shown by Faltinsen (1990). The method has been widely applied for predicting the hydrodynamic forces on prismatic bodies entering water (e.g. Payne, 1981, and Greenhow, 1987) and, for instance, by Gran et al. (1976) for estimating the hydrodynamic impact forces on a bow with a large flare. Here the bow visor has been considered as a small body entering water. The non-linear forces arising from the momentum consideration and the hydrostatic and hydrodynamic forces, as defined in the strip theory (Raff, 1972), are taken into account. However, the term involving the longitudinal derivative of the sectional heave added mass has been neglected. This simplification has probably a minor effect on the results. The instantaneous waterplane has been used for determining the added mass, damping and hydrostatic coefficients of the bow visor. All viscous and memory effects have been disregarded.

2.1 IRREGULAR WAVES

In the simulations, time histories of irregular waves, surface velocities and accelerations are generated by applying the linear superposition principle, i.e. a large number of regular sinusoidal wave components are summed. In order to get non-repeating random time histories of arbitrary length, each harmonic wave component has a random phase angle and its frequency ω is chosen at random in each narrow frequency band.

The wave time histories have been simulated according to the JONSWAP spectrum. The number of regular wave components used in generating the wave time histories has been 20. This should give an adequate representation of the wave field without lengthening too much the computer time required by the simulation. The high-frequency end of the wave spectrum has been cut off at ω = 1.72 rad/s to have only wave components with length large relative to the dimensions of the bow visor. In this way, the assumption of constant water particle velocity and acceleration over the space occupied by the visor is fulfilled. The high-frequency components have an insignificant effect on the significant wave height but may increase the velocity and acceleration unrealistically. The effect of the cut-off frequency and the number of regular wave components on the visor loads should, however, be investigated more carefully.

2.2 WAVE-INDUCED MOTIONS

The heave and pitch in the simulated irregular long-crested seas are obtained by determining first the responses to each regular wave component on the basis of heave and pitch response amplitude operators and phase lags predicted by the strip method (Raff, 1972). Summing the heave and pitch responses to the regular wave componets gives the time histories of heave and pitch.

During the simulation, at each time step the vertical relative displacement, relative velocity and relative acceleration at the bow visor are determined as the difference between the rigid body vertical displacement, velocity, and acceleration, and the wave surface displacement, velocity and acceleration, respectively. The undisturbed, incident wave surface is used. The vertical relative motion at the bow visor is given by:

$$\xi_r(t) = \eta - \xi_3 - x_b \xi_5 \quad (1)$$

where η is the wave surface elevation, x_b is the longitudinal coordinate of the centre of the bow visor. Here the heave, ξ_3, is assumed positive upwards and the pitch, ξ_5, positive bow up. The vertical relative velocity may be expressed as:

$$\dot{\xi}_r(t) = \dot{\eta} - \dot{\xi}_3 - x_b \dot{\xi}_5 + V\xi_5 \quad (2)$$

where the dots indicate the time derivative and V is the forward speed of the vessel. The vertical relative acceleration is obtained as a time derivative of (2).

2.3 VERTICAL FORCE ON THE VISOR

The total vertical force component on the visor is predicted by:

$$F_z = F_i + F_{rd} + F_s + F_{FK} + F_{imp} + F_{st} - m_v g \quad (3)$$

where

F_i = Inertia force
F_{rd} = Linear radiation plus diffraction force
F_s = Hydrostatic, or displacement force
F_{FK} = Froude-Krylov force
F_{imp} = Non-linear hydrodynamic impact force
F_{st} = Vertical hydrodynamic force due to the stationary flow
m_v = Mass of the visor
g = Acceleration due to the gravity

The inertia force F_i is obtained as the mass of the visor, m_v, times the rigid body vertical acceleration of the ship at the centre of the visor:

$$F_i = -m_v(\ddot{\xi}_3 + x_b\ddot{\xi}_5) \quad (4)$$

The linear radiation plus the diffraction force is determined by:

$$F_{rd} = m_{33}(t)\ddot{\xi}_r + b_{33}(t)\dot{\xi}_r \quad (5)$$

where

m_{33} = heave added mass of the visor
b_{33} = heave damping coefficient of the visor

Both the heave added mass and damping coefficient are taken up to the instantaneous wave surface.

2.3.1 Added mass and damping coefficients

The heave added mass and damping coefficients of the visor at different waterlines have been computed by a three-dimensional sink-source method (Kalske et al., 1985) which is based on the numerical algorithm developed by Garrison (1974). In these numerical predictions, the surface of the visor has been described by triangular elements (Fig. 1). Different numbers of elements have been used at different draughts. The shape of the visor has been simplified so that the back bulkhead is vertical and the lower end is sharp. Thus, the original visor has more volume at the lower end than the model used in the simulations. Higher up the difference in volume gets equalised.

The predictions were made for three frequencies, f = 0.172, 0.208 and 0.263 Hz covering the range of wave encounter frequencies with the major wave components. The oscillation frequency had a small effect on the results. The largest values of the coefficients were used in the simulations. The added mass versus draught follows closely the displaced volume of the visor.

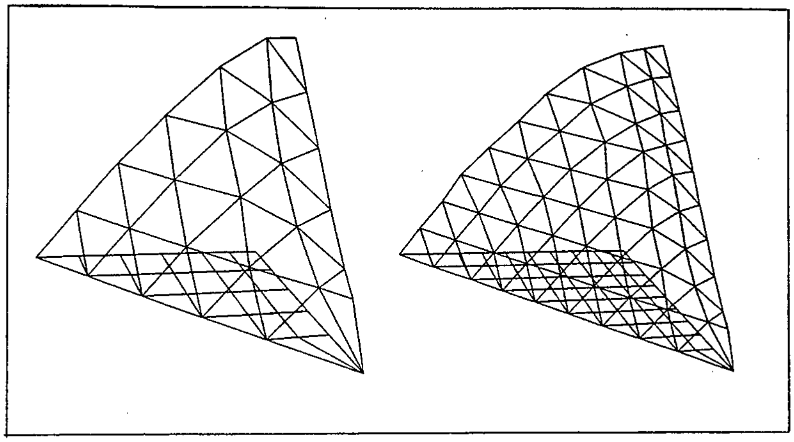


Fig. 1. Element mesh of the visor at 11 m and 15.4 m (right) draughts.

2.3.2 Hydrostatic and Froude-Krylov force

The vertical component of the hydrostatic plus the Froude-Krylov force is given by (de Kat & Paulling, 1989):

$$F_s + F_{FK} = \iint_S (p_s + p_d) n_z dS \qquad (6)$$

where

p_s = Hydrostatic pressure = $\rho g z$
p_d = Dynamic pressure in the undisturbed, incident wave
n_z = Vertical component of the unit normal to the body surface

The intergration is carried out over the instantaneous total wetted surface. Thus, in the expression of the hydrostatic pressure, z is the height of the water column up to the wave surface, $\eta(t)$. In the simulation, the hydrostatic force is expressed as:

$$F_S = \rho g \nabla_V(t) \qquad (7)$$

where

ρ = Water density
∇_V = Instantaneous submerged volume of the visor

The Froude-Krylov force is defined as the force that is obtained by integrating the pressure in the undisturbed, incident wave over the wetted surface of the visor. Thus, it is assumed that the ship does not disturb the incident wave. Using the linearized Bernoulli's equation and the linearised wave theory, where the free fluid surface is defined by the plane z = 0, the following approximation is obtained for the dynamic pressure near the wave surface:

$$p_d = \rho g \eta(t) \tag{8}$$

Assuming further that the pressure variation in the horizontal plane within the dimensions of the bow visor may be neglected, the vertical component of the Froude-Krylov force on the visor may be expressed as:

$$F_{FK} = \rho g A_{wv}(t)\eta(t) \tag{9}$$

where

A_{WV} = Instantaneous waterplane area of the visor

Thus, the undisturbed, dynamic wave pressure has been assumed constant over the surface of the visor. This assumption is consistent with the assumption of small dimensions of the visor compared to the wave length. A similar approach has been used by Hooft (1970), Karppinen (1975) and many others for estimating the wave loads on small structural members of offshore structures. The method is thoroughly discussed by Newman (1977). Consistent with this approach is that in the simulation the vertical relative velocity and acceleration are determined at the centre of the visor.

2.3.3 Non-linear impact force

The non-linear impact force is expressed in the form:

$$F_{imp} = \frac{\partial m_{33}}{\partial z}\dot{\xi}_r^2 + \frac{\partial b_{33}}{\partial z}\xi_r\dot{\xi}_r \tag{10}$$

The impact force consists of two parts, one of which is proportional to the vertical rate of change of the added mass and the other to the rate of change of the damping. The term involving the derivative of the damping coefficient is much smaller than the added mass term which is proportional to the relative vertical velocity squared. At each time step, the values of the coefficients and the relative motion and velocity are updated.

2.3.4 Force due to the stationary flow

The final term in the force equation takes into account the effect of the stationary flow when the bow pitches down to the water. The pressure distribution on the bow in calm water at different fore draughts has been computed by the SHIPFLOW program (Larsson et al. 1990) at 10, 15 and 20 knots speed of the vessel (Sundell, 1995). An integration of the pressure over the visor area up to the bow wave surface yields the vertical and horizontal component of the force on the visor, while an integration of the horizontal pressure component over the total wetted surface of the ship would give the wave resistance. The vertical force component on the visor has been programmed to the simulation method as a simple function giving the force versus the draught at FP (Fig. 2).

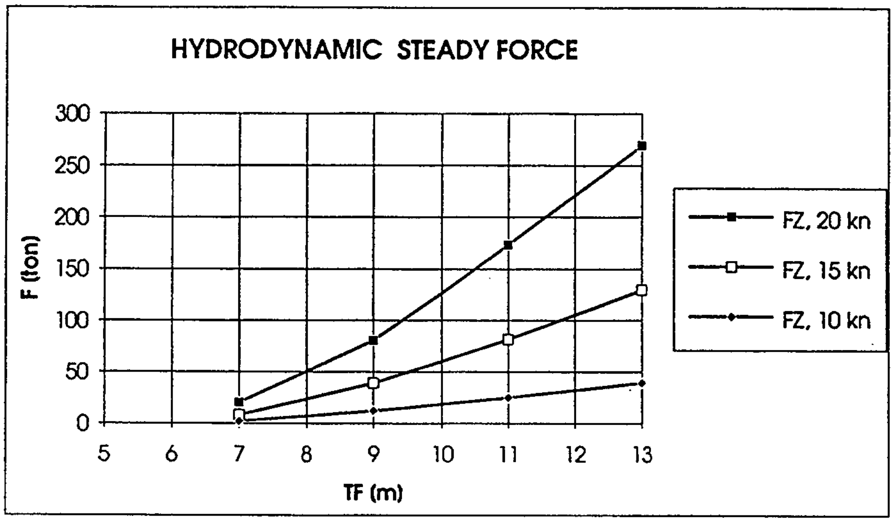


Fig. 2. The effect of ship speed and bow submergence on the steady, vertical hydrodynamic force.

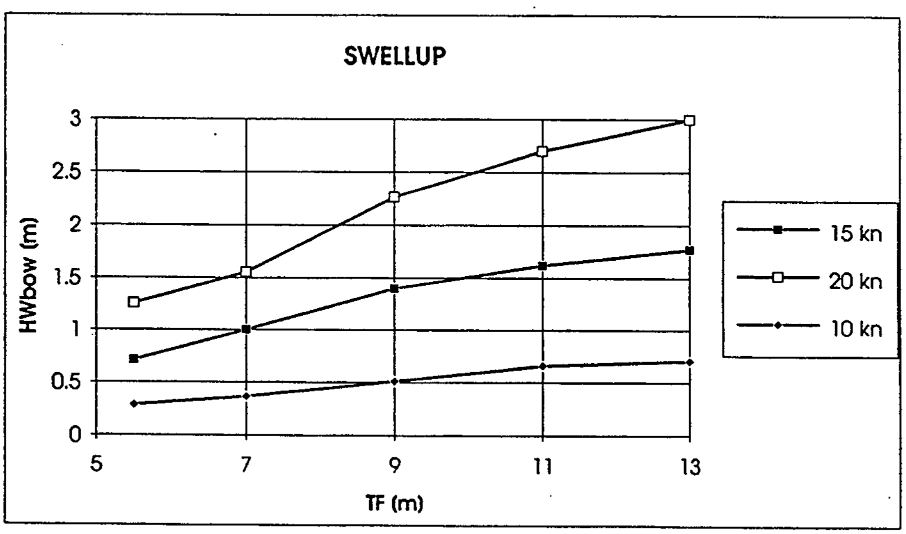


Fig. 3. The bow wave height as a function of draught at FP and ship speed.

Figure 2 shows that the vertical force due to the stationary flow increases quickly with inceasing speed and forward draught. At a large bow submergence, the force is about 100 tons at 15 kn speed and over 200 tons at 20 kn speed. The large force at 20 kn speed is due to the bow wave height rising to over 2.5 m (Fig. 3). The numerical method does not model wave breaking which would probably take place before the wave grows so high. At 15 kn speed, the bow wave height is 1 to 1.5 m. The predictions are for a steady situation, while in waves the bow is pitching up and down at the quite short wave encounter period. It is questionable whether the bow wave rises to the same height during this pitch period as in calm water in a steady flow. However, the predictions by the SHIPLOW program have not been tried to correct for these effects. On the other hand, the effect of the horizontal water particle velocity in the incoming wave has been disregarded and only the stationary flow due to the vessel forward speed has been considered in the predictions. The neglected effect of the horizontal water particle velocity, in particular if the waves are breaking, probably more than compensates for the effect of a too high bow wave.

The bow wave has also the important effect of decreasing the freeboard, or helping lower waves to reach the visor. Since the displacement and the waterplane area of the visor increase dramatically higher up, the bow wave height may have a significant effect on the wave loads of the visor. In the simulations, the bow wave has been considered as a constant offset increasing the submergence of the visor. Thus, the height of the bow wave has been added to the relative motion. In reality, there must be interaction between the bow wave, incoming wave and the waves generated by ship motion so that the simple superposition does not strictly hold. A proper numerical method would give the behaviour of the bow wave as part of the solution.

3 DISCUSSION

Figure 4 shows short sequences of simulated irregular waves and vertical wave loads on the bow visor. The wave time history includes a wave crest of about 5 m high but otherwise the record seems to be approximately symmetric about the still water level, i.e. the heights of crests and troughs follow the same distribution. The wave load record is highly asymmetric showing only high positive peaks due to the bow submergence. Low waves don't even reach the visor and the vertical force on the visor remains close to its weight of 600 kN. Both the wave and the load record have time scales as the vessel encounters head waves at 15 knots speed. Qualitatively the simulated load time histories agree well with the experimental data.

An example of a time history of a high vertical load on the visor together with time histories of different load components are given in Figure 5. The figure shows also the wave and the relative motion time histories which caused the high load.

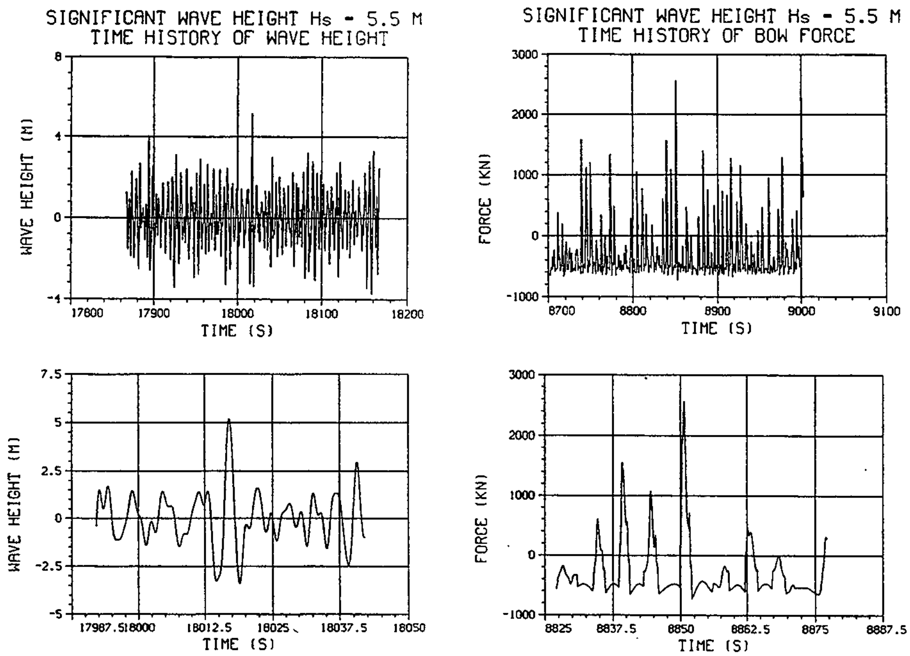


Fig. 4. Short sequences of simulated irregular waves H_s = 5.5 m (left) and vertical wave load on the visor (right).

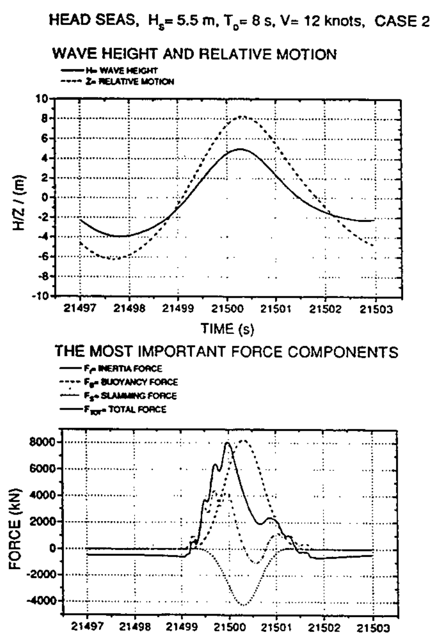


Fig. 5. An incident of high visor load in head seas at 12 kn speed.

The upper plot in Figure 5 presents the simulated wave elevation and the vertical relative motion as a function of time. On the vertical axis, the zero level corresponds to the mean free surface, i.e. to the still water level. The relative motion computed by formula (1) is the submergence (positive) or emergence (negative) of the bow measured from the mean waterplane. The relative motion given in the figures does not include the bow wave height, which has been added to the motion before predicting the wave load on the visor.

The lower plot in the figure shows the most important components of the vertical wave load on the visor. The inertia force is the added mass of the visor times the vertical relative acceleration, i.e. the first part of the force given by formula (5). The buoyancy force includes both the hydrostatic and the Froude-Krylov force predicted by formulas (7) and (9), respectively. The slamming force has been computed by (10), and finally the total force by (3).

The vertical load increases quickly, in about 0.1 s, to a high value which is almost entirely due to the impact force term, or the term proportional to the relative velocity squared. Then also the hydrostatic plus the Froude-Krylov force becomes important and at the maximum load value this "buoyancy" force is approximately as large as the impact force. The added mass inertia force acts in the opposite direction and decreases the total force. The inertia force has its minimum and the Froude-Krylov force its maximum when the relative motion has the maximum, i.e. the bow is deeply submerged. This occurs approximately when the wave crest passes the visor. The impact force oscillates on a high level about half a second and then drops down. The oscillations seem to be due to the numerical derivation of the visor added mass and have thus no physical origin. The impact force is nearly zero at the maximum of relative motion. In all cases of high loads, the time histories of the load components follow approximately the same pattern.

Both the simulations and model experiments seem to indicate that high loads are often excited by waves which have a flat trough and a steep front. The crest following the trough may be twice as high as the through is deep. Deep wave troughs, even when followed by a relatively high crest, never seem to excite high loads on the visor. Waves associated with the largest loads are not necessarily the highest. This was observed also in the model tests. Of the four highest load peaks in one six hours long simulation, usually one or two load peaks are associated with the four highest wave crests in the wave time history. It seems thus that waves with only small differences in the shape may excite significantly different loads on the visor. It would be interesting to analyse more closely the characteristics of a short sequence of waves preceeding a high load on the visor and try to relate the wave characteristics to the load. Kagemoto et al. (1995) show that a group of high successive waves may induce a significantly larger motion displacement for a floating body than just one high wave.

Main results of the simulations are curves presenting probabilites at which the vertical component of the wave force on the visor exceeds different levels (Fig. 6). The exceedance probabilities are plotted on a logarithmic scale while the vertical force is on a linear scale. In this form, straight lines seem to fit the data quite well for high load values. There is no theoretical basis for the linear relationship between the logarithm of the exceedance probability and the vertical visor load. In many cases, for instance, the long-term distributions of wave heights and hull wave bending moments, the Weibull-distribution gives a good fit to the data.

The wave load on the bow visor is highly non-linear with regard to the wave amplitude, and the statistical distribution of the loads is not known. Since the distribution is unknown, long simulations have been made to get relatively accurate estimates for the extreme load values. The simulated sequences have been 36 hours long, in which time the vessel encountered about 30 000 waves depending on the speed, heading to waves and wave period. The simulations were carried out in each case in six runs, each of a six-hour duration.

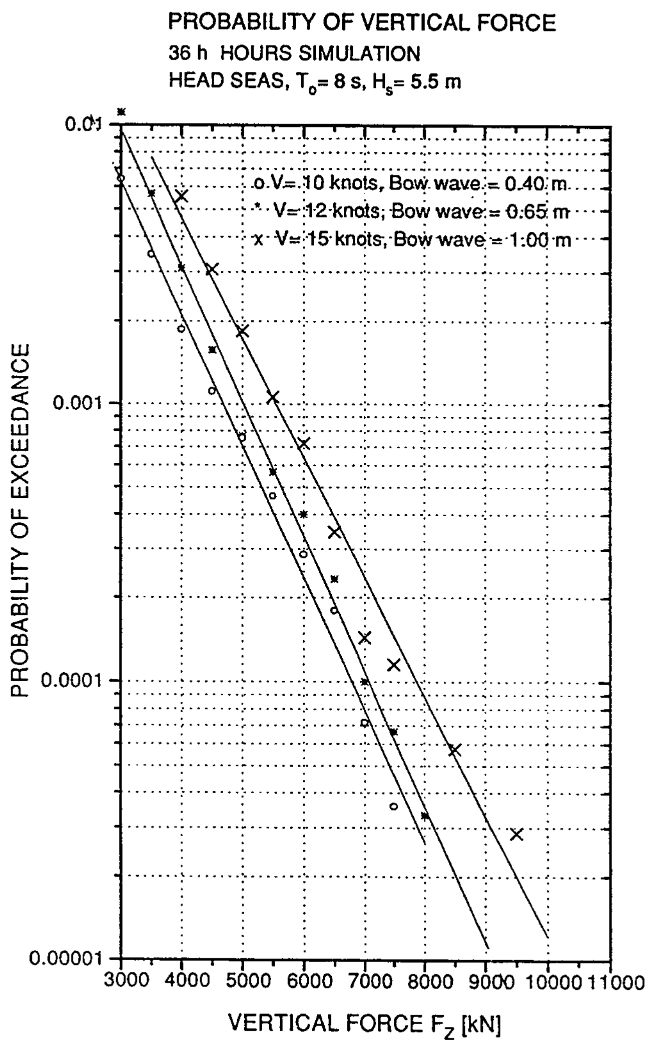


Fig. 6. Probability of exceedance curves of the vertical visor force in head seas H_s = 5.5 m at different speeds.

In a six hours long simulation, the distribution of the load peaks has typically a long tail, i.e. a few highest peaks are significantly higher than all the other (Fig. 7). It is common that over 99 % of the peaks are smaller than half of the maximum. The distributions of wave maxima and minima (crests and troughs, respectively) and the distributions of amplitudes of wave-induced motions, on the other hand, are very nearly symmetric.

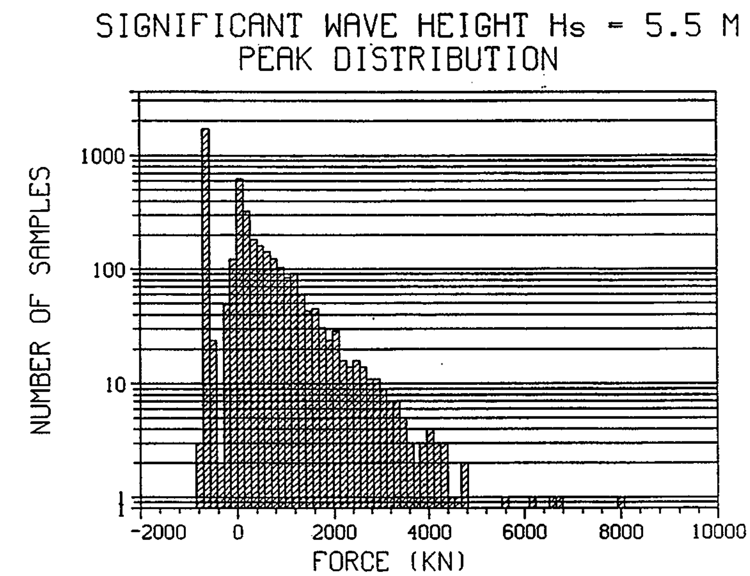


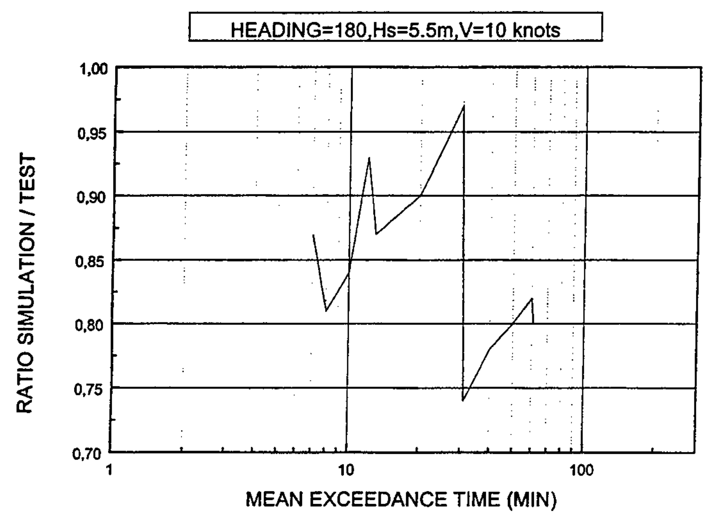
Fig. 7. Distribution of visor load peak values in head seas H_s = 5.5 m at 12 kn.

The significant wave height has a very strong effect on the vertical component of the visor load which has also been confirmed by model experiments. An increase of the significant wave height from 4 to 4.5 m may increase the wave load by over 40 % on a certain exceedance probability level, for instance 1 to 1000. By increasing the significant wave height from 4.0 to 5.5 m may increase the vertical loads by a factor of about 2.5. It seems that the highest loads roughly follow the submerged volume of the visor.

Both the simulations and the model experiments clearly indicate that the wave load on the visor increases approximately linearly with the forward speed of the vessel. At 15 knots speed, the vertical load is about 50 % larger than at 10 kn speed when the significant wave height is 4.0 m. When the significant wave height is 5.5 m, the visor load increases according to the simulations by about 20 % with an increase of speed from 10 to 15 knots. In this case, however, the assumption of a 1.33 m high bow wave at 15 knots speed may be too low, since the bow submerges deep down, much deeper than in the lower seastate. If a bow wave height of 1.83 m is assumed at 15 knots speed when H_S = 5.5 m, the wave load raises by 40 % as the speed goes up from 10 to 15 knots. The behaviour of the bow wave and its effect on the loads should be included in the numerical solution.

Due to the larger wave-induced motions in bow seas than in direct head seas, the loads on the visor are higher at 150° heading than in head seas when the modal wave period is 8 s. The difference is about 20 % at the level of an 1 to 10 000 exceedance probability in 4 m high seas.

The simulated visor loads at a certain exceedance probability level are in general smaller than the experimental loads, as the examples in Figure 8 show. The difference is more pronounced at longer mean exceedance times, or lower exceedance probabilites where only a few large loads have been measured. The correlation in Figure 8 may have been influenced by the significant wave height having been slightly lower, 5.2 to 5.4 m, in the experiments than in the simulations.



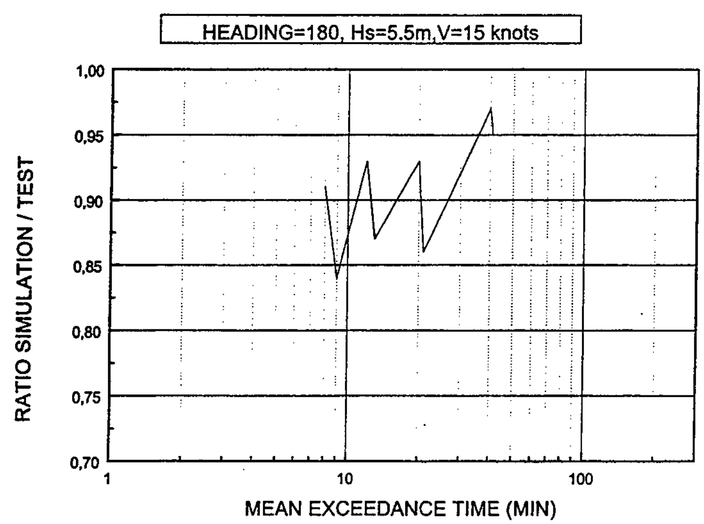


Fig. 8. Correlation of the simulated vertical visor force in head seas $H_s = 5.5$ *m with experimental data at 10 and 15 kn speeds.*

The difference between the experimental and theoretical loads cannot be explained by viscous effects which are of the order of 0.01 MN. Also the computed significant relative motions and velocities agree well with the measured data so that a discrepancy in the simulated and experimental wave-induced motions does not seem to be the source of the difference.

One possible explanation for the difference may be that in the simulations the dynamic wave pressure and the water particle velocity have been determined by the linear wave theory on the level of the mean free surface, or the still water plane. Experimental observations show that the dynamic pressure and the water particle velocity in a wave crest may significantly rise above the still water level.

Other differences in wave characteristics in the simulations and in the experiments may also have contributed to the differences in the results. An analysis of one wave record from the experiments containing about 150 waves shows that the exceedance probabilities of high crest amplitudes differ considerably from the Rayleigh distribution which the low wave trough amplitudes follow closely (Fig. 9). The simulated waves follow the Rayleigh distribution.

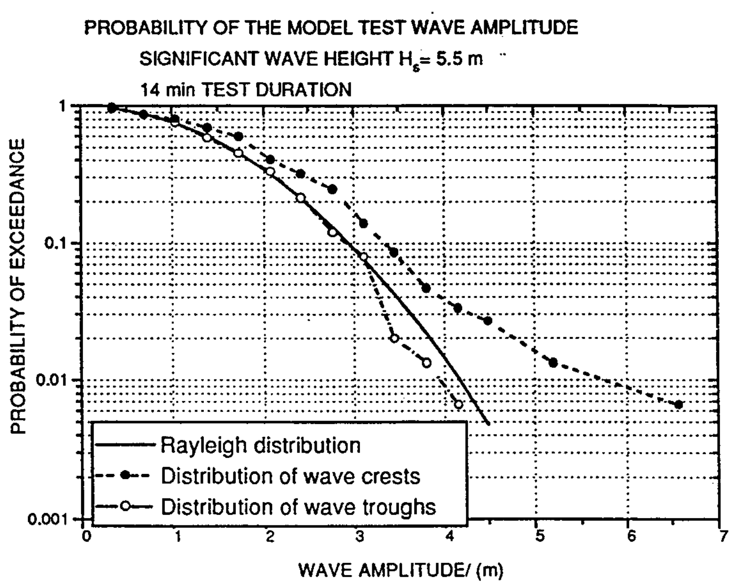
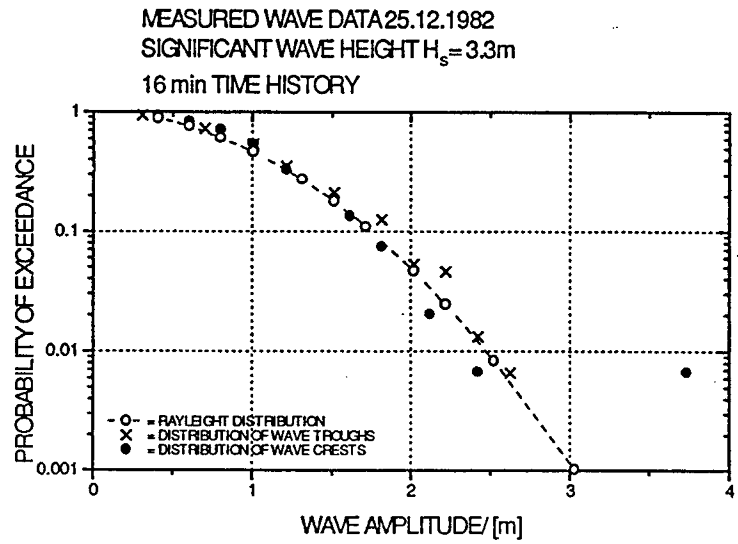


Fig. 9. Distributions of wave crest and trough amplitudes from model experiments compared to the Rayleigh distribution.

Two 16 minutes long wave time histories measured by the Finnish Institute of Marine Research with a waverider buoy south of Bogskär in December 1982 and in January 1983 have been analysed after the MV Estonia accident to compare the wave crest and trough height distributions with the Rayleigh distribution. Figure 10 shows that both the crest and trough distributions correlate well with the Rayleigh distribution. However, the wave time history measured in December 1982 contains one exceptionally high wave crest. This crest, which is about 3.7 m high, while the significant height is 3.3 m, differs significantly from the Rayleigh distribution. In certain storm conditions, so-called episodic waves which have a height of about $2.4H_s$ have been observed (Buckley, 1983), but it is not known whether this kind of waves appear in the Baltic. Andrew & Lloyd (1981) measured wave-induced motions of two British frigates in severe head seas on a full-scale trial south-west of Ireland and found that the wave-induced motions follow quite well the Rayleigh distribution.



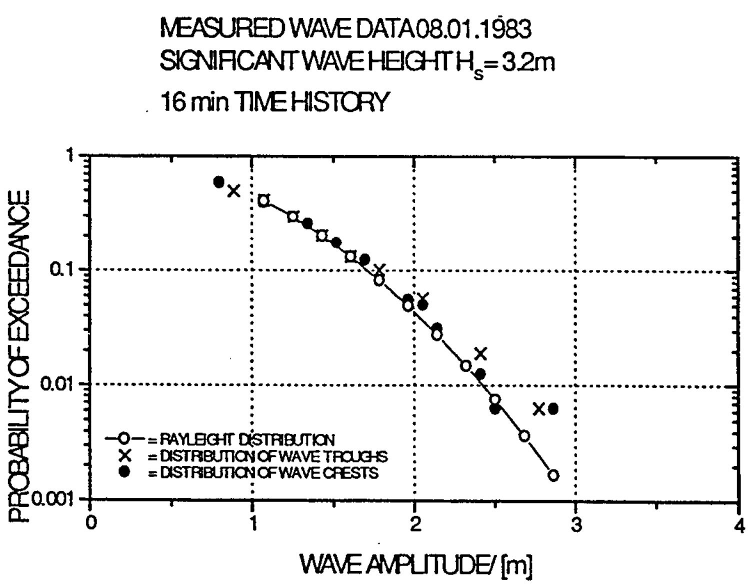


Fig. 10. Distributions of wave crest and trough amplitudes measured in December 1982 (upper plot) and in January 1983 (lower plot) by the Finnish Institute of Marine Research south of Bogskär.

4 CONCLUSION

The vertical component of the wave load on the bow visor of MV Estonia has been simulated in irregular head and bow seas by a numerical method based on the so-called non-linear strip method and momentum consideration. The method is practical and seems to give reasonable results, in spite of the simplifying assumptions involved in the method. The simplifications seem to decrease the numerical visor load values. The method has not been fully validated, but in some cases the results for MV Estonia have been compared with results of model tests with some other hull forms and with a model of MV Estonia. The comparison of numerical predictions with experimental results of MV Estonia is encouraging, though the different factors contributing to high visor loads are not clear.

The very strong dependence of the visor loads on the wave height and even on the wave shape adds uncertainty in the results. This dependence arises partly from the wide flare of the bow visor of MV Estonia. The dependence of the vertical visor load on the forward speed of the vessel is not nearly as strong as on the significant wave height. The load on the bow visor of MV Estonia seems to be approximately directly proportional to the forward speed over a speed range relevant to the accident night.

The behaviour of the "steady" bow wave, when the bow submerges deeply, is not well known. In the numerical predictions, the bow wave height estimated by a non-linear numerical method in calm water has simply been superposed to the vertical relative motion at bow. Assuming a higher bow wave increases the loads. The behaviour of the bow wave should be part of the numerical solution.

The irregular seas used in the simulation have been generated by applying the linear superposition principle. This means that wave crests and troughs are symmetrical with respect to the still water level and the crest and trough amplitudes follow the Rayleigh distribution. In reality in rough sea conditions, the wave troughs get flatter and the wave crests sharper, resulting finally in wave breaking. This increases the number of high wave crest amplitudes and decreases the number of deep throughs. The result is evidently an increase in the magnitude and probability of high wave loads on the bow visor. Wave groups of successive high waves act also in this direction by inducing large motion displacements to the vessel. These are problems which require further study.

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METHODS FOR DESIGN BY DIRECT CALCULATION AND FATIGUE DESIGN - REVIEW

Timo P. J. Mikkola
VTT Manufacturing Technology
Espoo, Finland

Timo Kukkanen
TKK Ship Laboratory
Espoo, Finland

Abstract

Direct design is increasingly applied for ship structures. Classification Societies have recently published or revised their guidance in this field. The recent developments are critically reviewed with emphasis on fatigue assessment. Several aspects are discussed where the approaches could still be improved. Topics for further research and development work are proposed.

1 INTRODUCTION

Design by direct calculation of loads and load effects is increasingly applied for ship structures. Design is no more based only on the knowledge collected and implemented by the Classification Societies in their rules and procedures. This development is caused by increase in the size and/or speed of ships, higher utilisation of structures and increased use of higher tensile strength steels, aluminium and other materials. Certain damage incidents and the public awareness of risks have also had a similar effect.

Increased fatigue sensitivity is an example of changes in the design basis. It was treated implicitly in the past. At present, guidance documents, programs and rules are emerging aimed at fatigue assessment of ship structures. In the future, fatigue assessment will be a routine part of the ship design process.

Classification Societies have recently published or revised their fatigue design procedures for ship structures. The design philosophy seems still to be 'safe life' although this is not explicitly stated and safety factors are too low for this. The procedures are adaptations of simplified approaches and calibrated to some extent with other rule requirements. Comparison has been conducted within the International Association of Classification Societies (IACS). The possibility of using full direct calculation is given as an option. The role of fatigue assessment is, at present, still unclear and the approaches vary between Societies. Ships are still being built and classified without explicit fatigue assessment. In future applications, the explicit fatigue assessment will be more and more widely applied. It can well be assumed that this will also affect the design of ship structural details.

Fatigue cracking has been observed in practice, as documented in several references, see e.g. (Cramer et al. 1995, FAIRPLAY 1991, Ferguson 1991, Motor Ship 1994 and Ramwell 1993). In usual cases, fatigue cracking can be treated as a maintenance problem, but in some cases catastrophic consequences have resulted. Those incidents have promoted the development and modification of design rules, such as the introduction and implementation of fatigue design procedures. A logical step further would be the implementation of the 'fail-safe' or 'damage-tolerant' design philosophy. A basis for this already exist, see e.g. refs. (Guedes Soares et al. 1996 and Cramer et al. 1995). They could be used to further increase the safety and efficient use of ship structures, especially if supported by strength monitoring.

Several problems are still only partially solved in fatigue assessment on the level at which the Classification Societies procedures operate. Further development is required to account for the uncertainties in the loading environment description, load and stress calculation and fatigue strength. Increased speed and the flexibility of ship hull girders will make the non-linearity and dynamic effects in loading more important, and their effects and design procedures need still to be developed.

This paper addresses the topic of design by direct calculation with a special emphasis on fatigue assessment. Several national and international research project results are discussed. The paper concludes with a discussion on future research and development needs.

2 DIRECT DESIGN PROCEDURES FOR FATIGUE

A complete fatigue assessment procedure consists of load spectrum assessment, stress evaluation and fatigue damage calculation. Such procedures have existed and been used for long in other engineering fields. Similar procedures are being introduced and applied to ship structures. When doing so, adaptation to the several features specific to ship structures must be performed.

Load assessment and stress evaluation are strongly dependent on application-specific structures and the environment. The difficulties with ship structures are associated with the modelling of the random cyclic load environment, the complex structures, and with the relatively small product series. The main cause of fatigue is cyclic stresses caused by quasi-static wave loads. Other types of loads causing fatigue, including e.g. temperature and cargo variations and dynamic wave loads, are usually not relevant for design, except in special cases. Guidelines for other loading types and for the combination of separate loading types are rare.

A typical ship hull includes a vast amount of details which are potential initiation sites for a fatigue failure. A comprehensive stress analysis is still a very demanding task, requiring usually several hierarchically refined structural models. As a consequence, several procedures are required in practice, ranging from the screening of potential fatigue failure sites to more accurate procedures for detailed analysis. Furthermore, special guidelines are required for different structures in order to properly take into account structure-specific loads.

The fatigue strength of a ship hull is defined by the fatigue behaviour of welded joints in the structural details. Here the large public database, common with several other engineering fields, can be applied. However, certain important differences exist. The yard practice in maufacture defines the tolerances in joints, which strongly affect the fatigue strength. Furthermore, the stress history of a typical ship detail includes large changes in the mean stress due to changes in cargo conditions. This may have strong effects on the fatigue strength.

2.1 LONG-TERM STRESS RESPONSE ASSESSMENT

Three basically different approaches are available for the long-term stress response assessment. They are based on the simplified 'rule-based' or 'design wave' approaches, the spectral frequency domain procedure or direct time-domain analysis. The adaptation of these can vary to a large extent.

In the 'rule-based' approach, the fatigue assessment is simplified to a level comparable to strength assessment. The load history is described by global cross-section forces and wave pressure along the ship length at a certain exceedance probability and a given probability function for the long-term distribution. In this case, stress ranges can be assessed on the basis of the analysis of only of few loading conditions. Additional information is required for combining different load cases.

The 'design wave' approach is a modification in which loads are defined by a wave corresponding to a certain exceedance probability and which gives the maximum response. The 'design wave' varies with the response. In practice, several wave frequency and heading combinations must be analysed for each response studied.

The simplified approaches have the advantage of easy analysis and they can be scaled to give feasible result practice. Thus the simplified approaches can implicitly include all relevant effects including non-linearities. However, experimental data is required for the scaling. Thus difficulties may arise when these procedures are applied to new types of design.

The spectral procedure operates in the frequency domain for the calculation of a long-term stress spectrum. The stress responses are evaluated for a range of unit wave loads with varying wave length, wave angle, ship speed and loading conditions. A wave spectrum and statistical data are applied for creating short-term response spectra for the relevant range of combinations of sea states, ship speed and loading conditions. The long-term stress spectrum and associated fatigue damage are calculated by weighting each short-term spectrum or corresponding damage with the probability of its occurrence. The spectral procedure can be simplified in several ways and thus it allows a variety of approaches in practice. Several approaches have also been proposed for extending the spectral procedure to account for non-linear effects.

The time-domain analyses have been subdivided into two groups in ref. (API RP 2A-WSD 1994), according to the method used to develop transfer functions which can be based on time-domain analysis of regular waves or random waves. In the first approach with time-domain analysis for regular waves, the response transfer functions are linearised for a chosen wave height. In the second approach, the transfer functions are developed using random waves in the time domain. After calculating the response transfer functions, the analysis continues as in the usual spectral analysis. The second approach can in principle take into account all non-linearities arising from the wave-structure interaction depending only on the numerical time-domain simulation procedure. The time-domain analysis is applied mainly for offshore structures.

2.2 FATIGUE DESIGN PROCEDURES

The fatigue design procedures by the Classification Societies were reviewed by the ISSC-97 Technical Committee III.2 on 'Fatigue and Fracture' as part of the committee work. The resulting document will be published at the Trondheim Congress in August 1997.

All the rules and guidance documents for ship structures have recently been published or revised, see Table 1. Most of the procedures are aimed at a simplified fatigue assessment and are typically characterised as follows:

- A rule-based approach is used with Weibull two-parameter distribution. The spectral approach is recommended for a more accurate fatigue assessment although guidelines are not always given. Guidance is given only for wave-induced quasi-static loads.

- Simplified procedures are given for calculation of stresses due to global and local deformations of the hull girder. Partial FE models are applied. Correlation factors are defined for calculating combined stresses.

- The design life is taken as 20 years without safety factors. The fatigue model is based on the nominal or hot-spot stress approach. The fatigue failure is defined by cumulative damage reaching one when calculated using the Palmgren-Miner linear summation and lower bound S-N curves.

A large variation in the details of the different approaches exists in practically all aspects. The total variation in the predicted fatigue lives could be assessed only by comparing the procedures at each stage and applying them to several types of ships and details. Such comparison is quite laborious and the procedures have also still too much of a status of 'under development'. Some comparative analyses have been conducted within the IACS and these results will hopefully be published.

Table 1. Procedures for fatigue assessment of ship structures.

Reference Program	Short description of the document
ABS 1996, 1996b SafeHull	Step 1 is a designer-oriented assessment for connections of longitudinal stiffeners to transverse webs and bulkheads. Step 2 is a simplified fatigue analysis for local hull structures. Step 3 is a comprehensive structural analysis based on the spectral approach for details found inadequately covered in Step 2. The procedure is applicable for tankers, bulk carriers and containerships.
BV 1994 VeriStar	Simplified 'rule-based' fatigue strength analysis.
DNV 1995 Nauticus	Various levels of fatigue assessment procedures defined, including simplified approaches and a direct spectral-based approach. Its application is required for structural details 'subjected to extensive dynamic loading'.
GL 1996 Poseidon	Simplified 'rule-based' fatigue strength analysis. Its application is required for structures which are 'predominantly subjected to cyclic loads'.
LR 1996 ShipRight	The procedure is available through the use of the ShipRight programme. Level 1 includes a comparison of the existing structural design to recommended designs. Level 2 is a simplified spectral procedure. Level 3 (applied by LR) is a full spectral procedure. Application of levels 1 and 2 are mandatory for new oil tankers and bulk carriers over 190 m in length.
NK 1996 PrimeShip	Simplified spectral-based approach. The procedure is applicable for longitudinal, transverse and local strength members of oil tankers, bulk carriers and container ships.
RINA 1995	Simplified 'rule-based' fatigue strength analysis. Application is required for the special notation FTC by RINA.
KR 1995	Simplified 'rule-based' fatigue strength analysis.

A common base for the fatigue strength of classified details is applied, although the approaches to special aspects, such as corrosion, mean stress and thickness effects, vary. A common agreement exists on the use of the structural (hot-spot) stress approach for improving the accuracy of fatigue strength assessment. The definition of the hot-spot stress is generally accepted as given by ref. (Niemi 1995). The hot-spot S-N curves vary to a large extent and they alone give a variation of > 2 in predicted fatigue lives, see Fig. 1. Naturally, this variation is affected also by the definition of loads, local nominal stresses and the stress concentration factor (SCF).

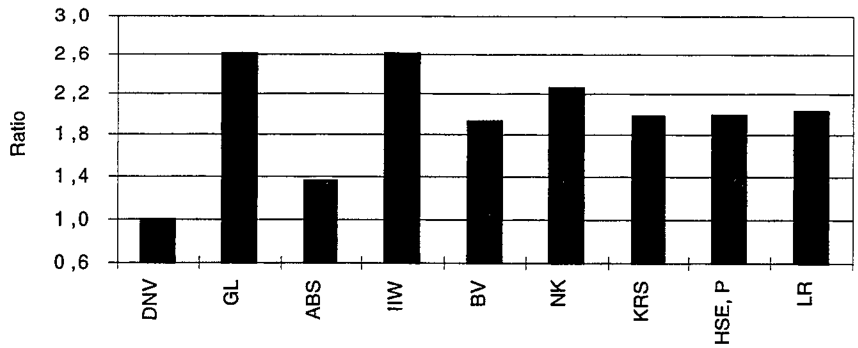

Figure 1. Effect of differences in local approach S-N curve in fatigue life. The DNV result is scaled to one and the other results accordingly.

On the basis of the publications it is not possible to judge whether specific ship details would be similarly classified. One would not expect large variations in this. Several of the procedures give guidance on hot-spot stress SCF calculation by the FE method and these are commented in ch. 4. The data for the necessary SCF are still lacking.

The approaches to how the reduction in fatigue life due to corrosion is taken into account vary to a large extent. In some cases, the corrosion protection is assumed effective for the whole design life. In other procedures corrosion causes a reduction of appr. 2 in fatigue life.

Manufacturing practices affect the fatigue strength through weld quality and misalignments. In most of the procedures, these aspects are covered by a general statement on the use of normal good workmanship and by referring to respective standards. The actual manufacturing tolerances are not directly connected to the fatigue strength of the detail.

Considering the approaches for fatigue life prediction and the large amount of details, occasional fatigue cracking can be expected and has also been observed in practice. Ships are being designed using the fail safe principle although this is not explicitly stated. The recognition of this could expand the scope of analysis in the direction of reliability assessment of damaged structures and inspection scheduling as e.g. in ref. (Cramer et al. 1995).

2.3 SPECTRAL FATIGUE PROCEDURE

An integrated programme system for spectral analysis of ship structures was developed in the T2000 spin-off project (Kukkanen 1996, and Mikkola et al. 1995), see Fig. 2. The programme includes calculation of wave-induced loads and hull stresses, short- and long-term prediction of stress responses, and fatigue damage predictions on hull structural details.

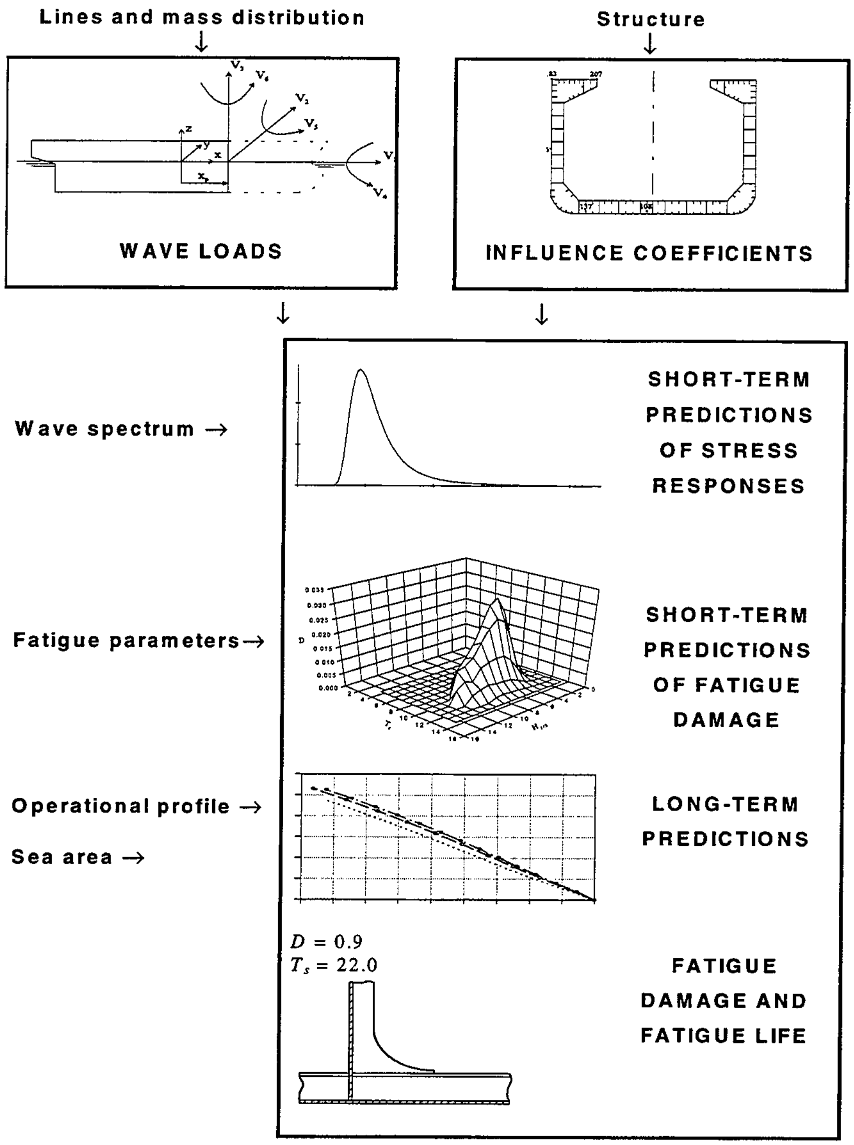

Figure 2. Programme system for spectral-based analysis of ship structures.

Cross-sectional properties and structural stress responses at a cross-section are calculated by the SECPRO programme, based on the FE method. Detail FE analysis can be used also to determine stress responses for complex ship structures. Wave loads are determined by the SHIPLOAD programme, based on the linear strip-method. A spectral method is applied to determine stress responses in different short-term conditions, and long-term predictions for stress responses are calculated by taking into account different operational and environmental conditions. All different load components are combined with the correct phases, and thus constant correlation coefficients between load components are not required. Miner's fatigue accumulation hypothesis is used together with probabilistic models for stress ranges and stress cycles. Material characteristics and structural details are taken into account by applying S-N curve data and stress concentration factors. Both short- and long-term predictions as well as fatigue calculations are performed by the LONGTD programme, see Fig. 3. Typical results from hull girder analyses are presented in Fig. 3.

Classification societies allow the use of direct calculation for a more refined fatigue analysis, see e.g. (DNV 1995). Usually programmes for such analysis are not available, but procedures are defined or computational services are offered, or both. The present programme can be applied for a full spectral fatigue analysis as defined by the Classification Societies. This is advantageous especially at this phase when the procedures of the Classification Societies are still, at least partially, in the development stage. Designing based on results from direct calculation is not yet fully established.

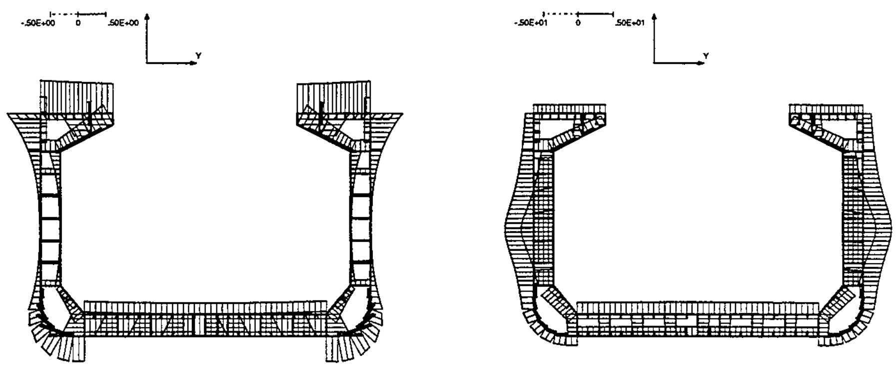

Figure 3. Fatigue analysis results for a ship cross section: a) Fatigue Damage, b) Allowable stress concentration factor SCF.

The programme can also be applied together with the simplified 'rule-based' approach, see Fig. 4. In this case, a two-dimensional Weibull distribution is applied, and different load effects are combined by separate correlation coefficients.

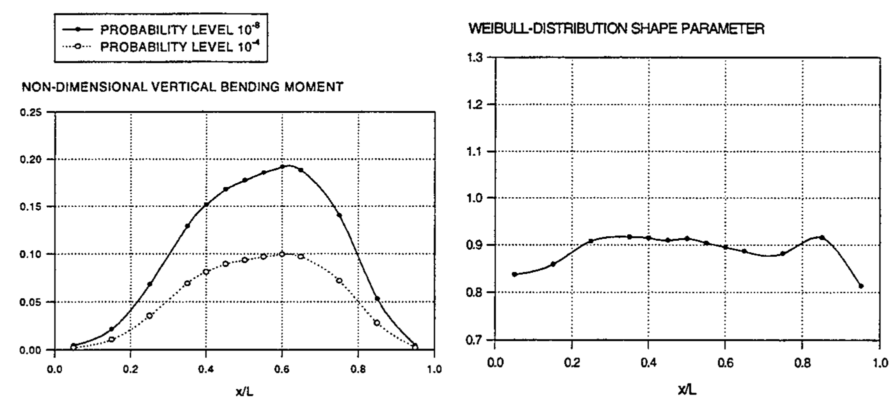

Figure 4. Bending moment and Weibull distribution shape parameter for 'rule-based' fatigue analysis.

3 UNCERTAINTIES IN DIRECT DESIGN

In the spectral fatigue analysis, calculation of wave loads, modeling of environmental and operational conditions, and probabilistic models of stress ranges are important factors in the procedure. Hence, knowledge of the uncertainties involved in these components is crucial to obtain reliable predictions for fatigue strength. Below some main factors are given that affect the uncertainties in the spectral fatigue analysis procedure presented in Ch. 2.3 (Kukkanen 1996). Other investigations are also briefly referred to.

Uncertainties in wave loads have a great influence on the long-term distribution, and hence also on the fatigue strength predictions. At present, wave loads are calculated by a linear strip method in the direct calculation procedure. Typically, the vertical bending moment is estimated well, see Fig. 5, although in following seas there are large deviations. Results for the lateral bending moment are usually less satisfactory. The calculation of wave loads becomes even more important, when local wave loads are taken into account. Accurate hydrodynamic pressures are needed for a realistic fatigue assessment below the waterline area. Further, when 3D FE models are applied to the structural analysis, wave loads must be given as distributed pressures. Predictions for hydrodynamic pressures are usually less satisfactory than predictions for global hull girder loads, especially if a two-dimensional approach is applied (ISSC 1991). In addition, another problem in the pressure loads is that near the waterline the structure is part of the time out of the water and negative pressures are not possible. The linear theory assumes that the pressure varies sinusoidally up to still water level, and above the still water level there are no pressure variations. This problem can be solved, for example, by applying linear relative motions and probabilities for the occurrences when this part of the structure is in or out of the water, see e.g (Fricke et al. 1995).

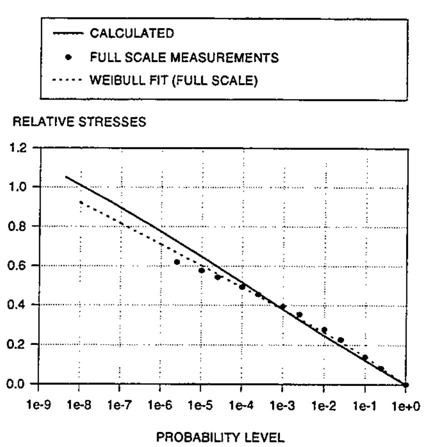

Figure 5. Calculated and full scale long-term predictions.

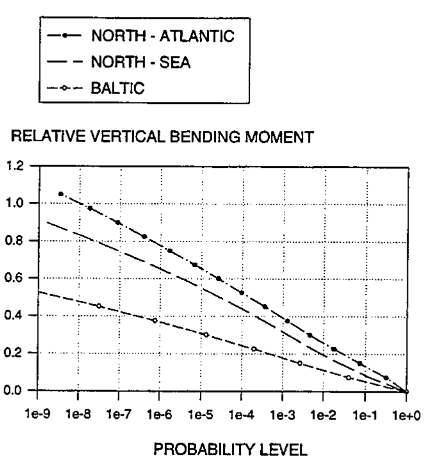

Figure 6. Long-term predictions in different sea areas.

Schellin et al. (1996) have studied uncertainties in long-term predictions of hull girder loads by using different wave load calculation methods. These methods were three different strip programmes and one simplified three-dimensional panel method. Investigations show that relatively large differences exist between different methods when predicting midship wave-induced sectional loads.

In the direct calculation procedure, responses in irregular seas are determined by using standard wave spectra. Usually in the structural analysis and design consideration the modified Pierson-Moskowitz wave spectrum is applied. This spectrum is applicable for open and fully developed seas. Ochi & Hubble (1976) have presented a six-parameter spectral family that is double peaked and describes also partially developed sea states. However, when applying these two different spectra the differences between long-term predictions of primary stresses were small. However, a short-crested sea has a large influence on long-term predictions. In short-crested sea, the long-term predictions of responses are considerably lower than the values obtained in long-crested seas. The applied cosine-squared spreading function is still an approximate description of short-crested seas, and more detailed investigations have shown that this spreading function might be unconservative (Guedes Soares 1995).

In long-term predictions the occurrence probabilities of the prevailing sea state are often taken from Global Wave Statistics data (GWS 1986). These data were collected onboard ships in normal service and were derived by visual observations. These data were analysed carefully by using also wind observations to improve the reliability of the wave statistics. Applying these wave statistics data it is suggested that bad weather avoidance should not be taken into account because this is already built in the data (Guedes Soares 1996). The reason for this is that the data is based on observations on ships and the ship crew tries to avoid severe storm conditions. However, analyses have shown that uncertainties in Global Wave Statistics data may be large (Bitner-Gregersen et al. 1995). Satellite measurements might improve the reliability of wave and wind statistics. At the moment at least one commercial package is available (CLIOSAT 1996).

When predicting long-term distributions for responses, the operational conditions of the ship and the environment have to be known. All operational conditions and main dimensions of the ship have an effect on the shape and magnitude of the long-term distribution, see Fig. 6, which means that these also have an effect on the fatigue strength prediction. Ship lifetime operational conditions include relative fractions of the different loading conditions, speeds, heading angles and sea states. Besides, all occurrence probabilities are dependent on each other, at least to some extent. For example, the ship's speed varies during the ship's voyage, due to manoeuvring and voluntary or involuntary speed reductions. Furthermore, the ship crew tries to change the course of the ship relative to the waves to avoid large ship motions. In addition, for a definite route there might be a prevailing wind, and thus certain wave directions that are more common than other directions. This has an effect on the long-term predictions of response if the ship is sailing most of her service time in the same route. This has been studied by Guedes Soares (1995) and his conclusion was that neglecting the directionality of wave conditions can result to an underestimated prediction of up to 20 %.

If the ship is designed for a specific route where wave statistics are available, then the life time operational profile of the ship can be determined and in principle take into account in the programme. However, operational conditions are usually difficult to determine beforehand, because the ship is not usually designed for a certain route and sea area. One reason for this is that the ship will be sold, and the operating area will not be restricted to specific sea areas. For unrestricted service, the applied sea area is generally the North Atlantic where the ship is assumed to operate her 20-year service time. These criteria are applied generally in direct calculations, even if the ship is not going to operate the whole of her service time in the North Atlantic, or the ship cannot operate there, due to other restrictions than structural strength.

The probabilistic Rayleigh model applied assumes a narrow-banded response spectrum. Thus it assumes that stress history consists of separate cycles with a varying amplitude. In practice, the stress spectrum is broad-banded and the true stress history is a combination of cycles with a variable frequency and amplitude. The fatigue damage calculated by the Rayleigh model is conservative. If an empirical broad-band correction is applied to the Rayleigh fatigue model, the fatigue damage predictions are at most 20% lower than predictions without correction.

The spectral procedure (Ch. 2.3) is based on linear theory and only low-frequency loads are taken into account. The hull girder is assumed to behave as a rigid beam and the wave loads are determined by using a linear strip method. Especially for fast ships, non-linearities in whipping and springing responses might be significant. The stress response may be non-Gaussian for non-linear response conditions. In these cases, the fatigue damage calculated by the Rayleigh model may be non-conservative.

4 SCF ANALYSIS BY THE FE METHOD

The fatigue strength of ship structures is governed by the fatigue strength of its details. In most design procedures the fatigue strength of a detail is calculated by using an S-N curve and an associated SCF. The accuracy of the fatigue strength evaluation can be increased by a more detailed SCF analysis, and this option is included in all the fatigue procedures by the Classification Societies. The methods are typically adaptations of the hot-spot approach or other local approaches. The few published SCF data are still given in a very general form. The actual geometric dimensions, for example, do not, in most cases affect the SCF directly.

A national research project was conducted by LTKK and VTT (1994 - 1996) aimed at developing modelling techniques and SCF data for welded steel details. The details analysed were mainly basic ones for which the SCF results were given also by parametric formulae, see e.g. (Poutiainen 1996). In addition two ship structural details were analysed (Mikkola 1997), see Fig. 7. The work by VTT concentrated on developing robust and practical tools for the hot-spot stress analysis by the finite element (FE) method using shell elements (Mikkola 1997). This part of the work included a study of hot-spot stress accuracy, calculated with various FE modelling techniques. Furthermore, tools were developed for a hierarchical approach to be used in the fatigue assessment of ship structures.

The resulting recommended approach consisted of shell element modelling without modelling the weld seam. The structural members were connected at their geometrically correct locations by rigid offsets, see Fig. 7. The hot-spot stress was calculated by linear or parabolic extrapolation. Stresses at the extrapolation points were calculated using the continuous stress field defined by the nodal stresses and element shape functions. Further, transverse averaging was applied to compensate for the artificially narrow high structural stress area ahead of the hot-spot. A sufficient requirement for the mesh density was that the distance between the first extrapolation point and the hot-spot point was larger than the element edge length at the hot-spot. Furthermore, gradual mesh refinement towards the hot spot was required.

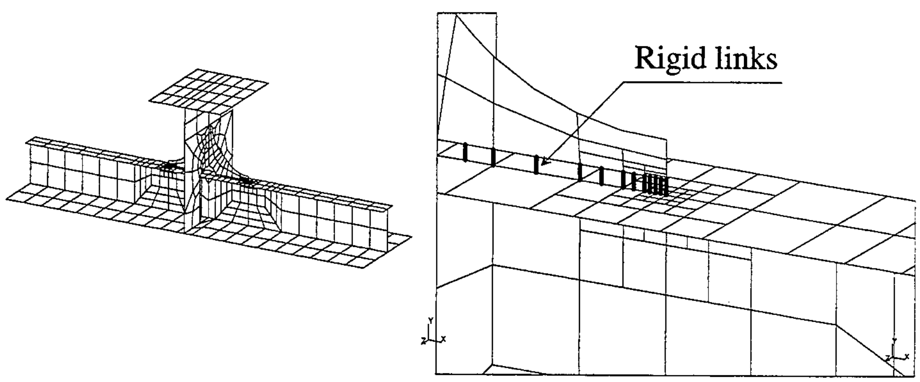

Figure 7. A shell FE model of a ship structural detail for SCF analysis.

The traditional modelling technique of connecting shell elements directly at the mid-surface was shown to produce an unconservative SCF in some cases. The shell model combined with a rigid offset model gave consistently conservative hot-spot stresses with acceptable accuracy in all cases studied.

Considering the two ship structural details studied, only limited data was available for comparison and contradicting results were found. The results indicated a strong influence of the actual geometry and loading mode on the stress concentration. These effects are often neglected in the published results and the use of such generalisations may cause large errors.

The guidelines of the Classification Societies documents typically define a linear extrapolation procedure for calculating the SCF from FE results. Traditional shell element modelling is allowed with element size equal to plate thickness at the hot-spot. The study showed that this approach will not produce converged stress results. In some cases even unconservative SCF may be produced. The SCF and the S-N curve are related and it may well be that calibration has been done at least by some Classification Societies to justify the too loose guidelines given for SCF determination. The resulting SCF is also very much dependent on the extrapolation procedure applied.

5 INTERNATIONAL RESEARCH ON RELATED TOPICS

5.1 APPLICATION OF HIGH-TENSILE STEEL

To be competitive in the shipbuilding industry the application of high-tensile steels is indispensable. The use of high-strength steels with yield stresses up to 390 MPa is gradually increasing in conventional and novel ship structures, at least for parts of those structures. This leads to lighter ship structures due to the higher allowable stress levels. However, special care has to be taken to reduce the probability of fatigue failure to acceptable levels, because the fatigue characteristics of high-strength steels are hardly any better than those of conventional steel.

Therefore adequate design tools are required to predict failure due to fatigue damage. Improving structural details by applying mechanized or robotised manufacturing methods will decrease their sensitivity to fatigue. In that case not only can the superior strength properties of high-strength steel fully be exploited, but due to the improved manufacturing methods, lower cost prices can be realised as well.

These topics are addressed by a Brite-EuRam project titled 'FATIGUE-BASED DESIGN RULES FOR THE APPLICATION OF HIGH-TENSILE STEELS IN SHIPS' (FatHTS, 1996 - 1999). Objectives strived for are:

(1) A fatigue-based design methodology for the strength of ships made (partly) of high-strength steels with yield stresses up to 690 MPa.
(2) Mechanised or robotised manufacturing methods to obtain fatigue-resistant welded structural details.
(3) Recommendations for design standards based on probabilistic procedures and for the implementation of these standards in ship structural strength analysis, as given in Classification Rules.

The FatHTS consortium consist of five shipyards (CdA, Fincantieri, Lisnave, Odense and Schelde), three classification societies (BV, RINA and GL), AF group (Engineering company), three universities (Lisbon, Hamburg and Göteborg) and the research institutes TNO (The Netherlands) and VTT. The duration of the project is 3.5 years and the total volume is appr. 425 manmonths.

In offshore industries HTS steels are applied to a much larger extent and the steel strengths are higher. The problems faced in applying the higher yield strength class steels in addition to fatigue are related to fracture toughness properties of welds. This topic has been addressed by two European research projects titled 'Acceptance criteria and level of safety for high strength steel weldments' and 'Properties of multipass welded joints'. The results of these projects will be presented and discussed in a two-day symposium 'Safety in application of high-strength steel' in June in Trondheim Norway.

5.2 SHIP MAINTENANCE PROJECT

A joint industry and government sponsored research programme was completed in U.S.A. during 1990 - 1995 under the title 'Ship Maintenance Project' (Cramer et al. 1995). It focused on the development of technology that could lead to improvements in structural maintenance for new and existing tankers.

The research programme included a large number of projects with varying focuses, such as damage evaluation, fatigue design, fitness-for-purpose assessment, repair, maintenance and inspection. The design philosophy behind the project was clearly 'fail-safe' or 'damage-tolerant'. The reported damages in e.g. tankers clearly demonstrate the importance of developing tools for 'fitness-for-purpose' studies. This topic was addressed by the programme and practical tools were developed based on fracture mechanics.

5.3 OFFSHORE FATIGUE GUIDANCE DEVELOPMENT

Fatigue analysis has been used as a design criterion for offshore structures for long and the structural (hot-spot) stress approach is in general use. The fatigue assessment guidelines for offshore structures have been under revision for several years. The revised fatigue guidelines have been published in (HSE 1995) and reviewed by ref. (Stacey, A. & Sharp, J.V. 1995). The development of the new ISO code for offshore structures is nearing completion and has been reviewed by ref. (Baerheim et al. 1996).

In fatigue guidelines for offshore structures the emphasis is more on the use of full spectral procedures or time-domain based procedures, see also ref. (API RP 2A-WSD 1994). The fatigue assessment must be more comprehensive and safety factors between 2 and 10 are applied in fatigue life.

The HSE fatigue guidance document is widely applied also in ship building. In the new guidance the S-N curve sets for welded joints given are T'-curve for tubular joints and P-curve for plate joints. The both sets include three curves corresponding to air, sea water with cathodic protection and sea water with free corrosion. All the S-N curves have a slope of 3 which changes to 5 for the air- and sea water with cathodic protection. The previous S-N curves for classified joints are now replaced by the use of the P-curve and associated classification factors.

The revised guidelines require a more stringent assessment of structures exposed to sea water, even for those having cathodic protection. The penalty factor for free corrosion is now 3. For sea water with cathodic protection the penalty factor applied is 2 for tubular joints and 2.5 for plated joints. For a higher number of cycles above 10^7, the sea water with cathodic protection curves coincide with the air curves.

The new HSE document includes guidelines on the use of SCF data for tubular joints. The recommendations are based on a critical review on existing data. Details of this study will be published. As a result of this study only two sets of SCF equations are recommended. Neither of these could be recommended for all situations and data is lacking for certain joint types.

5.4 FATIGUE OF FULL-SIZE COMPONENTS

The majority of S-N curves are defined by small-scale fatigue testing. Fatigue test results from full-size components usually show agreement with lower bound results of small-scale testing. Comparison between small and full-size test results is difficult and may be affected by the definition of failure and the stress measure used. The present understanding is that the major affecting parameters are residual welding stresses, which are higher in full-size components, the thickness, which reduces fatigue strength when increased and the manufacturing tolerances.

The definition of fatigue failure is problematic for full-size components. Fatigue cracking at one local detail will not directly cause failure of the structure. The crack will start to grow, but the growth rate may be lowered due to the load-shedding effect. The developed crack increases flexibility, and this causes a load redistribution. As a consequence, the present fatigue assessment procedures are very conservative. The load-shedding effect can be taken into account in the fatigue assessment by using fitness-for-purpose analyses based on fracture mechanics, as in ref. (Cramer et al. 1995).

A series of large-scale fatigue tests were conducted at the Krylov Institute in Russia on the commission of Lloyd's Register of Shipping, GB, since 1992 (Lloyd's Register Seminar 1995). The fatigue-testing program supported the development of the ShipRight procedure. The testing program has covered various modifications of two structural details. The results were also used for verifying the FE analysis procedure for SCF calculation.

5.5 IIW FATIGUE GUIDELINES

The International Institute of Welding (IIW) has published the latest version of the fatigue guidelines document in 1996 (Hobbacher 1996). This document includes comprehensive guidance on fatigue strength assessment and a large collection of fatigue S-N curves both for steel and aluminium. Some ship-specific details are included as well. The document is supplemented by a separate publication on stress determination for fatigue analysis (Niemi 1995). This document has gained wide acceptance also among Classification Societies and is often referred to as the basis for defining structural (hot-spot) stress.

A new working group has been established with the title 'Hot-spot stress method in the fatigue analysis of welded components' under the chairmanship of Prof. Niemi. The group will collect and produce hot-spot SCF data. An important aspect is the development of standard procedures for stress determination by FE analysis. At present the validity and applicability of SCF data produced is questionable, as was shown by the study concerning the data for offshore tubular joints referred to in (Stacey, A. & J.V. Sharp 1995).

Weld improvement techniques have been shown to give substantial increases in fatigue strength. At present the use of such methods in manufacturing is hampered by a lack of standardisation of methods and procedures which would result in controlled degree on improvement. Required guidelines have been developed by the IIW, which also manages a collaborative test program of improvement techniques, see ref. (Haagensen et al. 1995).

6 DISCUSSION AND CONCLUSIONS

Direct design procedures and programmes are still too much separate tools which should be integrated with other ship design tools. The data required by the direct calculation procedures already exist in other systems. The procedures should be capable of working with incomplete data and efficient enough to be used for reanalysis, as more precise data becomes available. Own implementation of the procedures, such as introduced in ch. 2.3, is advantageous in this respect. The programs provided by the Classification Societies are aimed more at analysis with completed designs.

Designing by direct calculation is not yet fully established. Development efforts are still required in several areas. The main emphasis in the work up to now has been in the field of fatigue. The procedure should be further developed for extreme load and ultimate strength analysis. The treatment of the pressure load is essential for realistic fatigue damage estimation in the ship hull below the waterline. Guidelines for other than quasi-static wave loads and for the combination of separate loading types are rare. Other types of loads can be caused by e.g. temperature and cargo variations.

The direct design procedure includes several uncertainties. This problem has been solved in earlier design rules by gradual time-consuming experimental calibration. Similar calibration is obviously being performed by the Classification Societies for their own direct design procedures. The design changes are taking place with increasing speed. It would be valuable to be able to verify the accuracy of direct design tools without any unknown calibration variables. This could be approached by using statically measured and monitored results. A comparison of numerical results by other approaches should be used as well.

The importance of dynamic wave loads will further increase in future designs, and research and development in this area is required. The response for dynamic loads can be analysed by time-domain simulation. It is also possible to improve the developed spectral procedure to take into account non-linear effects. They are important in extreme load and ultimate strength analysis and their significance for fatigue should be assessed.

Realistic fatigue failure assessment of ship structures requires analysis of crack growth with fracture mechanics. Knowledge and tools for such studies are readily available from other fields of application. The scope of such studies should be extended from design also to fitness-for-purpose analyses and they also have connection to strength monitoring.

Ship-specific SCF data is still lacking and modelling guidelines for FE analysis are incomplete. This is an area where misleading and erroneous results are easily produced. This topic is partially covered by the new IIW working group. More effort would be needed for studying ship structural details.

The fatigue strength of welded joints can be greatly improved by manufacturing stage improvement techniques and detail design optimisation. Ships have specific load spectra which affect the fatigue strength also through residual and mean stresses. These topics are studied e.g. in the FatHTS project.

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MODEL TESTING OF DAMAGED RO-RO PASSENGER FERRIES ACCORDING TO THE RECENT IMO REGULATIONS

Heikki Helasharju
VTT Manufacturing Technology
Espoo, Finland

Abstract

The paper describes the procedure of model tests to demonstrate the survivability of a damage ro-ro passenger ship in waves. The procedure is defined by the maritime administrations of North-West European and Scandinavian countries.

1 INTRODUCTION

After the Estonia accident in 1994, the International Maritime Organisation (IMO) established a Panel of Experts to develop recommendations and proposals to enhance the safety of ro-ro passenger ships. After a lengthy period of work a Regional Agreement concerning specific stability requirements of ro-ro passenger ships was agreed by the North-West European and Scandinavian countries and in July 1996 Guidance Notes to the Annexes of the Agreement were finally introduced. Compliance with SOLAS 90 requirements is called for existing vessels with water on the vehicle deck. In addition to the straightforward hydrostatic calculations, the Agreement gives an option to use model tests in waves to demonstrate the survivability of an individual ship.

The administration has had an obvious need to try to maintain the integrity of the model test procedure irrespective of the ship particulars or the model basin carrying out the tests. Therefore the Guidance Notes very precisely defined a good deal of the model test procedure. The aim of this paper is to briefly outline this procedure described in IMO Circular Letter No 1891/ Appendix 1 and in the subsequent Regional Guidance Notes 5 July 1996.

2 DAMAGE CASES

2.1 DAMAGE STABILITY ANALYSES

The study of a damaged ship is based on the worst damage case scenario according to SOLAS 90. That is the damage case providing the least area under the GZ-curve for any relevant loading condition of the ship.

An additional test case, an even keel damage amidships with the least residual freeboard, is required, if the worst damage location is outside the range $L_{pp}/2$ $\pm 0.1L_{pp}$. The cause for the alternative damage case requirement is probably the results of model tests carried out in Great Britain and Denmark after the accident of Herald of Free Enterprise 1987. Damage amidships quite frequently proved to be more critical than damage to fore or aft, as far as the ability of the damaged ship to survive in waves is concerned. The additional damage case is of course required only if the ro-ro deck area will be exposed to flood water.

2.2 DEFINITION OF THE DAMAGE GEOMETRY

The damage geometry is defined in SOLAS 90.

- rectangular side profile with a width of 0.03 * Lpp + 3 meters
- triangular profile in the horizontal plane with a height equal to B/5.

In vertical direction the damage height is unlimited. Additionally in cases where there are side casings of a width less than B/5 the damage length in the side casings should be at least two metres.

3 SHIP MODEL

3.1 MODEL CONSTRUCTION

The outer configuration of the model geometry should represent the ship hull geometry accurately in a common manner. However, the modelling of the damaged areas of the hull are a characteristic feature for the safety model tests and the techniques and materials are quite dissimilar to any of the conventional ship models for hydrodynamic testing.

The model size is restricted to 3 metres minimum length. Additionally a scale factor of 1:40 is recommended as an upper limit.

Suitable materials for the construction of the damage areas are fibreglass, lexan or plexiglass and aluminium. However, material thicknesses from 1 to 3 mm are inevitable, but the excessive thickness is allowable, as long as the geometry of the modelled damaged compartments is sufficient to provide the correct volumes of flood water and the corresponding centre of gravity. The number and location of the damage cases greatly defines the complexity of the model construction and, consequently, the time required and the expenses. In general the models built to safety model tests tend to be a bit more expensive compared to the ship models for more conventional hydrodynamic testing.

Ventilation, drainage or other piping need not be modelled, but it is important to arrange ventilation pipes for the lower compartments in order to prevent the formation of air pockets.
No detailed instructions are given for modelling the permeability of the damaged compartments. The main approach is that compartments are left empty. Large, solid blocks, such as main engines, obviously need to be modelled. The ro-ro deck is always left empty without cargo.

Superstructures are necessary up to three superstructure standard heights above the bulkhead deck so that large waves will not break over the model.

3.2 MASS PROPERTIES

The model must be ballasted in order to have a proper centre of gravity and weight distribution. These values are primarily checked for an intact hull. The values for vertical centre of gravity and initial metacentric height are to be demonstrated by inclining and roll decay tests of the intact hull. Furthermore, the draughts are inspected, first in the case of an intact and then of a damaged hull. The latter should be compared with the initial condition of the damage stability analyses. The Guidance Notes do allow small adjustments to the model, in order to make the draught values of the damaged model in a static condition match with the results of the damage stability analyses. The adjustments can be made by introducing intact volumes to the model or by adding or shifting the ballast weight. However, all adjustments should err on the side of safety.

Fixed values of rolling and pitching gyradii are defined by the Guidance Notes. For the pitching gyradius, the upper limit is $k_{yy} < 0.25L$, and for the rolling gyradius $k''_{xx} < 0.4B$.

The latter value is related to hull weight + added weight of water, i.e. the roll resonance period of the hull as defined by roll decay tests in water should be :

$$T_{roll} < 2 * \pi * 0.4B / (g * GM)^{1/2} \qquad (1)$$

The principle of setting a single fixed value for the roll gyradius can be criticised. However, the reasoning of the administration is easy to understand since roll decay tests are fairly simple to supervise. It was also stated, quite correctly, by the administration that at least in most of the cases the true gyradius of a ship is not really known and that any unknown factors in the test procedure should err on the side of safety. The principle of a fixed value of the roll period in water in practice efficiently invalidates the effect of any excessive hull damping features or roll damping devices.

Roll decay tests with the damaged hull should also be carried out in order to record the roll resonance period in the damaged condition.

4 WAVE CONDITIONS

The wave height cases for the tests can be selected for an unrestricted operation area or for a specific restricted sea area only. In the former case the significant wave height, H_s , is 4.0 m. The areal H_s values can be found in IMO Circular letter 1891 Annex 1, p. 2-3.

Examples:

Route:	H_s (m)
Helsinki - Tallinn	1.9
Vaasa - Umeå	1.7
Helsinki - Stockholm	3.1
Helsinki - Travemünde	3.1
Continent - Great Britain (across the English Channel)	2.5 ... 3.8
Great Britain - Ireland (across the Irish Sea)	2.8 ... 3.7

Two modal wave periods, T_P, are applied for each irregular seaway defined by the significant wave height value:

- $T_P = 4*(H_s)^{1/2}$; the numerical wave spectrum formula is taken according to the JONSWAP equation and $\gamma = 3.3$.

- $T_P = 6*(H_s)^{1/2}$ or $T_P = T_{roll}$, whichever is smaller; the numerical wave spectrum formula according to the JONSWAP equation and $\gamma = 1$, which equals to the Pierson & Moskowitz wave spectrum formula for fully developed seas. T_{roll} of the damaged ship is applied.

Five different time-histories for both modal periods are generated for the tests.

The quality of the model wave spectra is further controlled by demanding specific relations between the modal wave periods and zero-crossing wave periods, T_Z.

For steep waves with $\gamma = 3.3$	$T_P / T_Z = 1.2 .... 1.28$
and for mild waves with $\gamma = 1$	$T_P / T_Z = 1.3 .... 1.4$

The modal wave period defines the period of the maximum energy of the wave spectrum. The choice of the wave periods and spectrum formula is taken from two extreme ends. The spectra with $Tp = 4*(H_s)^{1/2}$ and $\gamma = 3.3$ represent steep waves with concentrated energy contents. For most of the ro-ro vessels, roll response is not too strongly excited, but the steep waves might break in through the damage opening and into the ro-ro deck. The mild waves, on the other hand, will excite a lot of rolling, at least during the early stage of a test run, and may cause violent motions to the volume of water on the ro-ro deck.

H_s - T_P values for two wave cases:

H_s	$T_P = 4*(H_s)^{1/2}$	$T_P = 6*(H_s)^{1/2}$
4.0 m	8.0 s	12.0 s
3.1 m	7.0 s	10.6 s

These modal wave period values can be compared to the roll resonance period values (I) calculated for a fictional ship with the initial metacentric height as a parameter:

Beam (m)	GM (m)		Troll (s)
27	1.5	=>	17.7
27	2.3	=>	14.2
27	3.2	=>	12.3

Lower initial metacentric height values result in longer roll resonance period values further away from the fixed upper limit of the modal wave periods of the fully developed seas. In practise this would mean less rolling, more synchronised rolling with waves, a smaller relative hull motion in the side, and eventually less water on the deck.

5 INSTRUMENTATION FOR THE TESTS

The model should have measuring equipment for recording the roll, heave and pitch motions. The same measuring instruments will give corresponding static (off-set from the initial state) values, i.e. heel, sinkage of centre of gravity and trim.

The waves should be measured at two locations. A stationary wave probe should be placed close to the wave maker. Another wave probe should measure the oncoming waves in the vicinity of the model hull. The acceptable relative positions of the wave probe in the vicinity of hull are precisely defined as narrow sectors ahead and behind the hull. The purpose is to avoid the wave diffraction and reflection caused by the model.

All test runs must be video recorded with at least one camera revealing the overall behaviour of the model in waves. If the ro-ro deck lay-out includes transverse barriers, then another video camera should be placed to record the "splashing over" and accumulation of water on the undamaged area of the deck.

6 TEST PERFORMANCE

At the initial stage, the model is placed beam seas with the damage side facing the oncoming waves. The model must be free to drift and should not be restricted in any manner, in order to enable unrestrained motions and capsizing. The duration of a single test run should be such that a stationary state is reached, but in any case no less than 30 minutes in full-scale time. If the hull in the initial damaged condition is upright, it should be given 1° heel towards the damaged side before the tests are begun.

For each modal wave period case, five repeated runs with different realisations of wave time-histories are required. The test entity for one damage case is thus altogether ten test runs.

In case none of the experiments results in stationary heel towards the waves, the tests must be repeated with another set of five waves at each of the specified wave conditions, or the model can be given an additional 1° heel towards the damaged side and the tests repeated with two runs at each of the specified wave conditions.

All tests must be witnessed by the Administration.

7 SURVIVAL CRITERIA

From the time-histories of the measured signals the values forming the safety criteria can be checked.

The ship is considered as surviving, if in all ten test runs:

- a stationary state of heel and trim is reached
- the steady heel is less than 20°
- roll amplitudes exceeding 30° with respect to the vertical axes occur in less than 20% of the roll cycles

8 REPORTING

Apart from standard research reporting, the Administration has specified a list of items to be included:

- damage stability calculations for worst SOLAS 90 and midship damage (if different)
- general arrangement drawing of the model together with details of the construction and instrumentation
- inclining experiment and rolling test reports
- calculations of actual ship and model rolling periods
- nominal and measured wave spectra (near the wave maker and near the model)
- representative records of model motions, attitude and drift; and
- relevant video recordings

The list is rather self-evident. The exact content of the phrases "representative" and "relevant" recordings should be agreed with the administration.

9 FINAL REMARKS

This model test procedure has been is use in many European model basins during the last year or so. The number of vessels tested, vessel characteristics or the outcome of the tests are not publicly known. The general opinion seems to be that the proof of survivability with model tests leads to less strict requirements to modifications of existing ships than the hydrostatic calculations according to the new requirements. In this respect the model tests provide a tempting alternative. The usual drawbacks of physical model testing are the time and money required, even though the model test expenses are but a fraction compared to the required investment if a ship is to be fitted, for example, with a pair of transverse barriers on the ro-ro deck.

As is the case in hydrodynamics in general, also in the case of the survivability tests numerical methods are eagerly developed to compete with, or at least supplement, the experimental approaches. The numerical simulation programmes, of which the one developed by Strathclyde University is perhaps the best known, do not have any official status. However, it can not be argued that feasible numerical methods could provide valuable preliminary knowledge when planning modifications. Numerical simulation programmes are also far more practical than physical model testing as a pure research tool.

ON THE STABILITY OF SHIPS IN WAVES

Jerzy Matusiak
Helsinki University of Technology, Ship Laboratory
Espoo, Finland

Abstract

In this paper the basic mechanisms of the loss of stability of ships in waves are reviewed. The loss of stability in following seas and the parametric roll are qualitatively described. The dynamics of a cargo shift aboard a ship in waves is presented in detail. An example of a cargo shift and its effect on ship capsizing in beam seas is presented. The concept of dynamic heel is applied to the problem of a ro-ro vessel with water on deck.

1 INTRODUCTION

Ship stability accidents occur very seldom in ideal conditions which can be regarded as static. Usually wave loads, wind forces or other environmental loading in conjunction with some sort of an accident are responsible for the loss of a ship. The problem of a loss of stability in waves is very complex. Usually ship motions prior to capsizing are large. As a result of these large amplitude motions, static capability of the ship to withstand external loading is radically reduced. This makes linear models of ship dynamics unsuitable for dealing with the stability problems. There are two ways to tackle the problem. The first approach is to simplify the model of ship dynamics by retaining only the most pertinent terms. Often this leads to a simplified model that can be easily solved. A solution obtained in this way yields at least a qualitative answer to the problem. The second approach, which is getting more popular and more feasible, is direct simulation of the large amplitude ship motions and external loading in time domain.

In this paper the important problem of cargo shifting due to ship motions in beam seas is analysed in detail. In particular, the dynamic model of cargo movement is presented. The effect of cargo shift on ship capsizing is illustrated by an example.

A qualitative description of two mechanisms for the loss of stability of an intact vessel in waves is presented, too.

A simplified mathematical model for the dynamic heeling of a ship known as weather criterion is applied to a ro-ro type vessel with water on deck.

2 LOSS OF STABILITY IN THE FOLLOWING SEAS

In following seas, if the wave length is close to ship length, the hull wetted surface area varies. When the wave crest is at the midship the metacentric height reduces dramatically due to a decrease of the waterplane area (see Fig. 1).

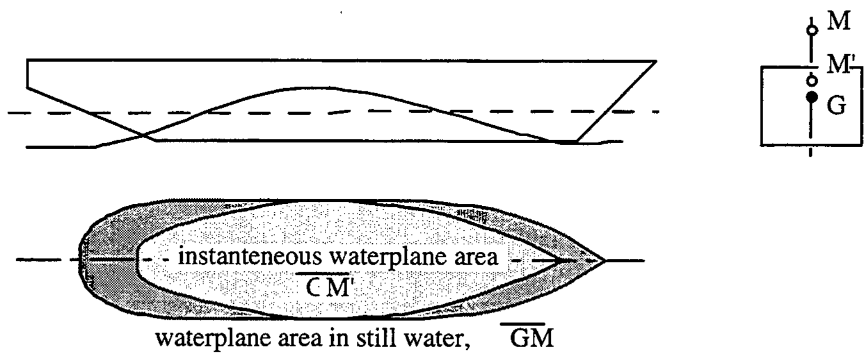

Fig. 1. Reduction of the metacentric height when the wave crest is at the midship (Matusiak, 1995).

As a result, the stability curve changes as shown schematically in Fig. 2.

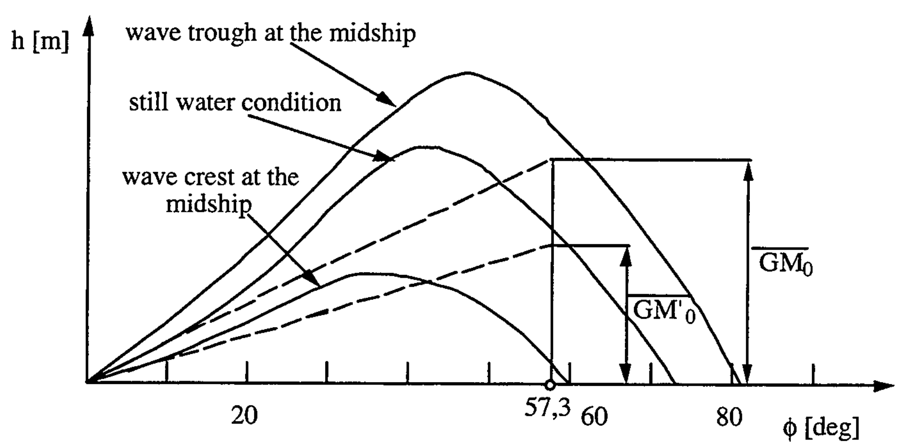

Fig. 2. Variation of the stability curve in following seas.

If the stability stays low for a sufficiently long time, there is a danger that external loading such as gusty winds or a shift of cargo may make the ship to capsize.

Thus there are three conditions to be fullfilled for a dangerous situation to occur. The first is the form of the hull, which must be such (for instance pram type stern) that heaving and pitching motion in following seas is associated with a large variation of the waterplane area. The two other conditions are associated with wave length and ship speed. The stability of a ship may be lost if the wave length

λ is about the same as the ship length L, and if the wave velocity (so called phase velocity) is close to the ship speed V. In other words, in following seas the encounter frequency tends to zero. The condition of zero frequency of encounter means that

$$\sqrt{\frac{2\pi g}{\lambda}}\frac{V}{g} \approx 1, \tag{1}$$

where g is gravitational acceleration. By substituting the wave length λ by a ship length L in Eq. 1, the critical Froude number is obtained

$$Fn \approx 0.4. \tag{2}$$

In other words, if the length of a following wave is close to ship waterline length and if the ship speed is $Fn \approx 0.4$, there is a danger of large heeling and possibly capsizing.

3 PARAMETRIC ROLLING

In head, following and quartering seas there is another danger of excessive roll motion which is associated with large waterplane area variations. This harmonic motion is called *parametric resonance of roll.* This resonance may occur when the period of waterplane area variations due to ship heaving and pitching motions is approximately half of the natural period of roll T_ϕ. As a result, the ship starts to roll heavily with a period twice the period of heaving and pitching motion. An example of such a situation is presented in the following.

Let us consider a ro-ro passenger vessel 170 m long and 25.4 m wide. The vessels metacentric height is $GM_0 = 2$ m. The natural period of heave is $T_z = 9$ s. We consider head wave of the length $\lambda = 170$ m. The natural period of roll can be estimated from the metacentric height and vessel's breadth to be $T_\phi = 18$ s (Matusiak, 1995). The frequency of encounter ω_e depends on the wave frequency ω, ship speed V and heading angle β as

$$\omega_e = \omega\left(1 - \frac{\omega V}{g}\cos\beta\right), \tag{3}$$

where $\beta = 180^\circ$ for head waves. In deep water the wave frequency is related to the wave length by the expression

$$\omega = \sqrt{\frac{2\pi g}{\lambda}}. \tag{4}$$

Let us consider two vessel speed values, 5 and 20 knots. The result of a qualitative analysis of parametric resonance of roll for both the velocities is shown in the table below.

V = 5 knots	V = 20 knots
$\omega_e = 0.697$ $T_e = 2\pi/\omega_e = 9$ s Small roll damping Heave at resonance Ship rolls heavily	$\omega_e = 0.982$ $T_e = 2\pi/\omega_e = 6.4$ s Higher roll damping Heave motion is decreased Ship does not roll

A qualitative explanation of the parametric resonance of roll can be obtained by applying a simple model to the restoring moment of the roll equation of motion that is separated from the other motion components. This model, which can be given as

$$M_{st} = -\Delta\,\overline{GM}_0\,(1+\delta\cos\omega_e t)\,\phi\,, \tag{5}$$

aims at representing the change of the metacentric height in waves as shown in Fig. 2. The parameter δ in Eq. 5 describes qualitatively the variations of waterplane area associated with heaving and pitching motions in waves. This parameter depends on the shape of a hull. If a ship has a pronounced bow flare and a pram type stern, δ is large. In addition, this parameter is a function of the wave length and amplitude. The equation of roll motion can be presented as

$$I'_{xx}\,\ddot{\phi} + \Delta\,\overline{GM}_0\,(1+\delta\cos\omega_e t)\,\phi + M_{x,dam} = 0, \tag{6}$$

where I'_{xx} is the moment of the ship's inertia about a longitudinal (x) axis that passes through the centre of gravity, Δ is the buoyancy force and $M_{x,dam}$ is the damping moment. Eq. 6 can be presented in a non-dimensional form as

$$\ddot{\phi} + 2\,\xi\,\omega_\phi\,\dot{\phi} + \omega_\phi^2\,(1+\delta\cos\omega_e t)\,\phi = 0\,, \tag{7}$$

where $\omega_\phi = 2\,\pi/T_\phi$ is the natural frequency of the roll motion. This kind of a non-linear second order ordinary differential equation is known as the Mathieu equation. It's solution is known to exhibit instabilities if the ratio of frequencies is

$$\omega_e/\omega_\phi = 2,\ 1,\ 2/3. \tag{8}$$

The first of the frequency ratios in Eq. 8 is called the main parametric resonance. The occurrence of the main parametric resonance was confirmed by model tests in head waves (Students' lab exercise, 1996) and astern waves (Hamamoto, 1996). Model tests and instabilities associated with the Mathieu equation indicate that parametric resonance may occur at encounter frequencies that deviate slightly from the critical values given by the Eq. 8. The susceptibility of resonance depends on the amount of roll damping.

4 CARGO SHIFT IN WAVES

According to the statistics, 11% of serious stability accidents of ships were caused by the shift of cargo and/or by waves and wind. These kind of accidents are quite common for bulkcarriers and ro-ro vessels (Aldwinckle, 1990).

Hua (1995) has presented a concept of an *equivalent roll angle* and probabilistic approach to the problem of cargo shifting. He discussed the effect of linearisation of the model on the predicted results.

In the following, a non-linear mathematical model which makes it possible to evaluate a risk of cargo shifting is presented. In addition, when combined with the method of evaluating in time domain the large amplitude motion of ship, the model makes it possible to simulate capsizing of a vessel. For the sake of simplicity, only the condition of beam seas is considered. Only three components of ship motions are considered: heave z, sway y and roll ϕ. This condition and the motion components are, however, very relevant for the risk of capsizing because it is usually associated with the largest roll motion.

4.1 MATHEMATICAL MODEL OF CARGO SHIFT IN A MOVING FRAME

Fig. 3 shows a transverse section of a vessel. Kinematics of this section represents the motion components of the considered beam seas condition.

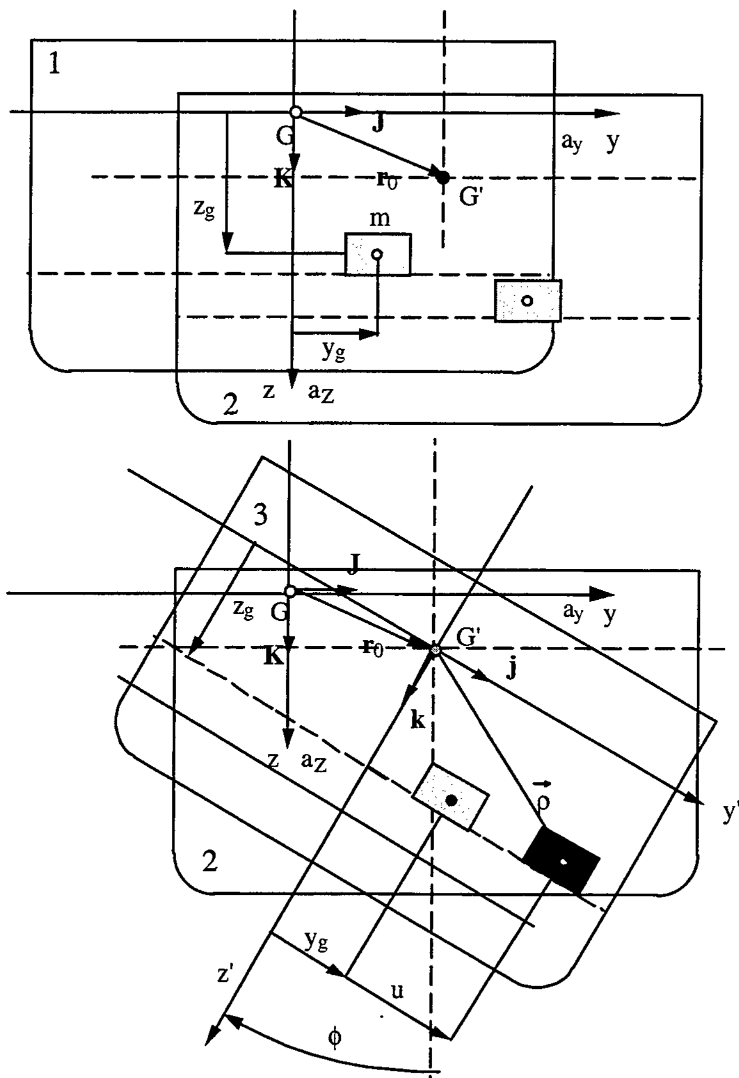

Fig. 3. Definition of the components of motions of cargo piece.

4.1.1 Motion kinematics

In the inertial coordinate system y-z, ship's origo G (centre of gravity) moves to a new location G' given by a vector $\mathbf{r_0}$ = y **J** + z **K**, where **J** and **K** are unit vectors associated with the inertial frame. After that the ship heels by ϕ along the longitudinal axis x' that passes through the centre of gravity G'. We define a second coordinate system y'-z' fixed to the moving ship. Unit vectors of this coordinate system are **j** and **k**. In the beginning, a piece of cargo is located at the location (y_g, z_g) in the coordinate system y'-z' of ship. Due to ship motions, this piece of cargo with a mass m moves along the deck by an amount of u to a location given by a vector $\vec{\rho} = (y_g + u)\,\mathbf{j} + z_g\,\mathbf{k}$. The location of cargo in the inertial coordinate system is

$$\mathbf{r} = \mathbf{r}_0 + \rho = y\,\mathbf{J} + z\,\mathbf{K} + (y_g + u)\,\mathbf{j} + z_g\,\mathbf{k}\,. \tag{9}$$

The relation between the two coordinate systems is

$$\mathbf{j} = \mathbf{J}\cos\phi + \mathbf{K}\sin\phi,\;\; \mathbf{k} = -\mathbf{J}\sin\phi + \mathbf{K}\cos\phi \tag{10}$$

$$\mathbf{J} = \mathbf{j}\cos\phi - \mathbf{k}\sin\phi,\;\; \mathbf{K} = \mathbf{j}\sin\phi + \mathbf{k}\cos\phi\,. \tag{11}$$

Applying Eqs. 10 and 11 we get a position of the cargo in the inertial frame as

$$\begin{aligned} \mathbf{r} = &\left[y + (y_g + u)\cos\phi - z_g \sin\phi\right]\mathbf{J} \\ &+ \left[z + (y_g + u)\sin\phi + z_g\cos\phi\right]\mathbf{K}\,. \end{aligned} \tag{12}$$

4.1.2 The equation of motion of a concentrated piece of cargo

Our aim is to derive an expression that describes the motion of cargo and it's dependence upon ship motions. In order to do it we apply the Lagrange's equation

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{u}} - \frac{\partial L}{\partial u} = F_\mu \tag{13}$$

where the Lagrange function L is the difference between the kinetic and potential energies L = T - V. F_μ is a generalised force that describes other external forces that act along the y'-axis. This force can be, for instance, the cargo lashing force or friction force.

The potential energy of the mass m depends on the instantaneous position of the cargo in the inertial frame as follows

$$\begin{aligned} V &= - m\, g\left[z + (y_g + u)\sin\phi + z_g \cos\phi - z_g\right] \\ &= m\, g\left[z_g\left(1 - \cos\phi\right) - z - (y_g + u)\sin\phi\right]. \end{aligned} \tag{14}$$

The kinetic energy depends on the velocity $\dot{\mathbf{r}}$ of the cargo in the inertial frame as follows:

$$T = \frac{1}{2} m\, \dot{\mathbf{r}}^2 . \tag{15}$$

Derivating Eq.12 for **r** we obtain

$$\begin{aligned} \dot{\mathbf{r}} &= \left\{\dot{y} + \dot{u}\cos\phi - \dot{\phi}\left[z_g\cos\phi + (y_g + u)\sin\phi\right]\right\}\mathbf{J} \\ &+ \left\{\dot{z} + \dot{u}\sin\phi - \dot{\phi}\left[z_g\sin\phi - (y_g + u)\cos\phi\right]\right\}\mathbf{K}. \end{aligned} \tag{16}$$

Velocity of the cargo in the coordinates fixed with the moving ship is

$$\begin{aligned} \dot{\mathbf{r}} &= \left\{\dot{y}\cos\phi + \dot{z}\sin\phi + \dot{u} - \dot{\phi}\, z_g\right\}\mathbf{j} \\ &+ \left\{\dot{z}\cos\phi - \dot{y}\sin\phi + \dot{\phi}\,(y_g + u)\right\}\mathbf{k} . \end{aligned} \tag{17}$$

Applying the Lagrange's equation, Eq. 13, we obtain the equation for the cargo motion u along ship's deck:

$$m\left[\ddot{u} + \ddot{y}\cos\phi + \ddot{z}\sin\phi - \ddot{\phi}\, z_g - \dot{\phi}^2\,(y_g + u) - g\sin\phi\right] = F_\mu . \tag{18}$$

This equation can be expressed also in a simple form as

$$\ddot{u} = - a_H + F_\mu/m , \tag{19}$$

where

$$a_H = \ddot{y}\cos\phi - (g + \ddot{z})\sin\phi - \ddot{\phi}\, z_g - \dot{\phi}^2\,(y_g + u) \tag{20}$$

is the 'total horizontal acceleration' oriented along deck. It includes the dynamic components and a component of the gravitational acceleration. F_μ/m is the constraining force related to the cargo mass. Actually acceleration a_H is the acceleration that is sensed by a so called g-sensitive accelerometer. The condition necessary for securing no cargo shift can be expressed as follows:

$$|a_H| < |F_\mu/m| . \tag{21}$$

4.1.3 The dynamic forces acting on a concentrated piece of cargo

The diagram of the forces acting on the cargo piece is presented in Fig. 4.

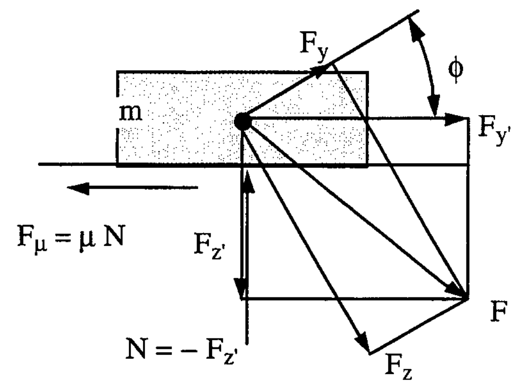

Fig. 4. The diagram of the forces acting on the cargo piece.

F_y and F_z are the components of the total force **F** in the global inertial coordinate system. These components can be derived from the Lagrange's equation as follows:

$$F_y = \frac{d}{dt}\frac{\partial L}{\partial \dot{y}} - \frac{\partial L}{\partial y} = m\{\ddot{y} + \ddot{u}\cos\phi - \ddot{\phi}[z_g \cos\phi + (y_g + u)\sin\phi] + \dot{\phi}^2[z_g \sin\phi - (y_g + u)\cos\phi] - \dot{u}\dot{\phi}\sin\phi\} \tag{22}$$

$$F_z = \frac{d}{dt}\frac{\partial L}{\partial \dot{z}} - \frac{\partial L}{\partial z} = m\{\ddot{z} + \ddot{u}\sin\phi - \ddot{\phi}[z_g \sin\phi - (y_g + u)\cos\phi] - \dot{\phi}^2[z_g \cos\phi + (y_g + u)\sin\phi] + \dot{u}\dot{\phi}\cos\phi - g\}. \tag{23}$$

As can be seen from Eqs. 22 and 23, force **F** has inertia, Coriolis and gravitational force components. The total force **F** is given by the components in the moving frame as

$$F_{y'} = m\left[\ddot{u} + \ddot{y}\cos\phi + \ddot{z}\sin\phi - \ddot{\phi}\, z_g - \dot{\phi}^2 (y_g + u) - g\sin\phi\right] \tag{24}$$

$$F_{z'} = m\left[\ddot{z}\cos\phi - \ddot{y}\sin\phi + \ddot{\phi}(y_g + u) - \dot{\phi}^2 z_g + \dot{\phi}\,\dot{u} - g\cos\phi\right]. \tag{25}$$

The Eqs. 24 and 25 can be used for determining the required strength of the cargo lashing system. In this case, cargo shift is set to zero ie. $u = du/dt = d^2u/dt^2 = 0$ in Eqs. 24 and 25 and the forces acting on the cargo are governed by the ship motions only. We note that the $F_{y'}$ force component (Eq. 24) is the same as the left side of the equation of motion (Eq. 18).

4.1.4 The equation of motion of a concentrated piece of cargo that is resting freely on a deck

In the following we consider the force F_μ restraining cargo motion. This force is assumed to be caused by the friction only and is related to the normal in respect to deck force N by a linear expression

$$F_\mu = \mu N = -\mu F_{z'}, \qquad (26)$$

where μ is the friction coefficient which is assumed to be constant.

For cargo that is freely resting on a deck, the frictional force is given by

$$F_\mu = -\mu F_{z'} = -\mu m\left[\ddot{z}\cos\phi - \ddot{y}\sin\phi + \ddot{\phi}(y_g + u) - \dot{\phi}^2 z_g + \dot{\phi}\dot{u} - g\cos\phi\right]. \qquad (27)$$

The Eq. 27 can be expressed in a simple form as

$$F_\mu = -\mu m a_v, \qquad (28)$$

where

$$a_v = (\ddot{z} - g)\cos\phi - \ddot{y}\sin\phi + \ddot{\phi}(y_g + u) - \dot{\phi}^2 z_g + \dot{\phi}\dot{u} \qquad (29)$$

is the total acceleration oriented normally towards the ship's deck and pointing downwards. This acceleration comprises the dynamic acceleration components of the ship and cargo movements and also a component of the gravitational force. This total acceleration is the same as that which would be measured by a g-sensitive accelerometer located on the moving cargo. Both the horizontal (Eq. 20) and vertical (Eq. 29) accelerations include non-linear terms. Disregarding these terms and assuming linearity and using a superposition technique may lead to an underestimation of the risk of cargo shift.

Substituting Eq. 28 into Eq. 19 yields the ultimate form of the equation of motion of a concentrated piece of cargo that is resting freely on a deck

$$\boxed{\ddot{u} + a_H + \mu a_v = 0,} \qquad (30)$$

where the accelerations a_H and a_V are given by the Eqs. 20 and 29.

4.2 AN EXAMPLE OF CAPSIZING OF A SHIP DUE TO CARGO SHIFT

The method of cargo shift dynamics presented above, combined with a time simulation of ship motions in irregular beam waves, is applied for a large containership. In this example the top layer of containers located on the weather deck is assumed not to be securely restrained from motion. The only force that prevents cargo from motion is the frictional force. The friction coefficient is assumed to be $\mu = 0.27 = \tan^{-1}(15^o)$. Moreover, an assumption is made that each of the containers moves by the same displacement u. If a container reaches the edge of the weather deck, the container falls outboards and it's mass is subtracted from the total mass m of the layer. Thus a mass contributing to the heeling moment of a ship is modified according to the cargo motion u. Centre of gravity of this mass is initially located at the symmetry plane of the ship, i.e. $y_g = 0$. The heeling moment due to the cargo shifting is

$$M_H = -m\, a_v \cdot u\,. \qquad (31)$$

Computer simulations are conducted by simulating in time domain hundreds of runs. Each of them is 10 minutes long in ship scale. Each of the runs is represented by a non-repeatable train of irregular waves. The ITTC wave spectrum is used with the significant wave height H_S = 7.5 m and zero-crossing period of 12.5 s.

An example of the simulated capsizing is shown in Figs. 5 and 6.

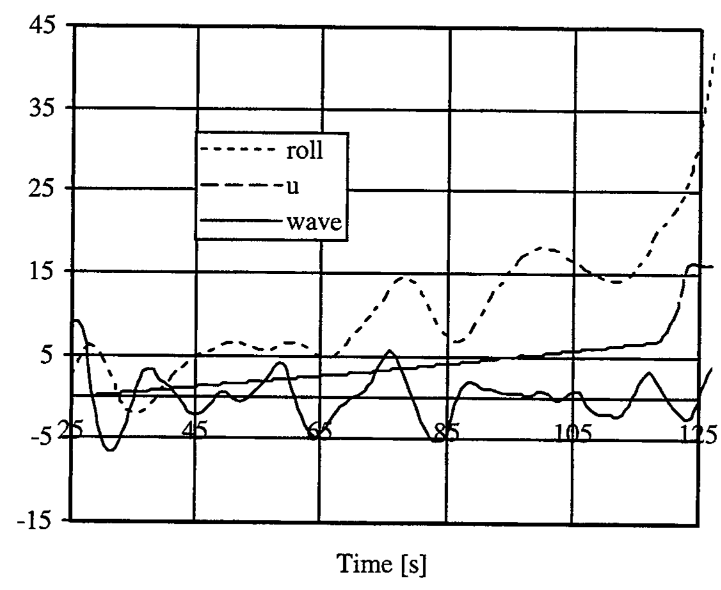

Fig. 5. Irregular beam waves, ship roll motion and cargo shift leading to capsizing.

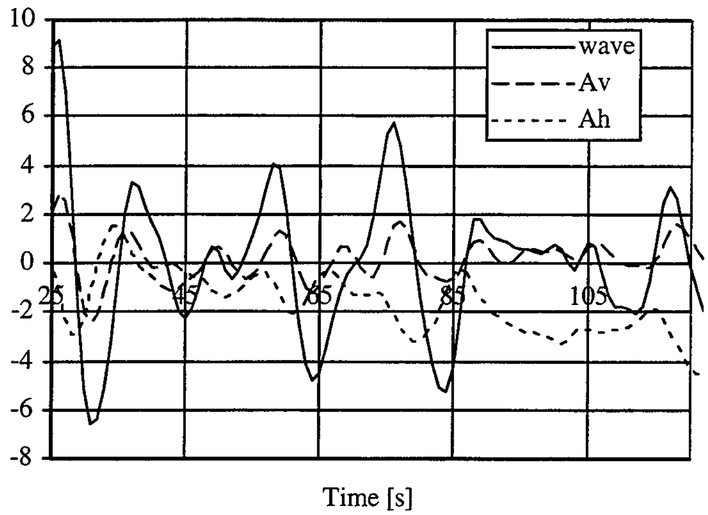

Fig. 6. Irregular beam waves and accelerations prior to ship capsizing.

An important effect of the accelerations on the shift of cargo and capsizing of a ship is seen from the Figs. 5 and 6. Prior to the beginning of cargo movement, the ship experiences a roll angle of only 7^{o}. It is mainly due to the accelerations and their unfavorable phasing that causes cargo movement. Movement of the cargo causes progressive heeling that ultimately results in capsizing of the vessel.

5 A SIMPLE MODEL OF DYNAMIC HEEL OF A SHIP WITH WATER ON DECK

5.1 DISCUSSION OF THE MATHEMATICAL MODEL BEHIND THE WEATHER CRITERION

The so called weather criterion (Code on Intact Stability, 1993) is an example of a simplified mathematical model of ship dynamics that retains very important non-linearity of the restoring moment and some dynamic effects. The model makes use of the concept of the dynamic lever introduced by Rahola (1939). Mathematical modelling of this concept is presented in detail, for example, by Semyonov-tyan-Shansky and Matusiak (1995). In the weather criterion the areas bounded by a static stability curve and a wind heeling moment lever are investigated. The general idea is that the work done by external loading (heeling moment) can not be higher than the work done by the heeling ship exposed to this load. The allowance for ship rolling is included.

There are some assumptions that make the weather criterion somewhat questionable for large vessels. In the criterion, wind velocity distribution in the vertical direction is assumed to be uniform. Wind gust is assumed to act simultaneously on the entire length of a ship. Thus boundary layer structure of wind is disregarded and wind turbulence (gust) is assumed to be of a large scale. Moreover, the assumed roll amplitude may be unrealistically large. Thus applying this criterion for a large passenger vessel may lead to an overestimation of the risk of capsizing. However, despite it's simplicity, the mathematical model behind the criterion is sound. For this reason and because of the lack of better environmental data, the concept of dynamic heeling and environmental loading as given by the weather criterion, is used in the following when investigating capsizing of a damaged vessel.

5.2 WATER ON DECK

Water on a deck may cause a serious danger for a ship. Water flooding to the weather deck may be caused by a combined action of extensive ship motion, wind or some sort of damage. Water on a car deck is a more dangerous situation. If damage leading to flooding an open car deck happens, the volume of flooded water tends to increase. As a result, the ship may loose stability very quickly.

The effect of liquid cargo on ship stability is normally modelled by the so called *free surface effect model*. This static model is sufficiently good when dealing with liquids in well-defined tanks. For car deck flooding this model is inadequate. A relatively thin layer of water on deck (the ratio of water layer thickness to deck breadth being of on order of magnitude 1/100) changes rapidly its shape because of ship motions. Thus the *free surface effect model* is not well suited for this situation.

A heeled vessel, with V_V volume of water on the car deck that is B_D wide and L_D long, is presented in Fig. 7 (Matusiak, 1995).

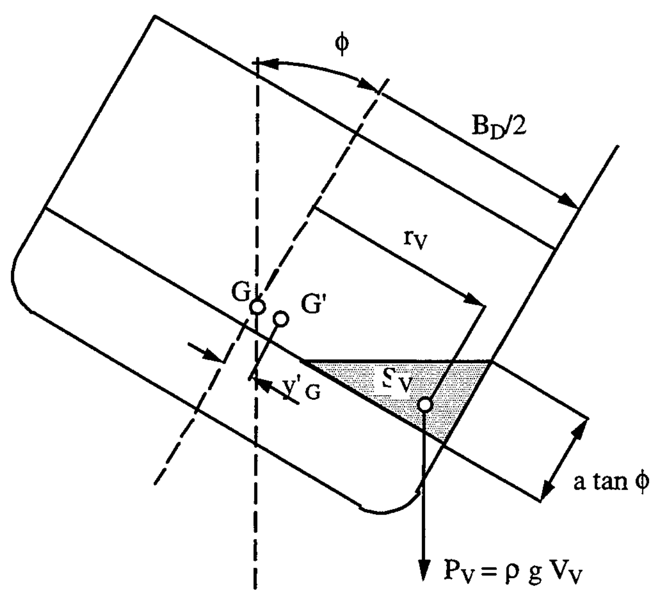

Fig. 7. Water on a car deck.

We assume that the flooded water follows the roll motion of the ship. In other words, the free surface of flooded water is horizontal. Moreover, inertial forces and sloshing of the flooded water are disregarded. These assumptions may be justified by the damping effect of cargo located on deck. By using these assumptions, we can evaluate the centre of gravity of the flooded water. In particular we are interested in lever r_V of the heeling moment M_V. This lever is related to heel, deck breadth and flooded water volume as

$$r_V = \frac{B_D}{2} - \frac{1}{3}\sqrt{2\, S_V/\tan\phi}, \tag{32}$$

where the area of the triangular cross section of the flooded water volume is

$$S_V = V_V/L_D = \frac{a^2}{2}\tan\phi. \tag{33}$$

The flooded water causes the heeling moment

$$M_V = \rho\, g\, V_V \left(\frac{B_D}{2} - \frac{1}{3}\sqrt{2\, S_V/\tan\phi}\right)\cos\phi. \tag{34}$$

Dividing expression (34) by the buoyancy force, we obtain the static lever of this heeling moment:

$$l_V = \frac{V_V}{\nabla}\left(\frac{B_D}{2} - \frac{1}{3}\sqrt{2\, S_V/\tan\phi}\right)\cos\phi. \tag{35}$$

Another way of treating the effect of flooded water is to consider its effect on stability and on the static lever $h(\phi)$ in particular. The ship's centre of gravity shifts from the original position (point G in Fig. 7) by

$$y'_G = \frac{V_V}{\nabla} r_V \tag{36}$$

to point G'.

This in turn affects the stability curve as

$$h'(\phi) = h(\phi) - y'_G \cos\phi = h(\phi) - l_V(\phi), \tag{37}$$

where $h(\phi)$ is the static righting lever with flooded water regarded as rigid cargo on the car deck and $h'(\phi)$ is the stability curve that includes the effect of water motion. Both models, that is heeling moment and change in stability curve model lead to the same result.

5.3 A SIMPLE DYNAMIC STABILITY ANALYSIS OF THE RO-RO TYPE SHIP WITH WATER ON DECK

Dynamic stability analysis will be illustrated by using as an example a ro-ro type vessel with displacement $\nabla = 11000$ m^3. The open car deck is 25 m wide and 120 m long. We investigate what is the volume of flooded water that causes the ship to capsize. Then we investigate the effect of environmental conditions on maximum heel and capsizing. For the sake of simplicity, we assume that the static stability curve does not depend on the extra weight of the flooded water.

5.3.1 Static equilibrium of the ship with flooded car deck

The original static righting lever curve is shown in Fig. 8 as a dashed line. The solid line represents the static lever curve (h' given by formula 37) with an effect of 1450 m^3 of flooded water on the car deck. This is the maximum volume of flooded water that the ship can tolerate without capsizing in ideal static conditions.

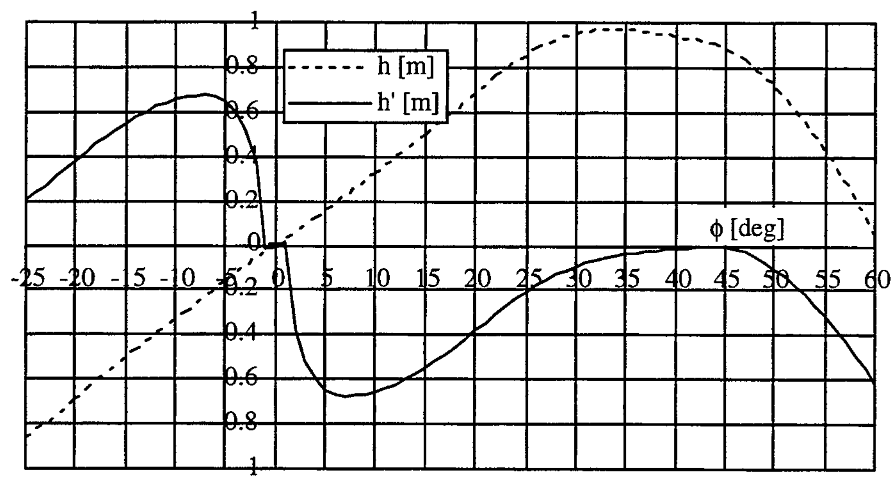

Fig. 8. Static lever of the righting moment (h- original, h' - after water flooding on the car deck). Flooded water volume is 1450 m^3.

Ship heels to an angle of $\phi_S = 44^0$ that is a static equilibrium position.

5.2.2 Dynamic heel due to water on the car deck and gusty wind

The situation illustrated in Fig 8 is somewhat artificial. It corresponds to the static condition that was achieved by slow flooding of the car deck in a calm sea. Next we consider the combined effect of flooded car deck, and gusty wind on the maximum heel developed by the vessel.

By assuming that volume of the flooded water is 1220 m^3, which is 84% of the maximum static balance value, the static equilibrium is reached at the heel angle $\phi_S = 27^0$ (Fig. 9).

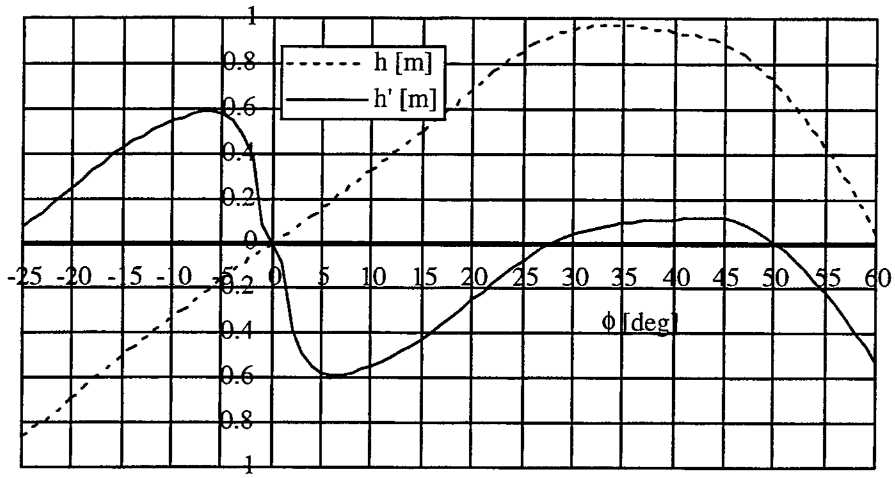

Fig. 9. Static lever of the righting moment (h- original, h' - after water flooding on the car deck). Flooded water volume is 1220 m^3.

Next we assume that the ship with water on the car deck is subjected to a gusty wind. The heeling moment due to steady wind is $M^S{}_W = 24$ MNm. This value is representative for a car and passenger ferry subjected to side wind of a speed $V_W = 26$ m/s. Due to a steady wind action ship heels by 3.5^0. Thus the heel becomes $\phi_S = 30.5^0$. At some instant the ship is hit by a gust. The heeling moment due to the gust is half of the steady wind moment, ie $M^S{}_W = 12$ MNm. We apply the dynamic heeling model. In other words we calculate the heel angle at which the work done by an external moment (moment of a gusty wind) equals the work done be a heeled ship. In order to include the effect of the flooded car deck we take the dynamic lever values that include the effect of flooding. That is, we calculate the dynamic lever function for the damaged condition

$$e'(\phi) = \int_0^{\phi} h'(\phi)\, d\phi = \int_0^{\phi} h(\phi)\, d\phi - \int_0^{\phi} l_V(\phi)\, d\phi, \qquad (38)$$

where $l_V(\phi)$ is given by Eq. 35. The dynamic lever curve for the damaged condition and the solution of the dynamic heel is shown in Fig. 10. The work done by the gusty wind when heeling the vessel (dashed line on the Fig. 10) exceeds the work done by ship righting moment (solid line). This means that the ship is unable to withstand the gusty wind loading and capsizes. This happens for 16% less water on deck than capsizing in still water requires. If the ship was rolling the volume of water required to capsize the vessel would be much lower (Matusiak, 1995).

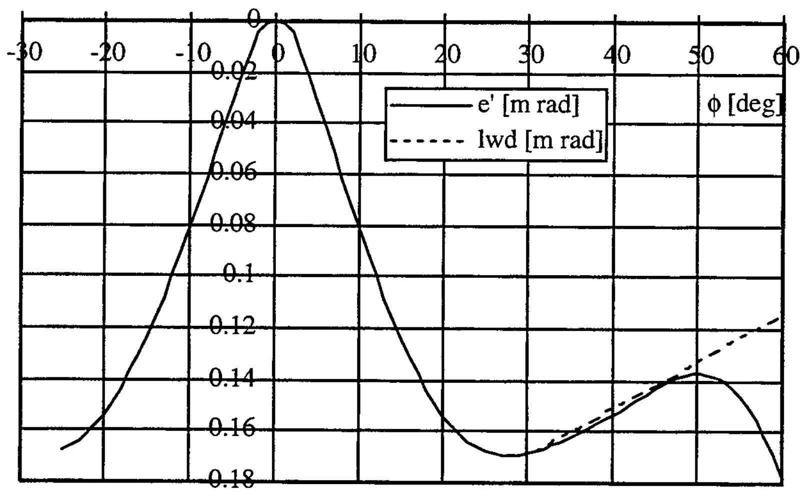

Fig. 10. Ship with flooded car deck capsizes by the action of gusty wind. The volume of flooded water $V_v = 1220\ m^3$.

The simple analysis of the dynamic heel of a ship with flooded deck presented above, indicates that stability of the vessel is strongly dependent on the volume of flooded water and on the environmental conditions. Although a flooded ship does not roll much, static analysis will underestimate the risk of capsizing in a windy environment. The concept of a dynamic lever is very useful when evaluating dynamic heel of the ship with water on deck. The method presented can be easily applied to evaluate stability of a damaged vessel. The method can also be used to evaluate the optimum division of the car decks.

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Matti Hellevaara (ed.)

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Abstract

The symposium proceedings include ten technical papers on maritime safety from both technical and human factors point of view. The first paper gives a state of art-presentation to previous and current activities of Maritime Institute of Finland on this topic. The second and third paper presents the status and targets of the comprehensive, still on-going maritime safety project carried out for the Finnish Board of Navigation. Other papers describe selected special topics of maritime safety.

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The technical aspects, e.g. stability, structural strength and the modern aids of navigation are essential to safe shipping but the understanding and controlling of human factors is the basement for safe maritime operations. The modern simulation techniques are a very effective tool to study the human factors in complex teamwork and communication situations both during the normal and emergency operations.

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