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EVALUATION OF ILS LOCALIZER SIGNAL SPECIFICATION DURING GROUND ROLLOUT

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16. Abstract The International Civil Aviation Organization (ICAO) has developed a specification for localizer information on the runway surface appropriate for rollout guidance during Category III B operations. The suitability of this specification was evaluated by systems analysis and simulation and is reported herein. The results of the performance evaluation for a representative rollout guidance system indicate that the specification is too stringent especially for higher frequency type localizer disturbances and therefore should consider the spectral characteristics of the localizer disturbance. A more relaxed specification was therefore developed by taking additional advantage of the sensitivity effect of the localizer receiver and the attenuating effect of the rollout guidance system on localizer disturbances. The revised specification is recommended for future localizer signal specification since it could allow Category III B certification, without degradation of overall rollout system performance or safety, that the current specification might otherwise preclude. Practical means for applying the revised localizer signal specification are discussed but other more simpler and practical means should be examined.

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PREFACE

The work described in this report was performed through the Landing Systems Programs Branch at the Transportation Systems Center (TSC) with computer simulation contract support from Kentron Hawaii Ltd. The work was part of an overall program sponsored by the Department of Transportation through the Federal Aviation Administration to support the research and development plan for implementing Category III landing capability in the United States.

Basic objectives of this program include the development of techniques for improved approach and landing performance on ILS through inertial augmentation, improved airborne flight control system design, and better definition of ILS beam characteristics. The specific task reported herein was concerned with the evaluation of a proposed specification for localizer information on the runway surface appropriate for rollout guidance during Category III B.

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LIST OF SYMBOLS

b	Wing span	feet
C_{n_β}	Non-dimensional yawing moment stability derivative-sideslip contribution	per radian
C_{n_r}	Non-dimensional yawing moment stability derivative-yaw rate contribution	per radian
$C_{n_{\delta r}}$	Non-dimensional yawing moment stability derivative-rudder contribution	per radian
C_{y_β}	Non-dimensional sideforce stability derivative-sideslip contribution	per radian
C_{y_r}	Non-dimensional sideforce stability derivative-yaw rate contribution	per radian
$C_{y_{\delta r}}$	Non-dimensional sideforce stability derivative-rudder contribution	per radian
d	Distance between center of gravity and equivalent landing gear (positive as shown in Figure B-1)	feet
d_r	Distance between equivalent landing gear and localizer receiver antenna (positive as shown in Figure B-1)	feet
D	Distance between localizer transmitter and stop end of runway	feet
f	Lateral force applied by the ground upon the wheels (positive as shown in Figure B-1)	pounds
i	Subscript representing initial condition	-
I_z	Moment of inertia about Z axis	slug-feet^2
K	Aircraft gain parameter	per sec^2
K_N	Localizer signal gain	radian/radian
K_R	Yaw rate gain	second
K_Ψ	Heading gain	radian/radian

LIST OF SYMBOLS (CONT.)

L	Distance between localizer transmitter and runway threshold	feet
m	Aircraft mass	slugs
N	Localizer disturbance signal	microamperes
N_c	Localizer command signal	microamperes
N_R	Localizer receiver output signal	microamperes
N_r	Yawing moment coefficient-yaw rate rate contribution	per second
N_β	Yawing moment coefficient - side-slip contribution	per second^2
$N_{\delta r}$	Yawing moment coefficient-rudder contribution	per second^2
q	Aerodynamic pressure	lb/ft^2
R	Distance between localizer antenna and transmitter	feet
R_F	Relaxation factor	-
R_L	Runway length	feet
s	Laplace transform variable	per second
S	Wing area	feet^2
v	Lateral velocity of the center of gravity of the aircraft	feet/second
V	Forward velocity of the center of gravity of the aircraft	feet/second
w	Aircraft break frequency parameter	radian/second
Y_{MG}	Lateral excursion of the equivalent main gear station on the fuselage centerline with respect to the runway centerline	feet
Y_R	Lateral excursion of the localizer receiver antenna with respect to the runway centerline	feet

Y_r	Sideforce coefficient-yaw rate contribution	-
Y_β	Sideforce coefficient-sideslip contribution	per second
$Y_{\delta r}$	Sideforce coefficient-rudder contribution	per second
$(\dot{\ })$	Differentiation with respect to time	per second
ψ	Aircraft heading angle with respect to runway centerline	radian
σ_N	Root mean square of localizer disturbance signal	microamperes
σ_y	Root mean square value of main gear lateral excursion	feet
ζ_N	Noise filter damping ratio	-
ω_N	Noise filter natural frequency	radians/second
δ_r	Rudder angle	radians
ρ	Atmospheric density	slug/feet^3

1.0 INTRODUCTION

The International Civil Aviation Organization (ICAO) has developed a specification (by committee action) for localizer information on the runway surface appropriate for rollout guidance during Category III B operations. The specification is essentially an extension of previous ICAO specifications for Category III A conditions which apply along the landing approach down to the runway threshold. The current specification is defined in terms of the maximum allowance bend amplitude on a 95% probability basis over the entire length of the runway. In addition, the specification permits larger signal deviations near the stop end of the runway as a result of the increasing receiver sensitivity as the aircraft approaches the localizer transmitter. However, the specification does not consider the spectral characteristics of the localizer disturbance signal.

The suitability of the current ICAO specification was evaluated by systems analysis and simulation and is reported herein. The results of the performance evaluation for a representative rollout guidance system indicate that the specification is too stringent especially for higher frequency type localizer distrubances and therefore should consider the spectral characteristics of the localizer disturbance. A more relaxed specification is therefore developed by taking additional advantage of the sensitivity effect of the localizer receiver and the attenuating effect of the rollout guidance system on localizer disturbances. Three different spectral classifications of disturbances are studied:

1. Sine wave
2. White noise passed through a first order filter
3. White noise passed through a second order filter with low frequency washout.

The revised specification is recommended for future localizer signal specification since it could allow Category III B ceritfication, without degradation of overall rollout system performance or safety that the current specification might otherwise preclude. Practical means for applying the revised localizer signal specification are discussed, but other more simpler and practical means should be examined.

3.0 GENERAL DISCUSSION

The evaluation and recommendation of this report are based on a systems analysis using a constant parameter model, and a systems simulation using a more realistic time varying parameter model. Most of the analysis was performed on the MIT 360/75 computer using the Matrix Differential Equation Linear Transform Analysis (MDELTA) program while the simulation was performed on the XDS 6600 computer.

The study assumed that ground rollout was completed when an acceptable velocity (i.e. 88 ft/sec) for a high speed taxiway entrance maneuver was achieved. Thus an aerodynamic aircraft model was appropriate and sufficient for the high speed ground roll condition. The study also assumed a smooth, no slip, no bounce, nose wheel down and free (i.e. disengaged) condition. The aircraft and rollout guidance systems are representative of a large jumbo jet which is likely to be equipped for Category III B landings. The equations of motion of the aircraft were obtained from the normal lateral equations of motion with a friction force constraint between the ground and main gear wheels. Longitudinal cross coupling effects were omitted. In addition, the study did not include the effects of landing gear dynamics, tire distortion, antenna location, runway anomalies, wind disturbances and sensor errors.

The localizer signal specification described in this report applies to the signals as they are actually "seen" by the localizer receiver. The characteristics of any localizer signals measured on the ground must therefore take into account the deceleration profile of the aircraft before applying the specification. This is discussed further in Appendix H.

2.0 SUMMARY

A systems analysis and simulation has been conducted to determine the suitability of the current ICAO specification for localizer information on the runway surface appropriate for rollout guidance during Category III B operations.

A rollout guidance system was first derived for a representative jumbo jet aircraft assuming a fixed point landing condition. The rollout guidance system was then changed to a more realistic time varying parameter system and the current specification was evaluated for different localizer beam disturbances. Rollout system performance criteria were defined for the evaluation. The results of the evaluation indicate that the current specification is too stringent especially for higher frequency type localizer disturbances. A revised specification for different classifications of localizer disturbances was then developed by taking additional advantage of the sensitivity effect of the receiver and the attenuating effect of the rollout guidance system on the disturbances. The revised specification was derived using a constant parameter analysis model and verified qualitatively using a more realistic time varying parameter simulation model. Practical means for applying the specification are discussed and recommendations are made for future studies.

4.0 ROLLOUT GUIDANCE SYSTEM MODEL

Based on knowledge of the C5A, L-1011, and Concorde rollout guidance systems, a representative and simple system was developed and is described by the block diagram in Figure 4-1. The aircraft model represents a rigid jumbo jet airframe during high speed ground rollout and is derived in Appendix B. The control system configuration and gains are derived and discussed in Appendix C. The system was synthesized to provide the necessary command signals through the rudder channel for steering the aircraft to and along the runway centerline. The system employs a standard yaw damper channel with washout circuit for stability augmentation. In addition, the system utilizes a heading feedback signal to reduce the initial cross runway velocity to zero quickly and a beam error feedback to return the aircraft to the runway centerline on a long term basis.

For purposes of analysis in this report, the rollout system parameters are assumed constant. The simulation model adds an extra degree of realism and complexity to the analysis model by assuming the aircraft has a constant longitudinal deceleration of 5 ft/sec^2, and allowing the range (R), velocity (V), and aerodynamic pressure (q), to vary accordingly.

The constant parameter analysis model and time varying parameter simulation model are compared in Appendix D for initial condition and localizer step responses.

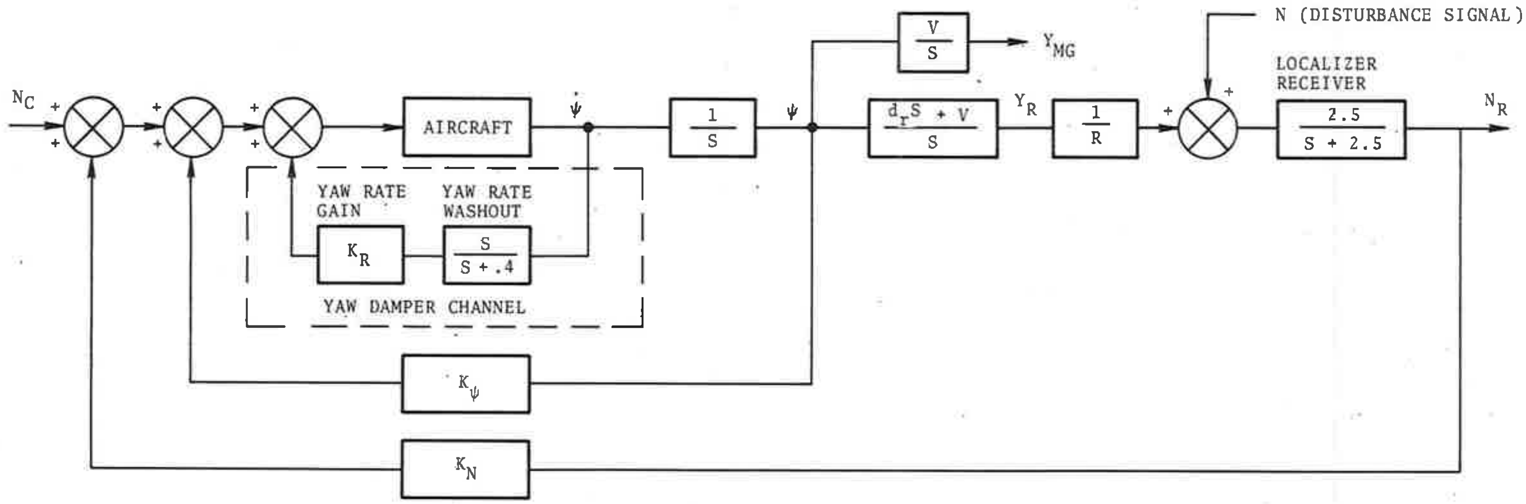


Figure 4-1 Block Diagram of Rollout Guidance System

The rollout guidance system parameters for a representative jumbo jet aircraft are given in Table 4-1.

TABLE 4-1 ROLLOUT GUIDANCE SYSTEM PARAMETERS FOR A REPRESENTATIVE JUMBO JET AIRCRAFT

PARAMETER	VALUE	DIMENSION
K_R	2.	sec
K_ψ	4.	rad/rad
K_N	30†	rad/rad
d'_r	110	ft.
V*	236.5	ft/sec
R*	9100	ft.

*time variable parameters for the simulation model

† nominal value (see appendix C)

5.0 ROLLOUT SYSTEM PERFORMANCE CRITERION

The following self generated performance criterion was used in this study to evaluate the current ICAO specification and to derive new specifications for localizer information on the runway surface appropriate for rollout guidance during Category III B operations: the lateral excursions, Y_{MG} of the equivalent main gear shall remain within 12 ft. of the runway centerline (on a 95% probability basis for random localizer disturbances).

Since there is no standard performance criterion for ground rollout, and since only ground guidance system errors (i.e. localizer disturbances) were included in this report, a lateral excursion limit was chosen that is only about half the limit required for safe tracking on the runway (i.e. outboard landing gear no closer than five feet from the lateral limits of a 150 ft. runway). This 12 ft. limit should allow ample budgeting for other sources of lateral errors including onboard equipment and environmental effects. In addition, the value of 12 ft. represents the lateral excursion limiting error for a localizer signal error of 5 microamperes, which is the current FAA standard specification at the runway threshold for Category III A operations. (This is based on a localizer sensitivity of .43 microamperes/foot at the runway threshold.)

The performance criterion did not include any dynamic requirements because the representative rollout guidance system was assumed to be sufficiently damped to provide acceptable responses.

Finally, performance criteria were implicitly imposed on other aircraft variables including heading, heading rate, rudder deflection and lateral ground force, but these all remained within reasonable limits and were therefore of no consequence to the study.

6.0 EVALUATION OF THE CURRENT SPECIFICATION

This section evaluates the current ICAO specification for various localizer disturbance signals. The current specification is defined in Appendix A. It specifies the maximum allowable bend amplitude, on a 95% probability basis, over the length of the runway. Based on the performance criterion established in the previous section, the following disturbance signals, N were evaluated:

a. Bias and ramp;

b. Sine wave with a frequency of 1 radian/second;

c. White noise passed through a first order filter with a break frequency of 1 radian/second;

d. White noise passed through a second order filter with low frequency washout, with a natural frequency of 1 radian/second and a damping ratio of .7 (a model of this noise filter is shown in Figure G-1).

The amplitudes of the deterministic signals above were assumed to be given directly by the maximum amplitude of the specification whereas the amplitudes of the random signals above were based on a 95% (two sigma) probability basis.

The main gear lateral responses, Y_{MG} for each of the localizer disturbance signals are shown in Figures 6-1 through 6-4.

The response to the bias and ramp signal shown in Figure 6-1, converges to the runway centerline as the aircraft approaches the localizer transmitter. This can be explained by the fact that the current specification does not completely tradeoff the increasing localizer sensitivity effect. Although the converging response is desirable, a more relaxed specification, that permits a steady state response closer to, but still within the performance criterion limit, is developed in the following section by taking more advantage of the localizer sensitivity effect.

The small responses shown in Figures 6-2, 6-3, and 6-4 reflect the attenuating effect of the rollout guidance system. (The frequency response of the rollout guidance system is presented in

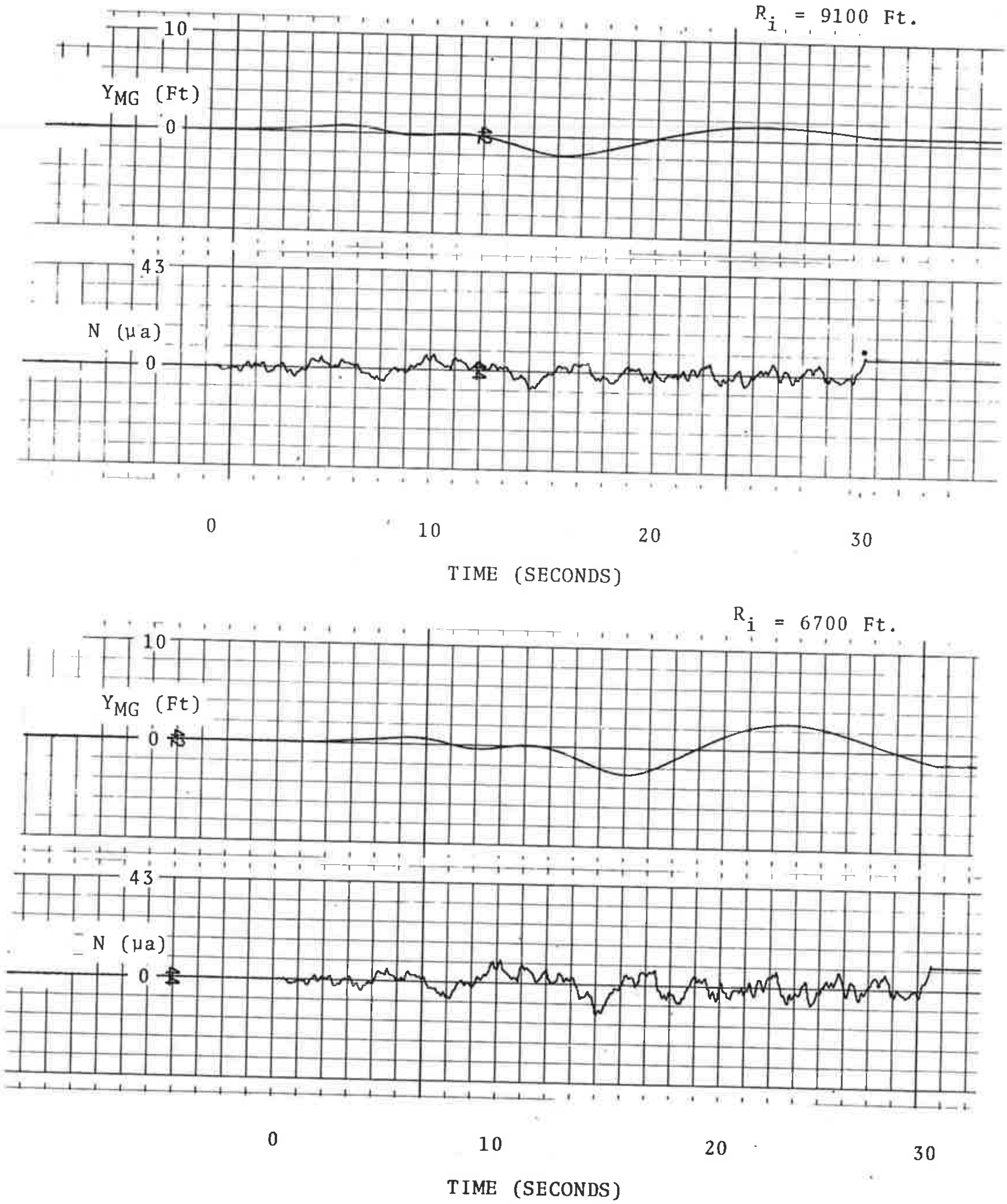


Figure 6-4 Main Gear Lateral Responses to White Noise passed through a Second Order Filter with Low Frequency Washout, 2 σ_N = Current Specification, ω_N = 1 Radian/Second, V_i = 236.5 ft./sec

7.0 DERIVATION OF A RELAXED SPECIFICATION ACCOUNTING FOR THE LOCALIZER RECEIVER SENSITIVITY EFFECT

This section derives a relaxed localizer signal specification by accounting for the localizer receiver sensitivity effect. The specification applies for localizer information on the runway surface appropriate for rollout guidance during Category III B operations and is based on the performance criterion established in Section 5.0. Since the localizer receiver sensitivity increases as the aircraft approaches the localizer transmitter, larger localizer disturbance signals can be tolerated for a constant aircraft lateral position error. Figure 7-1 shows the required localizer disturbance signal, as a function of the distance to the localizer transmitter, for a constant lateral position error of 12 ft. (i.e. the performance criterion limit). This is based on a localizer sensitivity of .43 microamperes/foot at the runway threshold. The localizer disturbance curve is simply a function of the inverse distance to the localizer transmitter. Thus it would seem appropriate to base the localizer signal specification on the distance to the localizer transmitter.

The current specification is independent of this distance, being expressed in terms of the runway length. In order to compare the current specification with the localizer disturbance curve, specific runway configurations must be postualted. Thus Figure 7-1 depicts the current specification for the following runway configurations:

a. A short runway;

b. A long runway;

c. The runway configuration studied in this report.

It can be concluded from Figure 7-1 that the current specification is somewhat conservative, based on the established performance criterion, for any runway configuration especially near the stop end of the runway.

Since the localizer disturbance curve would be cumbersome and tedious to implement as a localizer signal specification, an alternate specification is recommended that is more relaxed than the current specification, simple to represent and a better approximation to the localizer disturbance curve. It is also shown in Figure 7-1 and is based on the distance to the localizer transmitter. The specification is defined in terms of the maximum allowance bend amplitude (on a 95% probability basis for random localizer disturbances). The maximum allowance bend amplitude at the runway threshold is 5 microamperes. It remains constant at 5 microamperes down the runway for one fourth the distance to the localizer transmitter. At this point the maximum allowance bend amplitude increases linearly to 20 microamperes at the localizer transmitter (of course, the specification need be applied only over the runway).

The alternate specification was evaluated for the same localizer disturbances in the previous section but with the amplitudes adjusted accordingly. The main gear lateral responses are shown in Figures 7-2 through 7-5. The responses to the bias and ramp signal, shown in Figure 7-2, approach and remain near the performance criterion limit throughout rollout. This demonstrates that the alternate specification has taken more, but not complete, advantage of the localizer sensitivity effect.

Moreover, the responses shown in Figures 7-3, 7-4, and 7-5 are still small due to the attenuating effect of the rollout guidance system. With the alternate specification, the maximum main gear lateral excursions are increased to only 2.5 ft., 10 ft., and 4 ft., respectively. The fact that the excursions did not exceed the performance criterion limit of 12 ft. implies that the alternate specification can be relaxed further because of the attenuating effect of the rollout guidance system. Such a specification is developed in the following two sections for different classifications of localizer disturbances.

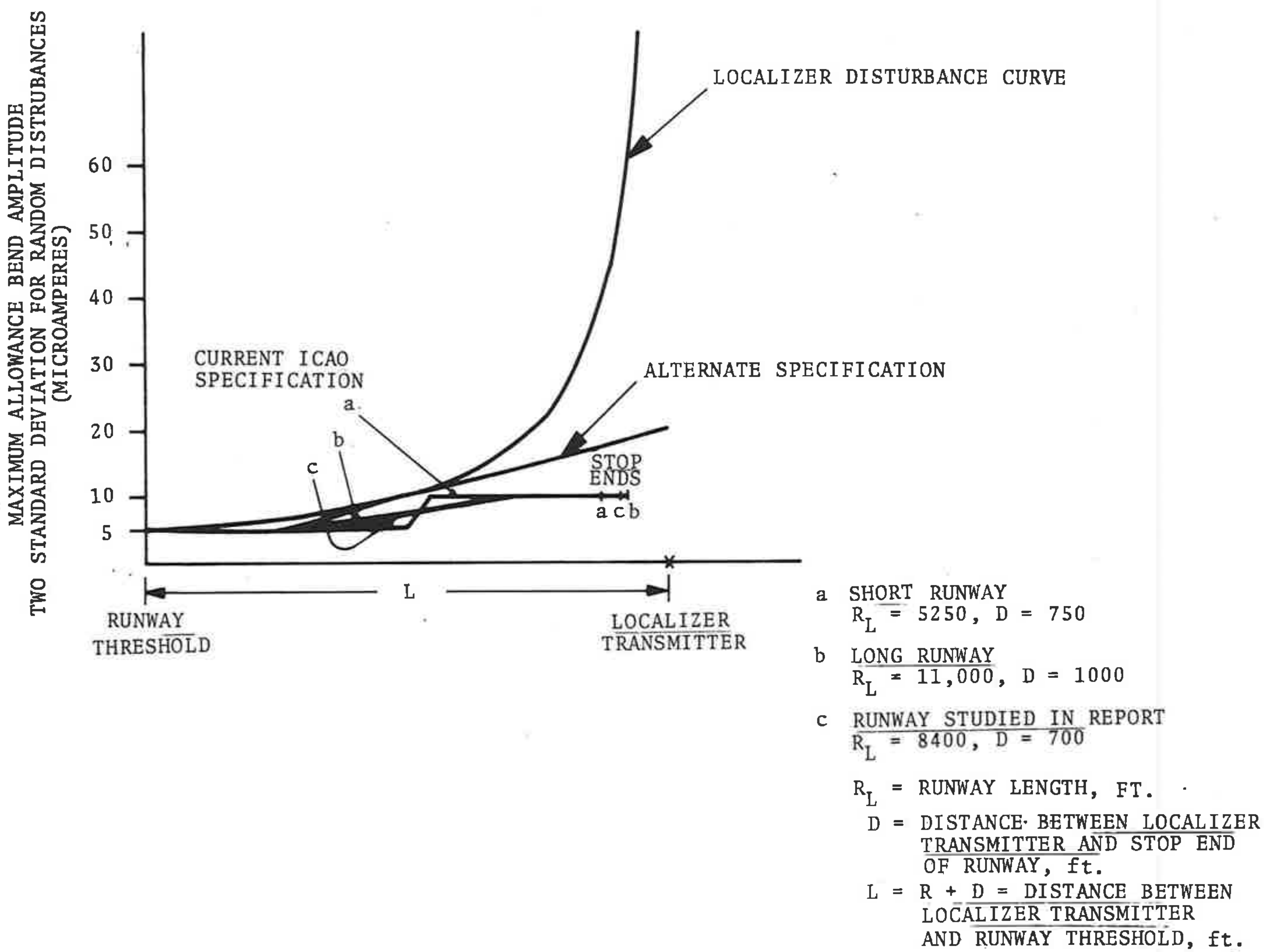


Figure 7-1 Localizer Signal Specification, Accounting for the Sensitivity Effect of the Localizer Receiver

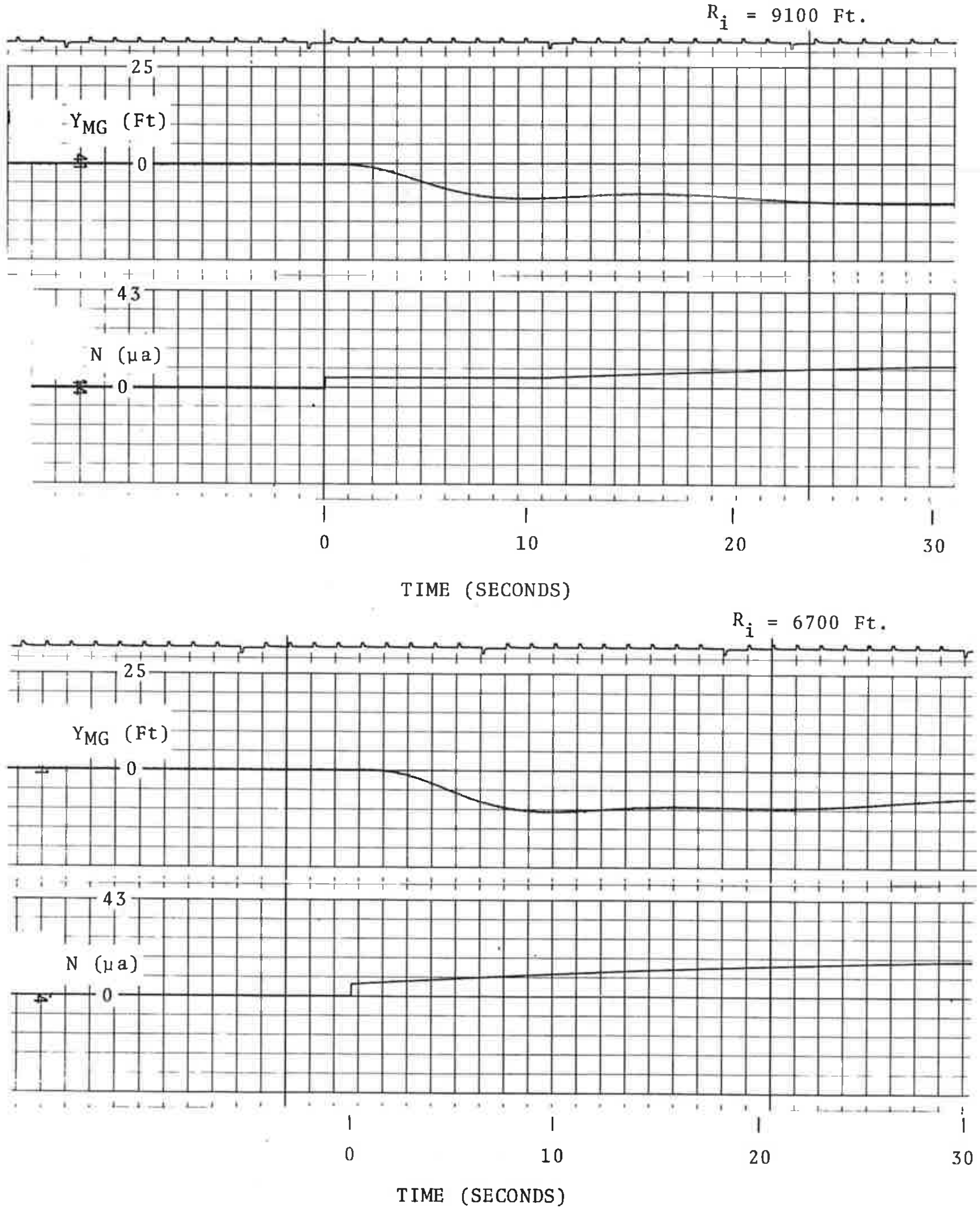


Figure 7-2 Main Gear Lateral Responses to Bias and Ramp, Amplitude = Alternate Specification, V_i = 236.5 ft./sec

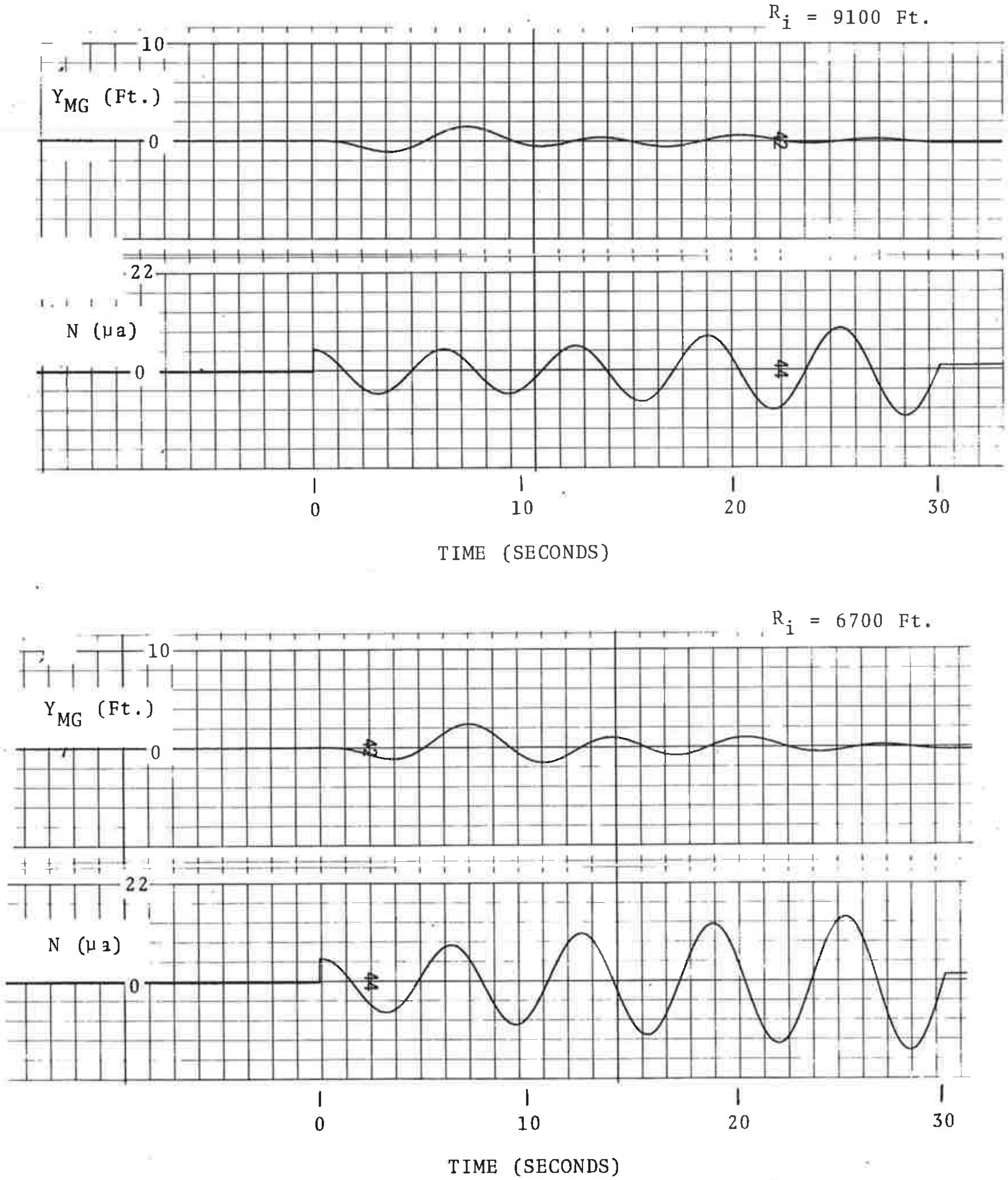


Figure 7-3 Main Gear Lateral Responses to Sine Wave with Frequency = 1 Radian/Second, Amplitude = Alternate Specification, V_i = 236.5 ft./sec

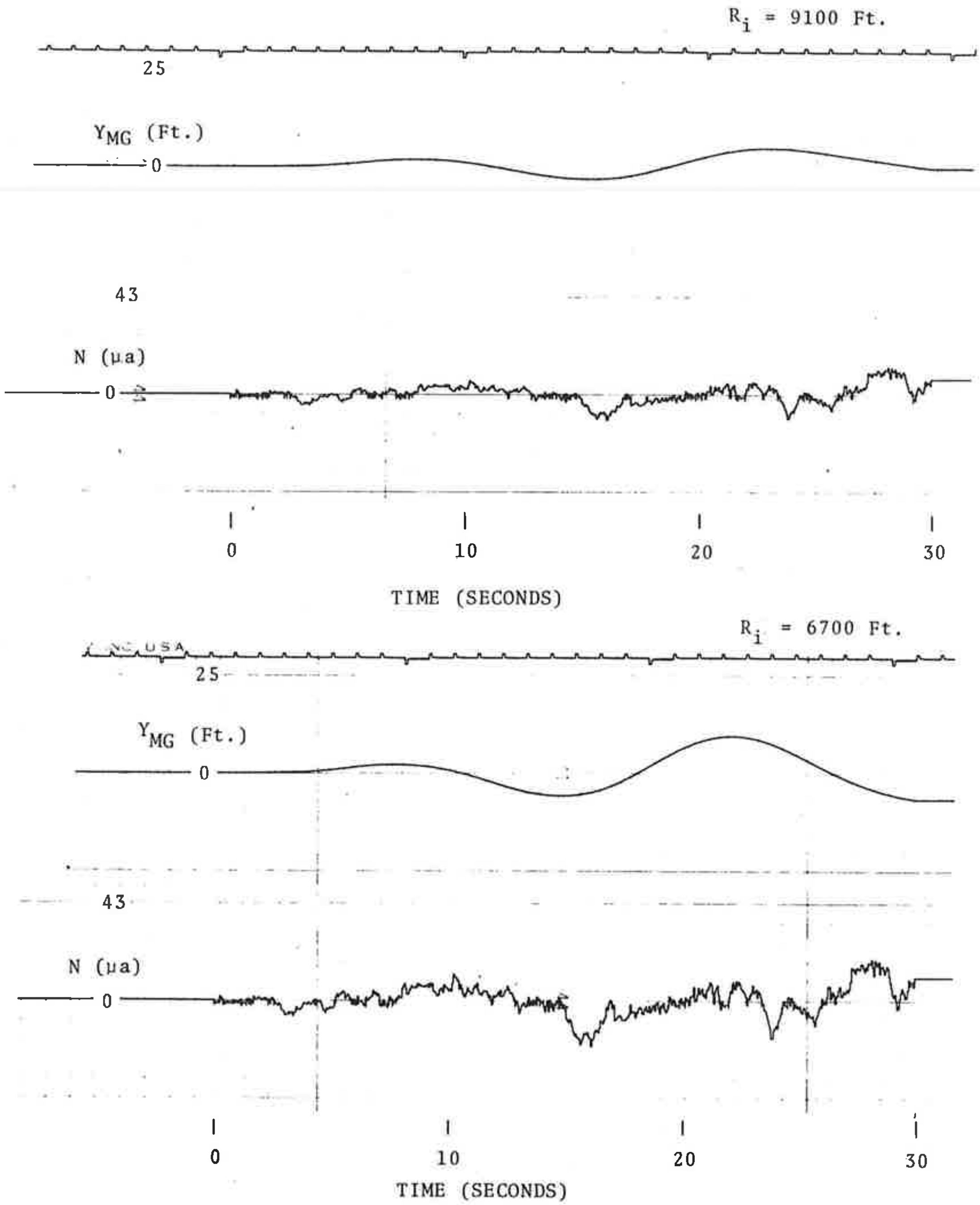


Figure 7-4 Main Gear Lateral Responses to White Noise passed through a First Order Filter, with a break frequency of 1 Radian/Sec, 2 σ_N = Alternate Specification, V_i = 236.5 ft./sec

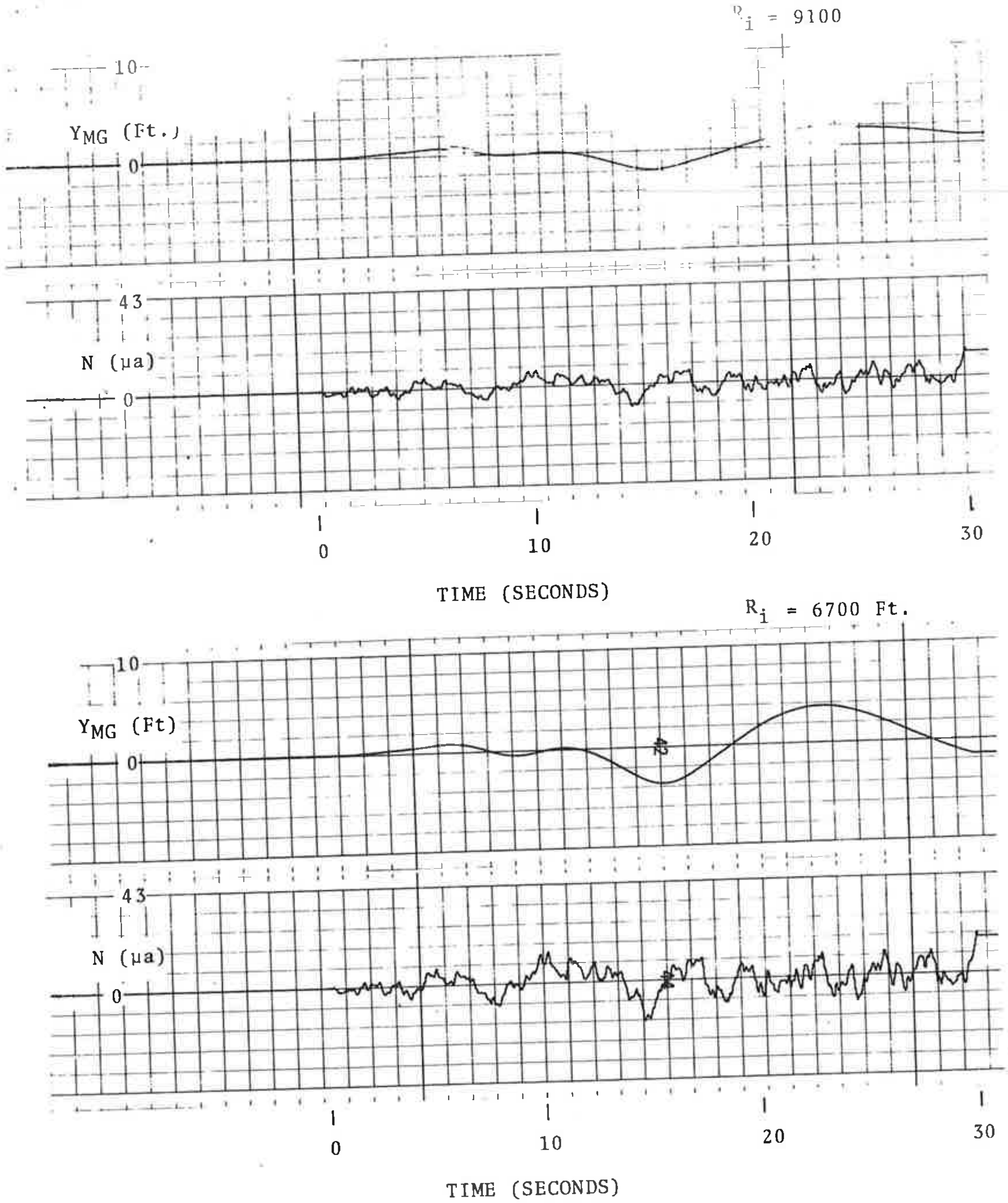


Figure 7-5 Main Gear Lateral Responses to White Noise passed through a Second Order Filter with low frequency washout, 2 σ_N = alternate specification, ω_N = 1 Radian/Second, V_i = 236.5 ft./sec

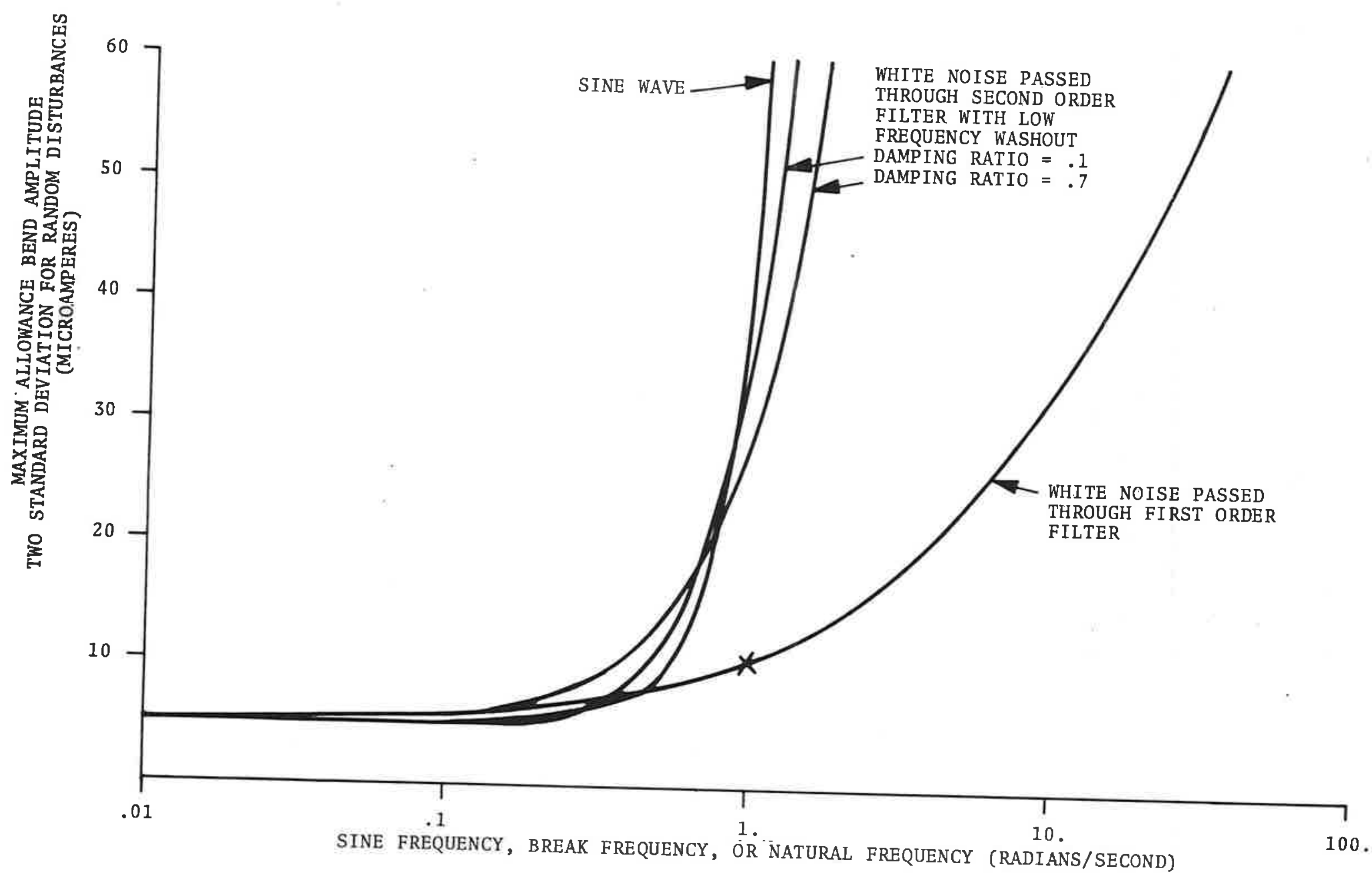


Figure 8-1 Localizer Signal Specification, Accounting for the Attenuating Effects of the Rollout Guidance System.

9.0 RECOMMENDED LOCALIZER SIGNAL SPECIFICATION

This section combines the results of the previous two sections in deriving a revised localizer signal specification for information on the runway surface appropriate for rollout guidance during Category III B operations. The revised specification is recommended for future application. Practical means for applying the specification are discussed in Appendix H.

The specification derived in Section 7.0 accounted only for the sensitivity effect of the localizer receiver and is expressed as a function of the distance to the localizer transmitter beginning at the runway threshold. Verification of this specification, via lateral position responses, showed that the specification could be relaxed further due to the attenuating effect of the rollout guidance system. The additional relaxations were represented by the specification in Section 8.0 for different classifications of localizer distrubances at the runway threshold. Thus the combined specification can be determined by multiplying the results of one specification by the additional relaxation factor of the other specification. The additional relaxation factor in either case is the ratio of the actual specification determined from one of the curves to 5 microamperes. The resulting localizer signal specification is presented in Figure 9-1.

The specification provides the maximum allowance bend amplitude (on a 95% probability basis for random localizer disturbances) over the length of the runway for various classifications of localizer disturbance signals. (The application of the specification to actual localizer measurements that cannot be precisely classified is discussed in Appendix H.) Once the classification of the disturbance signal has been determined (i.e. sine wave, white noise passed through a first order filter or white noise passed through a second order filter with low frequency washout) the maximum allowance bend amplitude is read directly from the ordinate in Figure 9-1 in terms of the relaxation factor R_F. The abscissa refers to frequency for sine wave signals; break frequency for white noise passed through a first order filter; and natural frequency for white noise passed through a second order filter with low frequency washout. The relaxation factor is expressed in terms of the distance to the localizer transmitter and is presented in the small insert in Figure 9-1. The specification is thus additionally relaxed by this factor, for a given classification of disturbance signal, as the aircraft receiver approaches the localizer transmitter.

The specification was evaluated qualitatively for the same localizer disturbances described in Section 6.0. The lateral responses to these disturbances are shown in Figures 9-2 through 9-4 for a nominal localizer signal gain of 30 rad/rad and in Figures 9-5 through 9-7 for a reduced localizer signal gain of 10 rad/rad. (The bias and ramp disturbance and hence lateral response are unchanged from that in Figure 7-2.)

With the nominal gain, the responses remain within the performance criterion limit established in Section 5.0 when the aircraft lands near the runway threshold (e.g. R_i = 9100 ft), but exceed the performance criterion limit when the aircraft lands farther down the runway (e.g. R_i = 6700 ft). This is due to the decrease in effective system damping as the aircraft approaches the localizer transmitter. In addition, as the aircraft lands farther down the runway, it operates in a larger disturbance level region of the specification during ground rollout. (The ground rollout phase in this study is assumed to last for 30 seconds or approximately 4800 ft. from touchdown). With the reduced localizer signal gain the effective system damping is larger and consequently the responses all remain within the performance criterion limit.

Since the rollout guidance system with nominal gain is a representative system for landings near the threshold (e.g. R_i = 9100 ft) and with reduced gain is a more representative system for landings farther down the runway, the above evaluation demonstrates that the localizer signal specification presented in Figure 9-1 is acceptable for typical rollout guidance systems over extreme landing ranges.

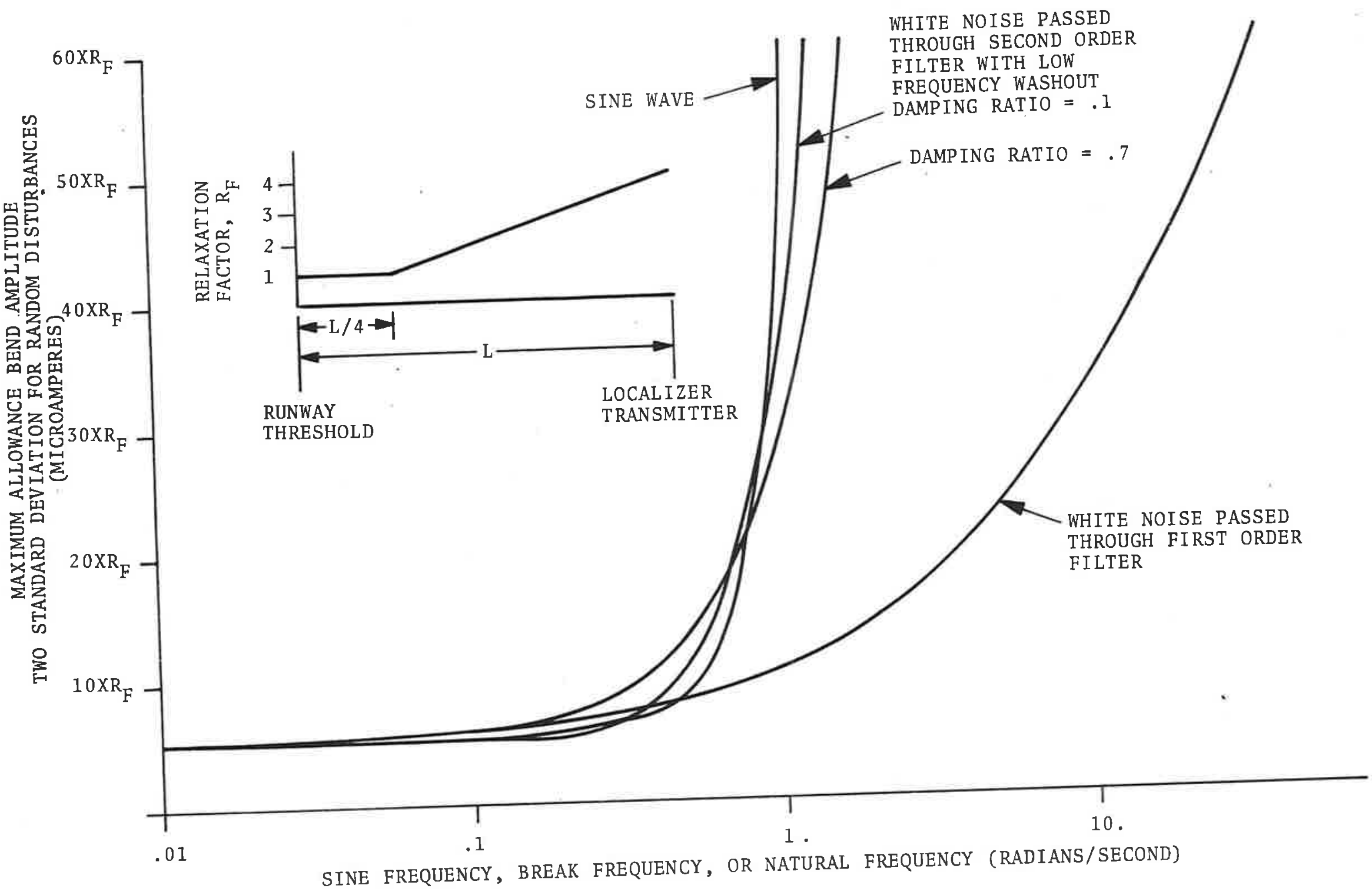


Figure 9-1 Recommended Localizer Signal Specification

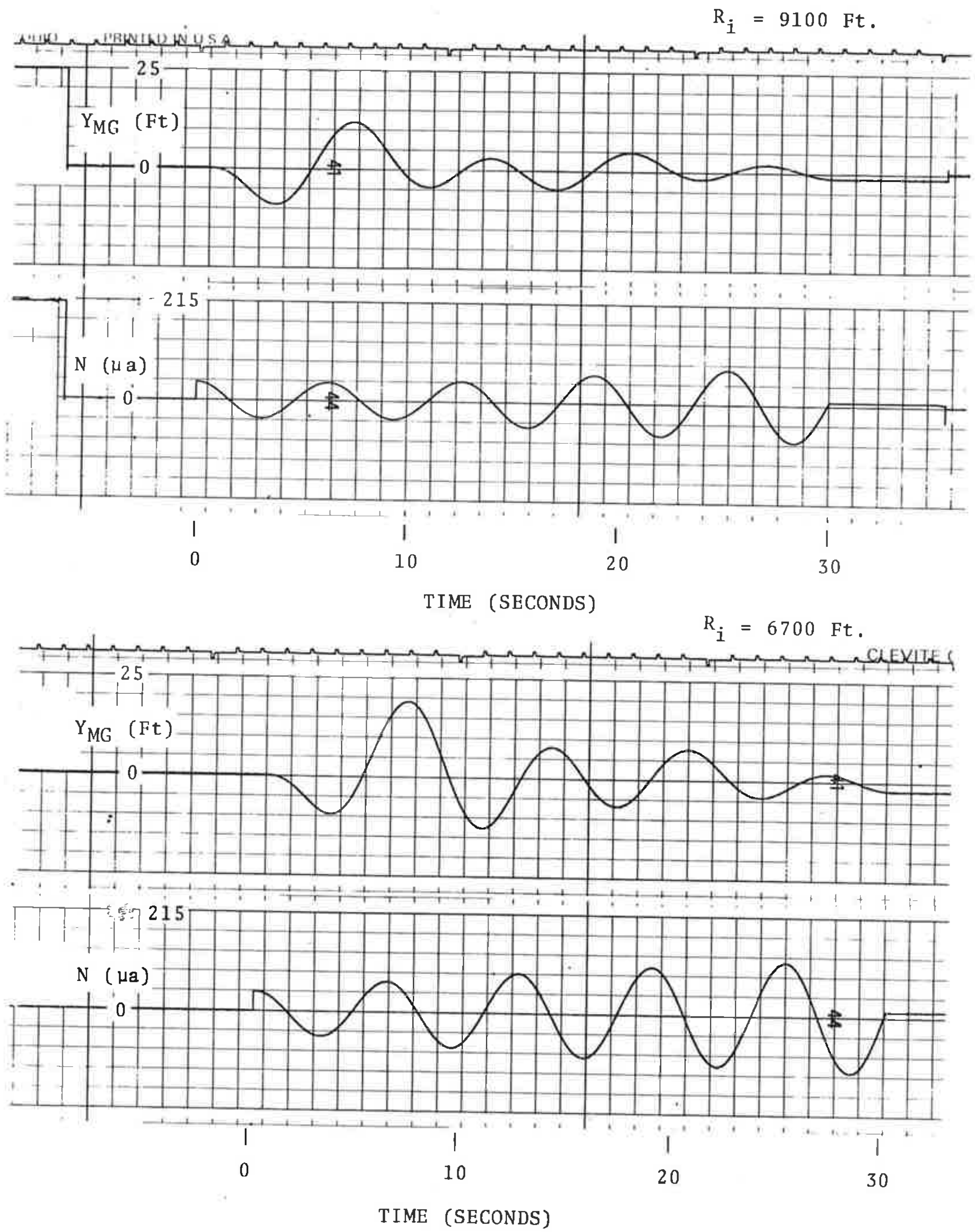


Figure 9-2 Main Gear Lateral Response to Sine Wave with frequency = 1 Radian/Second Amplitude = Recommended Specification, V_i = 236.5 ft./sec nominal system gain

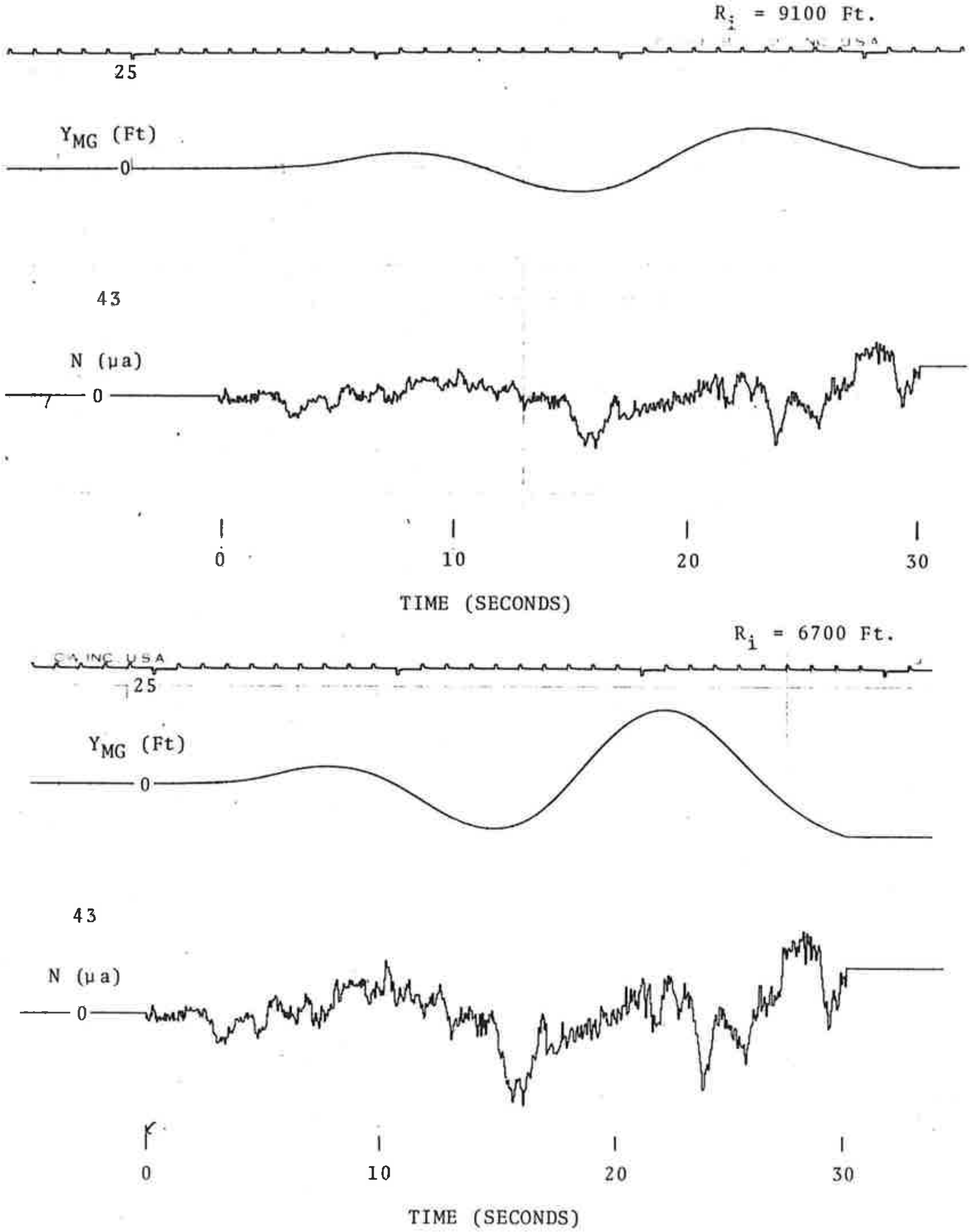
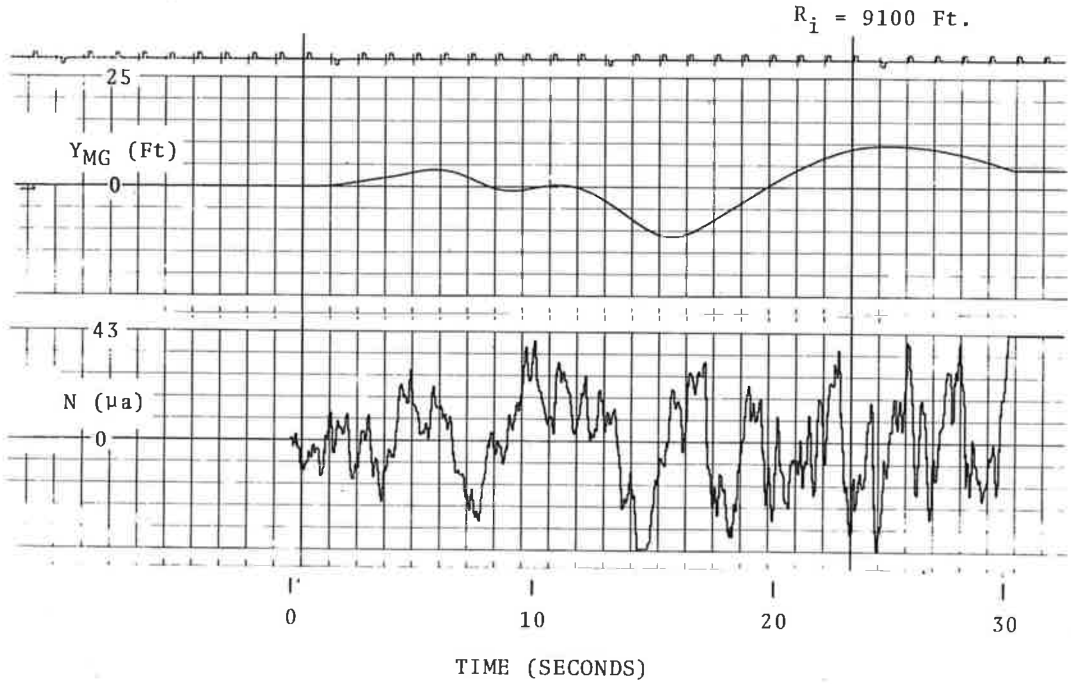


Figure 9-3 Main Gear Lateral Response to White Noise passed through a First Order Filter with break frequency of 1 Radian/Sec 2 σ_N = recommended specification, nominal system gain V_i = 236.5 ft./sec



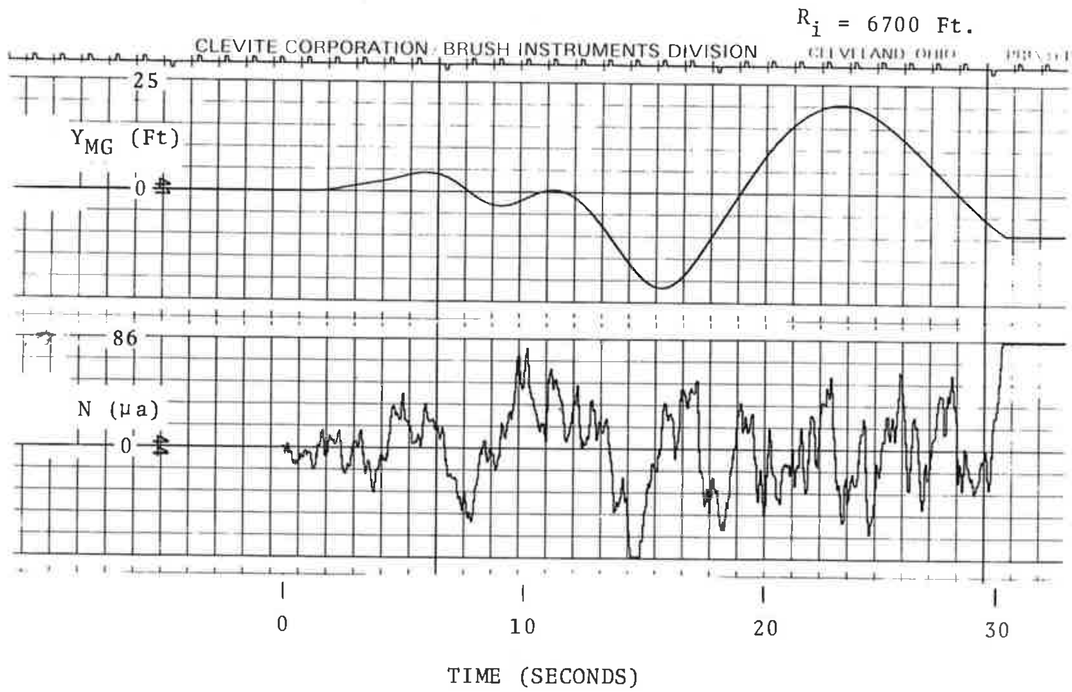


Figure 9-4 Main Gear Lateral responses to White Noise passed through a Second Order filter with low frequency washout, nominal system gain 2 σ_N = recommended specification, ω_N = 1 Radian/Second, V_i = 236.5 ft./sec

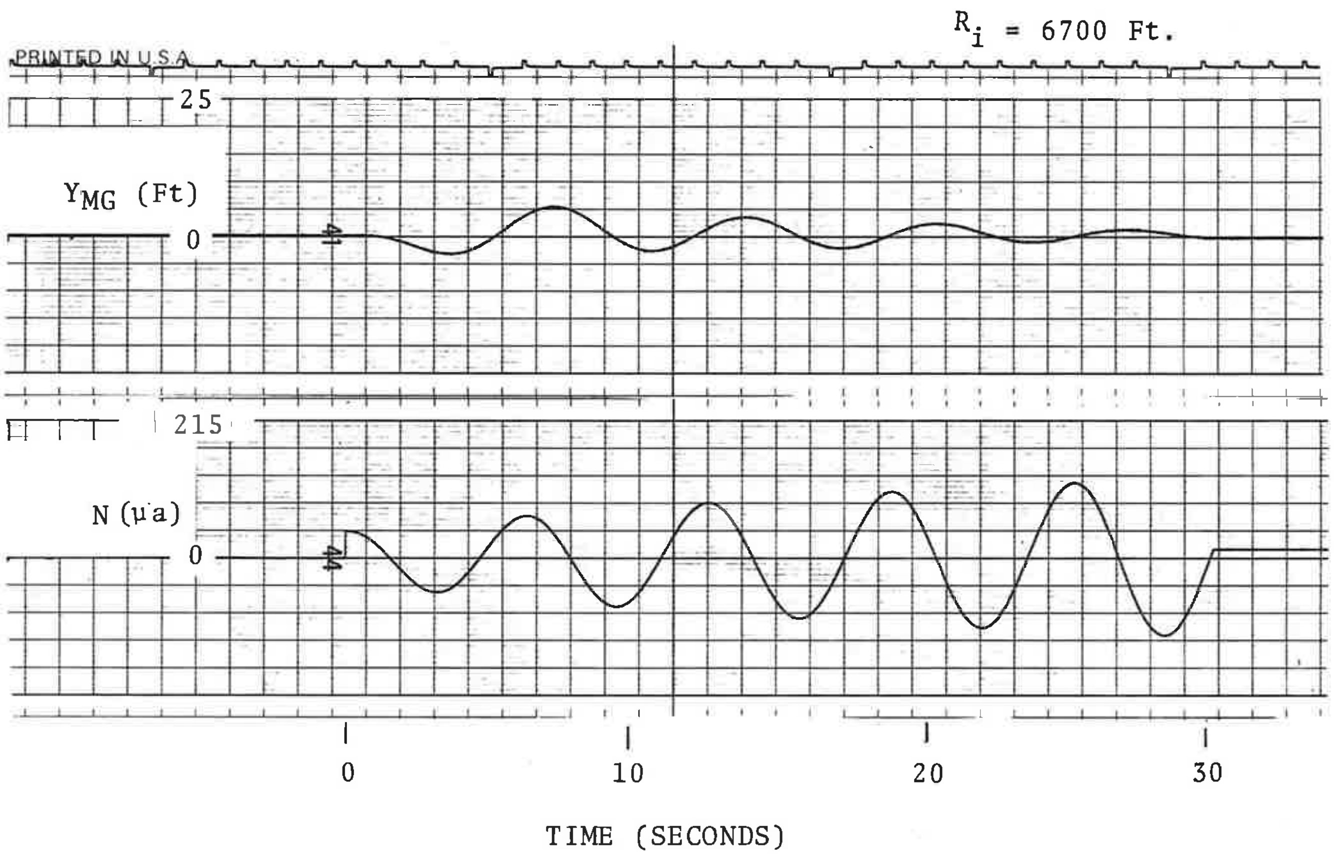


Figure 9-5. Main Gear Lateral response to Sine Wave with frequency = 1 Radian/Sec Amplitude = recommended specification, V_i = 236.5 ft./sec, reduced system gain

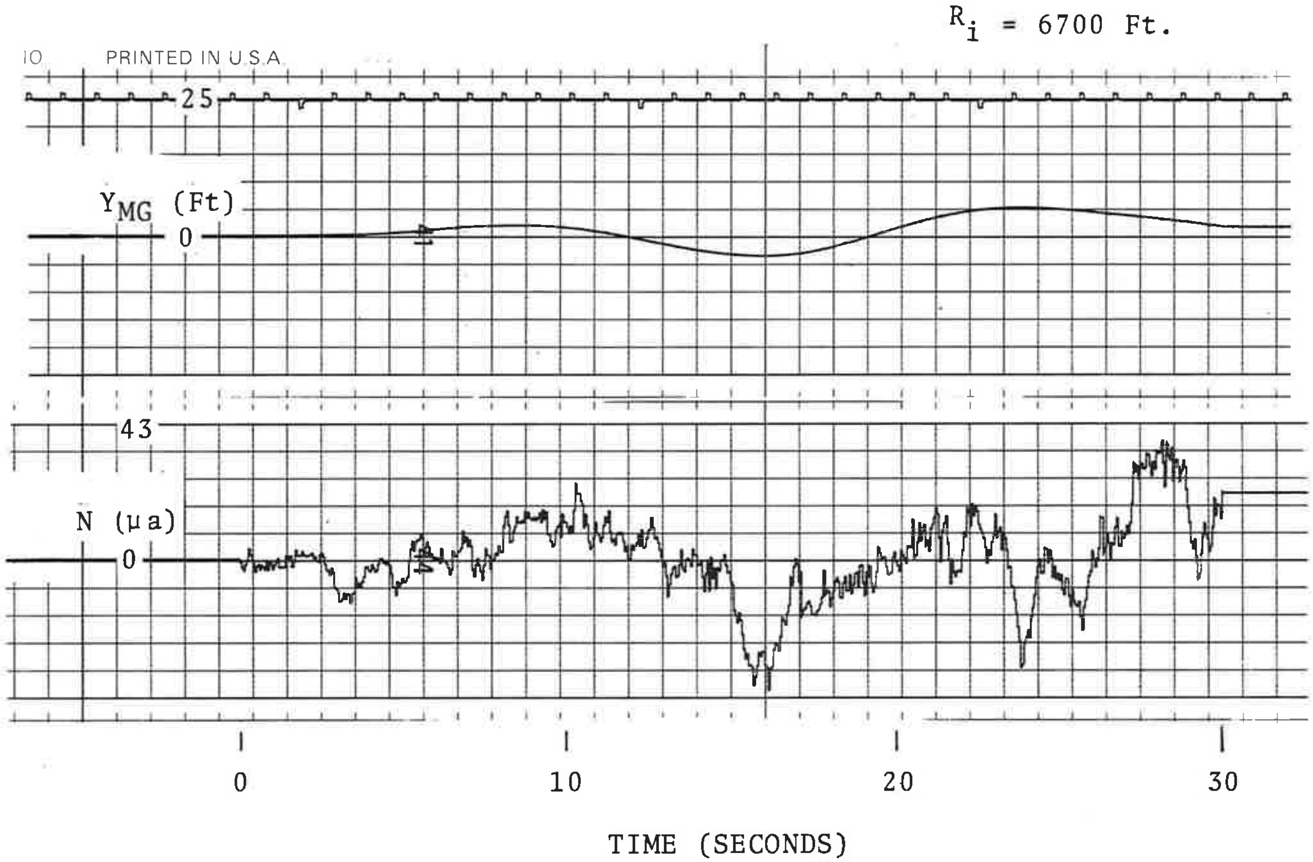


Figure 9-6. Main Gear Lateral response to White Noise passed through a First Order Filter with break frequency of 1 Radian/Second, reduced system gain, $2\sigma_N$ = recommended specification, V_i = 236.5 ft./sec

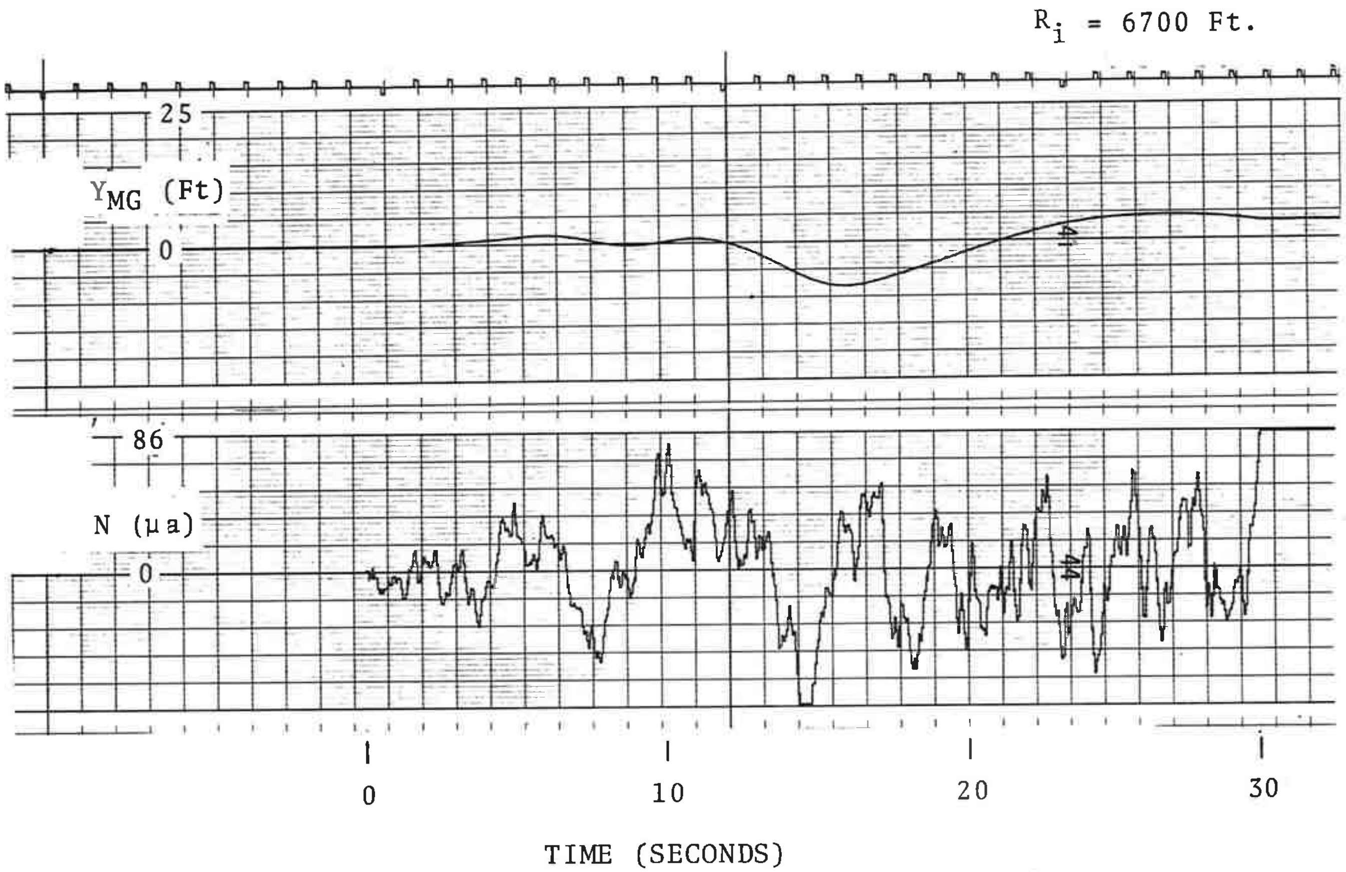


Figure 9-7. Main Gear Lateral response to White Noise passed through a Second Order filter with low frequency washout, reduced system gain, $2\sigma_N$ = recommended specification, ω_N = 1 Radian/Second, V_i = 236.5 ft./sec.

10.0 CONCLUSIONS

The current ICAO specification for localizer information on the runway surface appropriate for rollout guidance during Category III B operations has been evaluated by systems analysis and simulation. The evaluation was determined for a representative rollout guidance system which was assumed to be a minimum quality, well damped system. The results of the analysis and simulation indicate that the specification is too stringent, especially for higher frequency type localizer disturbances and therefore should consider the spectral characteristics of the localizer disturbance. A more relaxed specification was therefore developed by taking additional advantage of the sensitivity effect of the localizer receiver and the attenuating effect of the rollout guidance system on localizer disturbances. The revised specification is presented and recommended for future localizer signal specification since it could allow Category III B certification without degradation of overall rollout system performance or safety that the current specification might otherwise preclude. Practical means for applying the revised localizer signal specification are discussed but other simpler and practical means should be examined in detail and made the subject of an additional effort.

Although the revised localizer signal specification was derived for a single rollout guidance system representative of a large jumbo jet aircraft, it is expected to be somewhat conservative for most aircraft since the study did not include the additional damping effects of the nose wheel gear due to the frictional reactionary forces with the ground. In addition, the rollout guidance system model in this study lacked some of the more sophisticated design aspects that are not uncommon for Category III B landing systems, such as rate limits, complementary filtering, complementary nose wheel steering, and mode switching, and that all serve to further improve performance.

The specification is not expected to be dependent on aircraft size either since, by and large, the dynamics of the Category III B systems for different size aircraft are so conditioned by the guidance and control laws as to be undistinguishable. For example,

Figure 10-1 compares the frequency responses for a light, maneuverable twin engine aircraft, a medium size jet transport and the large jumbo jet aircraft in this report, all employing the same guidance and control laws. The similarities of these responses imply an insignificant difference in performance results.

Finally, the revised localizer signal specification does not directly apply to transient disturbances, such as those caused by overflight or the closing of a hangar door, because of their nonstationary characteristics. However, the specification can provide an indication of likely aircraft performance during ground rollout for a particular type of transient disturbance. If the predicted performance is unacceptable the specific flight operation or whatever cause of the disturbance can be regulated in order to prevent such disturbances from occurring during normal landing procedures.

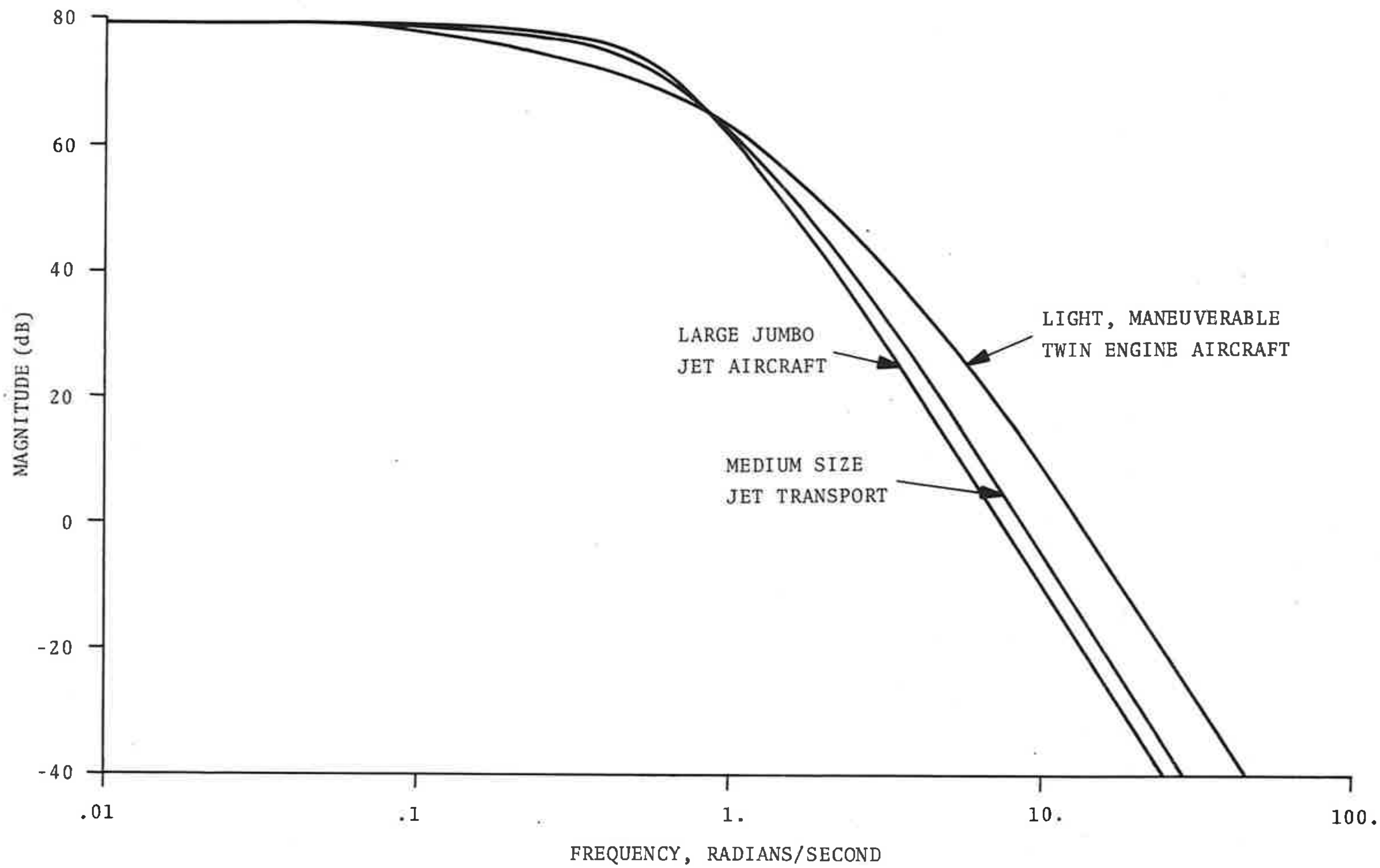


Figure 10-1 Rollout Guidance System Frequency Responses

11.0 RECOMMENDATIONS

Before implementing the localizer signal specification recommended in this report, frequency responses of all potential Category III B rollout guidance systems could be obtained and compared with that used in this study. Any major differences (i.e. the presence of strong natural exciting frequencies) can then be accommodated by altering the recommended localizer signal specification to account for the differences or by precluding the specific systems with the differences from Category III B operations at airports whose localizer disturbance characteristics might cause a violation of the performance criterion.

In addition, it is recommended that the revised localizer signal specification be substantiated via a more thorough simulation study including the effects of landing gear dynamics, touchdown transients, roll dynamics, environmental disturbances, nose wheel control prior and subsequent to aerodynamic ineffectiveness and cross runway signal anomalies. It is also recommended that manufacturers who apply for Category III B certification demonstrate by analysis, simulation, and flight test that their systems are in fact compatible with the localizer signal specification recommended herein.

APPENDIX A

CURRENT ICAO SPECIFICATION

The current specification for localizer information on the runway surface appropriate for rollout guidance during Category III B operations was developed by the International Civil Aviation Organization and is described in Figure A-1. The specification is defined in terms of the maximum allowance bend amplitude on a 95% probability basis over the entire length of the runway. The maximum allowance bend amplitude at the runway threshold is 5 microamperes (the same specification as for Category III A). The maximum allowance bend amplitude remains constant at 5 microamperes for 3000 ft. down the runway from the runway threshold at which point it increases linearly with runway distance to 10 microamperes at a point 2000 ft. from the stop end of the runway. The maximum allowance bend amplitude then remains constant at 10 microamperes for the rest of the runway. Note that the current specification is independent of the distance to the localizer transmitter and the spectral characteristics of the localizer information.

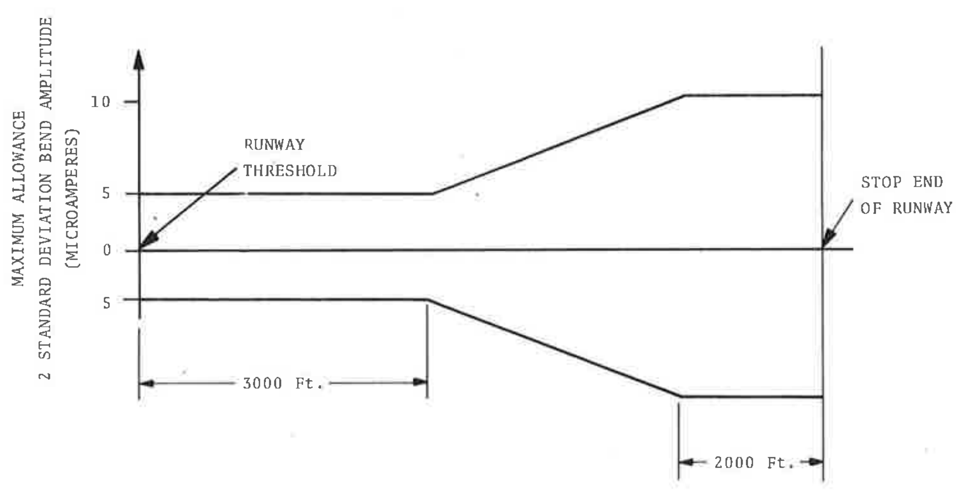


Figure A-1 Current ICAO Specification for Localizer Information on the Runway Surface

APPENDIX B

DERIVATION OF AIRCRAFT MODEL DURING GROUND ROLLOUT

The aircraft model during high speed ground rollout may be represented by the standard lateral equations of motion and an equivalent landing gear system. In addition to the assumptions in Section 3.0, it is assumed that the roll angle, roll rate and roll acceleration are all equal to zero.

Accounting for the lateral force exerted by the ground upon the wheels, the yawing moment and sideforce equations can be written as follows:

$$\ddot{\psi} = N_r \dot{\psi} + N_\beta \frac{v}{V} + N_{\delta_r} \delta_r - \frac{f}{I_z} d$$

$$\frac{\dot{v}}{V} + \dot{\psi} = Y_r \dot{\psi} + Y_\beta \frac{v}{V} + Y_{\delta r} \delta_r + \frac{f}{mV}$$

where, v = lateral velocity of the c.g. with respect to the fuselage reference line (positive as shown in Figure B-1)

d = distance between c.g. and equivalent landing gear (positive as shown in Figure B-1)

f = lateral force applied by the ground upon the wheels (positive as shown in Figure B-1)

The assumption was made during this study that the wheels did not skid* and therefore,

$$v = d\dot{\psi}$$

and

$$\dot{v} = d\ddot{\psi}$$

*This assumption was later supported by the fact that at no time in the study did the lateral ground force exceed the force required to produce skid.

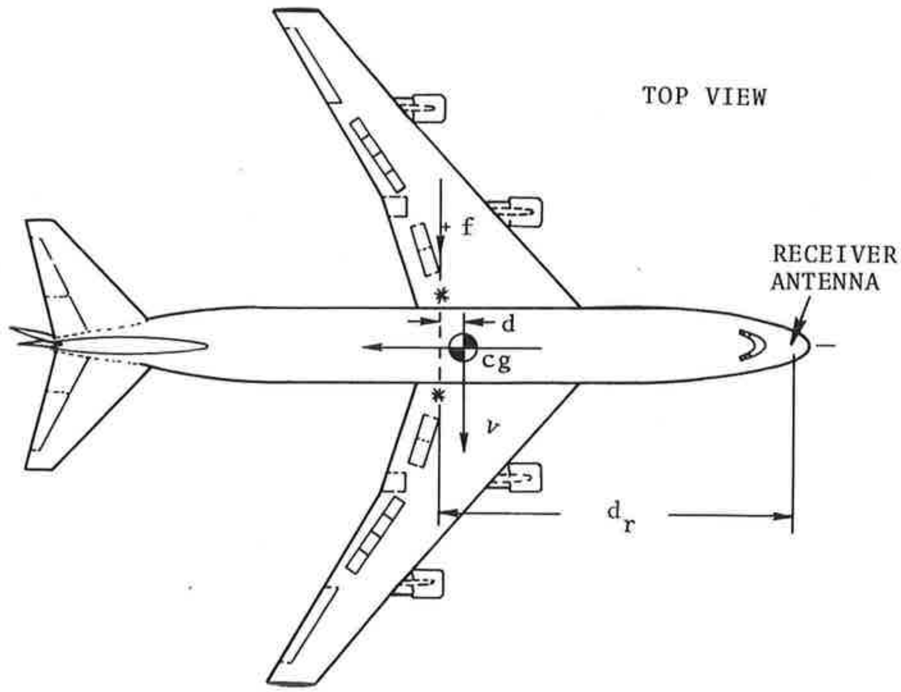


Figure B-1 Aircraft Geometry

Eliminating f from the yawing moment and sideforce equations and substituting $d\dot{\psi}$ for V yields the following equation:

$$\dot{\psi} + \frac{dmV}{I_z}\left(\frac{d}{V}\ddot{\psi} + \dot{\psi}\right) = \left(N_r + Y_r\frac{dmV}{I_z}\right)\dot{\psi} + \left(N_\beta + Y_\beta\frac{dmV}{I_z}\right)\frac{d\dot{\psi}}{V}$$

$$+\left(N_{\delta r} + Y_{\delta r}\frac{dmV}{I_z}\right)\delta_r$$

The ψ/δ_r transfer function may then be written in the form:

$$\psi/\delta_r = \frac{K}{s(s+w)}$$

where,

$$K = \left[\frac{N_{\delta r} + Y_{\delta r}(mdV/Iz)}{1 + \frac{md^2}{I_z}} \right] = \left[\frac{q^{SbC_{n_{\delta_r}}} + q^{SdC_{y_{\delta_r}}}}{I_z + md^2} \right]$$

$$w = \frac{\left[-N_r - (-mV/I_z + Y_r \, mV/I_z + N_\beta/V)d - Y_\beta(md^2/I_z) \right]}{1 + md^2/I_z}$$

$$= \frac{mVd - \frac{qSb^2}{2V} C_{n_r} - \frac{qSbd}{2V} C_{Y_r} - \frac{qSbd}{V} C_{n_\beta} - \frac{qSd^2}{V} C_{Y_\beta}}{I_z + md^2}$$

and s is the Laplace transform variable.

For purposes of analysis in this report all aircraft parameters are constant. The time-varying parameter simulation model in this report assumes that the aircraft is decelerating at a uniform rate of 5ft/sec^2. Hence the following equations are included in the simulation model.

$$V = V_i - 5t$$

$$q = 1/2\rho \ V^2$$

where V_i is the initial velocity and t is the time from the start of the simulation.

The parameters K and w are, of course, programmed accordingly. The parameters and aerodynamic stability coefficients for a representative jumbo jet aircraft during ground rollout are given in Table B-1.

TABLE B-1 PARAMETERS AND AERODYNAMIC STABILITY COEFFICIENTS FOR A REPRESENTATIVE JUMBO JET AIRCRAFT DURING GROUND ROLLOUT

PARAMETER	VALUE	DIMENSIONS
d	7.	ft.
b	196.	ft.
m	17,205.	slugs
I_z	44.8×10^6	slug-ft^2
S	5500	$ft.^2$
q*	66	$lb/ft.^2$
V*	236.5	ft/sec
c.g.	25	%MAC
K*	-.1677	per $second^2$
w*	+.823	radians/second
Stability Coefficient (dimensionless)		
$C_{n_{\delta_r}}$	-.114	-
$C_{y_{\delta_r}}$	+.18	-
C_{n_r}	-.3136	-
C_{y_r}	+.0432	-
C_{n_β}	+.0808	-
C_{y_β}	-.897	-

*variable parameters for the simulation model

APPENDIX C

ROLLOUT GUIDANCE SYSTEM SYNTHESIS

A representative and simple rollout guidance system for a jumbo jet aircraft was synthesized to provide the necessary command signals through the rudder channel for steering the aircraft to and along the runway centerline. The effect of the main gear becoming the center of rotation was taken into account. A block diagram of the system is shown in Figure C-1. The system employs a standard yaw damper channel with washout circuit for stability augmentation. In addition, the system utilizes a heading feedback signal to reduce the initial cross runway velocity to zero quickly and a beam error feedback to return the aircraft to the runway centerline on a long term basis.

Operational Category III B systems include additional features such as rate limits, complementary filtering, etc. that serve to further improve performance. The rollout guidance system model of Figure C-1 could thus be expected to yield conservative results and was therefore adequate for purposes of this study.

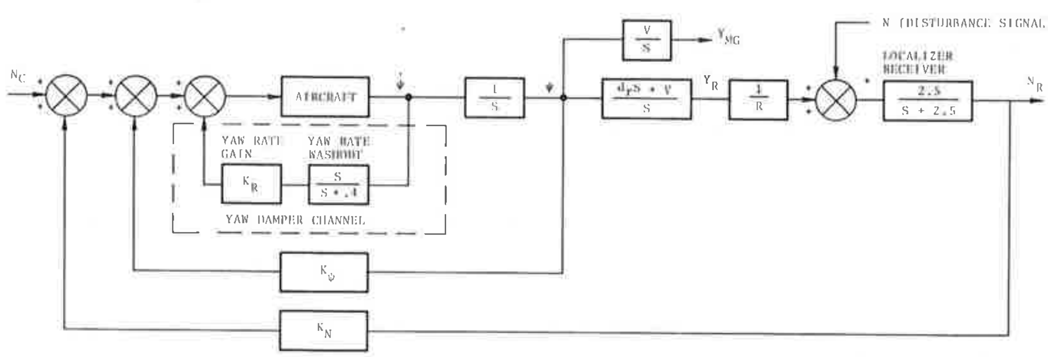


Figure C-1 Block Diagram of Rollout Guidance System

The yaw damper gain and washout parameter were selected from a representative system for a jumbo jet aircraft. The heading gain was determined from the root locus of the heading channel shown in Figure C-2. Selection of the heading gain was simply a matter of achieving high bandwidth while preserving adequate system damping. A heading gain of 4 rad/rad was chosen. This resulted in an effective system damping factor of .7.

The localizer signal gain, K_N, was determined from a time response analysis. Aircraft heading and main gear lateral responses are shown in Figure C-3 for gains of 20 rad/rad, 30 rad/rad, and 40 rad/rad, a range (R) of 9100 ft. from the localizer transmitter and a velocity (V) of 236.5 ft/sec. These responses were generated from an initial condition of 65 ft. on Y_{MG}. A gain of K_N = 30 rad/rad gave a fairly fast response without overshoot. However, the rollout guidance system was slightly sensitive to landing range as is shown in Figure C-4. For a landing range of 6700 ft. and a localizer signal gain of 30 rad/rad the system response is slightly faster and less damped with an overshoot of less than 10%. Although these results are considered acceptable by the performance criterion established in Section 5.0, a response without overshoot is more desirable and representative.

A programmed localizer signal gain as a function of the range to the localizer transmitter could preserve effective system damping throughout rollout but is undesirable to implement from a design viewpoint.

A reduced, fixed localizer signal gain could provide satisfactory, if not desirable, performance with the simplest possible system. For landings at R = 6700 ft. the effective system damping could be sufficiently increased to prevent overshoots. The system would then be overdamped and result in sluggish responses for landings at R = 9100 ft. However, a nominal localizer signal gain of 30 rad/rad was used throughout most of the report and provided responses that were representative of rollout guidance systems for landings near threshold (e.g. R = 9100 ft.) A reduced localizer gain of 10 rad/rad resulted in responses that were more representative for landings farther down the runway (e.g. R = 6700 ft.) and was used where necessary to demonstrate the effectiveness of the revised localizer signal specification (i.e. Section 9.0). The rollout guidance system parameters for a representative jumbo jet aircraft are summarized in Table C-1.

The ranges mentioned above represent near extreme landing conditions for a typical airport layout (i.e. from threshold to 1000 ft. down runway from the glide slope transmitter; see Figure 7-1 for the runway dimensions used in this report).

TABLE C-1 ROLLOUT GUIDANCE SYSTEM PARAMETERS FOR A REPRESENTATIVE JUMBO JET AIRCRAFT

GAIN	VALUE	UNIT
K_R	2.	sec.
K_ψ	4.	rad/rad
K_N	30.†	rad/rad
d_r	110.	ft.

† Nominal Value

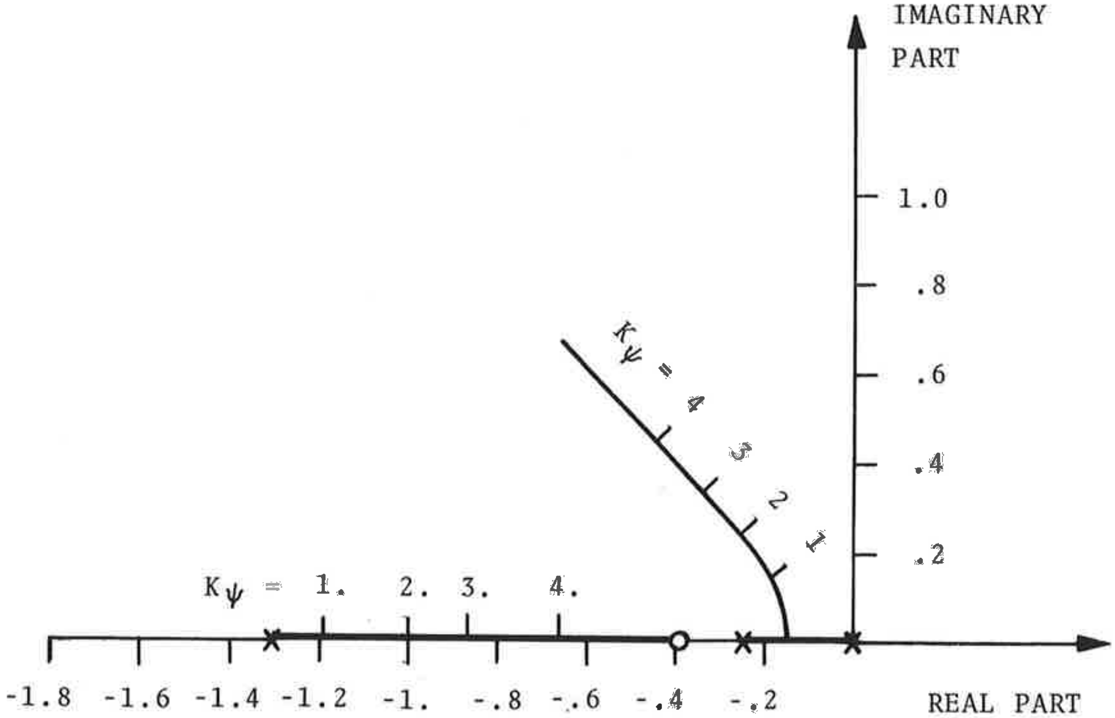


Figure C-2 Root Locus of Heading Channel

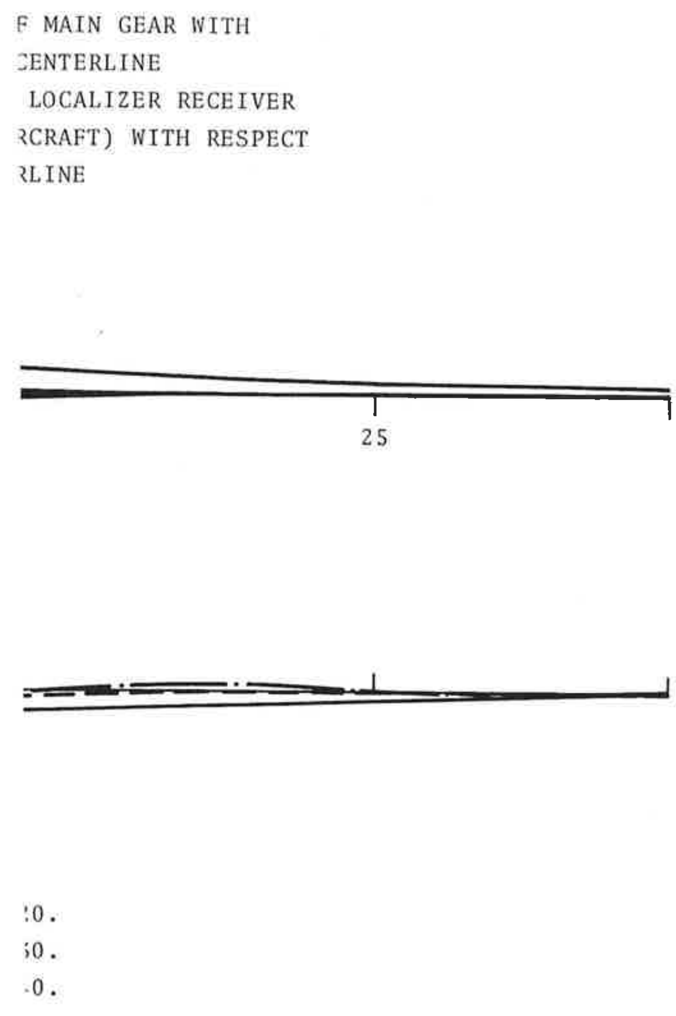


Figure C-3 Aircraft Responses to an Initial Lateral Position R = 9100 ft., V = 236.5 ft/sec

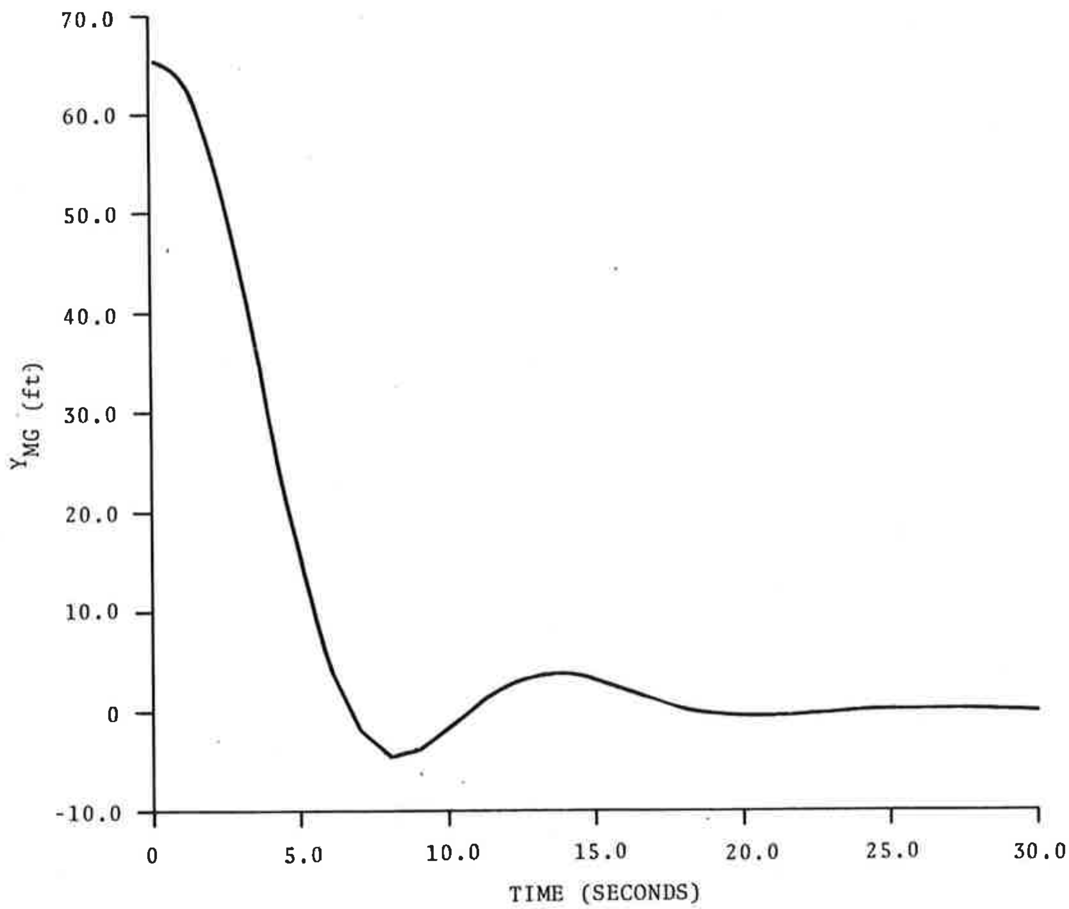


Figure C-4 Aircraft Response to an Initial Lateral Position, R = 6700 ft., V = 236.5 ft/sec

APPENDIX D

COMPARISON BETWEEN ANALYSIS MODEL AND SIMULATION MODEL

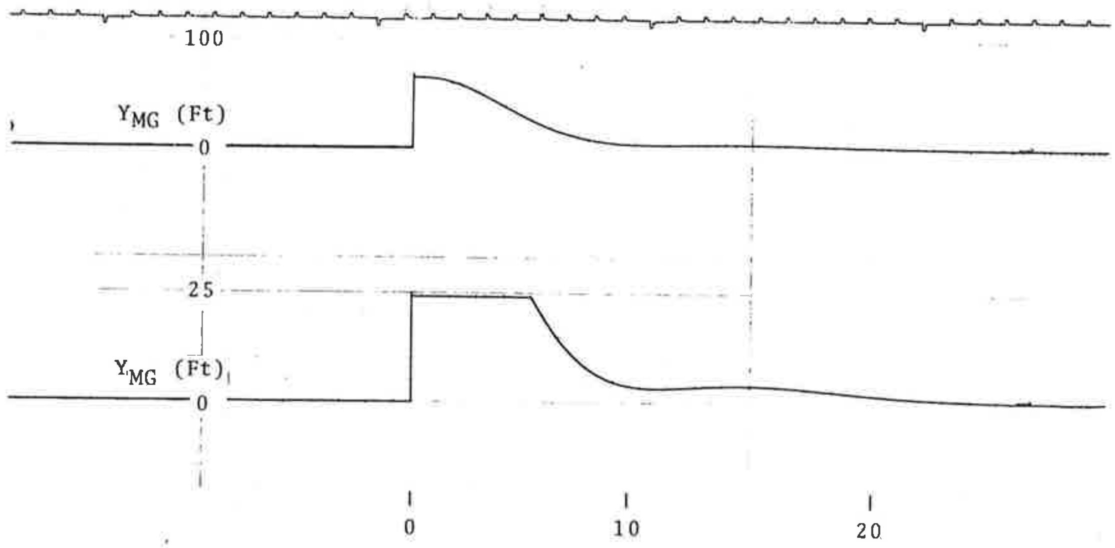
This section presents a brief time response comparison between the constant parameter analysis model and the time varying parameter simulation model. The nominal localizer signal gain was used in this comparison. Both of the models are described in Section 4.0. The analysis model was used primarily for the rollout guidance system synthesis and for deriving a specification for different classifications of localizer disturbances. The simulation model added more realism to the analysis model by accounting for the aircraft's deceleration profile and the increasing sensitivity of the localizer receiver during ground rollout. In addition, it accepted random and programmed localizer disturbances. The simulation model was used essentially to qualitatively substantiate the results obtained using the analysis model.

Figures D-1 and D-2 compare main gear lateral position responses for an initial lateral position condition of 65 ft. Figure D-3 compares the lateral position responses for a localizer step input signal of 5 microamperes (.067 deg.).

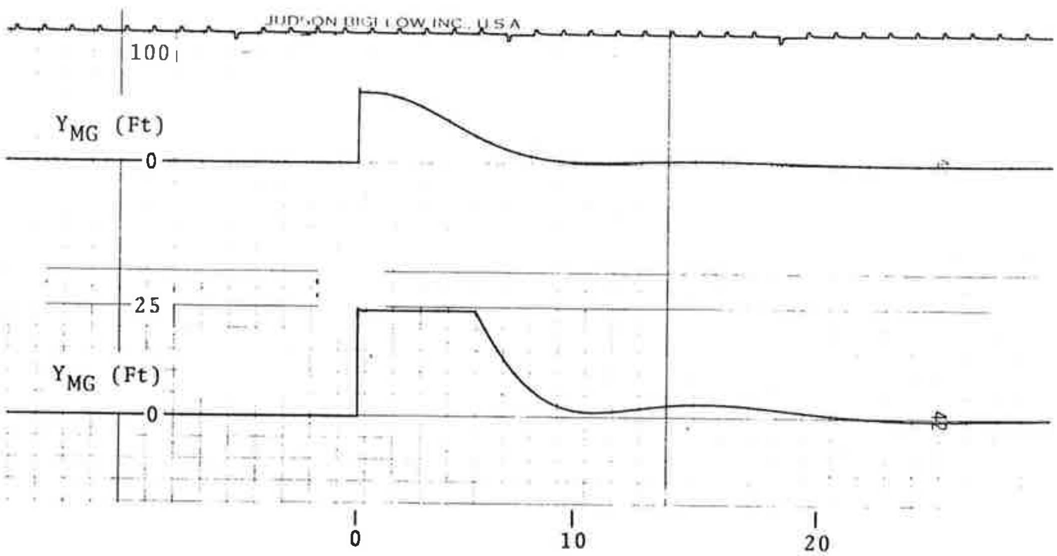
The responses for each case are rather similar. In general the simulation model is less damped due to the increasing gain and aerodynamic effects especially when the aircraft lands closer to the localizer transmitter.

In the case of the step response the simulation model shows the aircraft slightly overshooting the step signal and then converging to the localizer transmitter. The analysis model shows a fixed point response (at R = 9100 ft) with no overshoot.

The comparison indicates that a fixed-gain rollout guidance system can adequately steer the aircraft to the runway centerline in the absence of external disturbances.

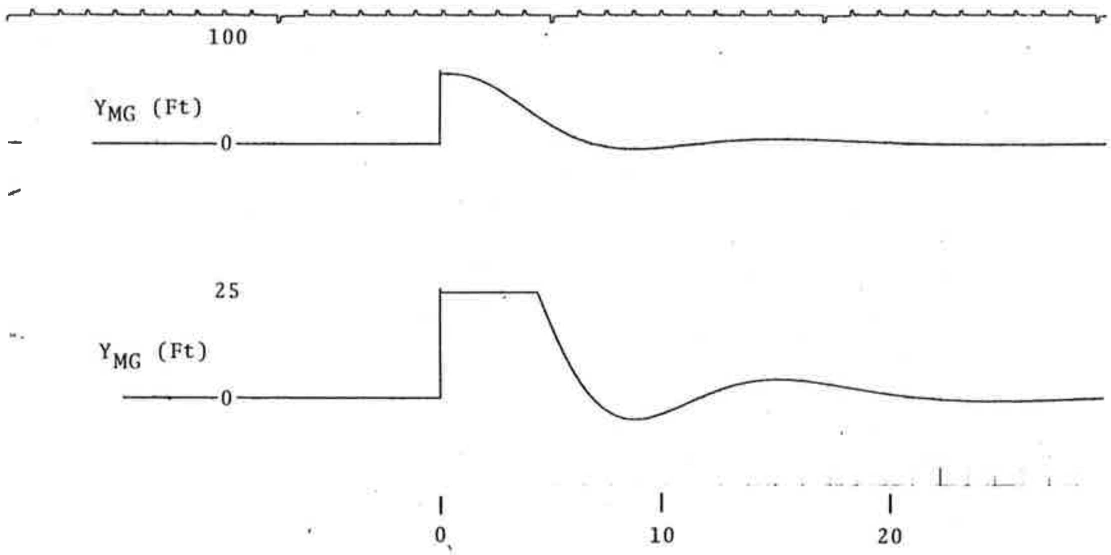


ANALYSIS MODEL R = 9100 Ft, V = 236.5 Ft/Sec



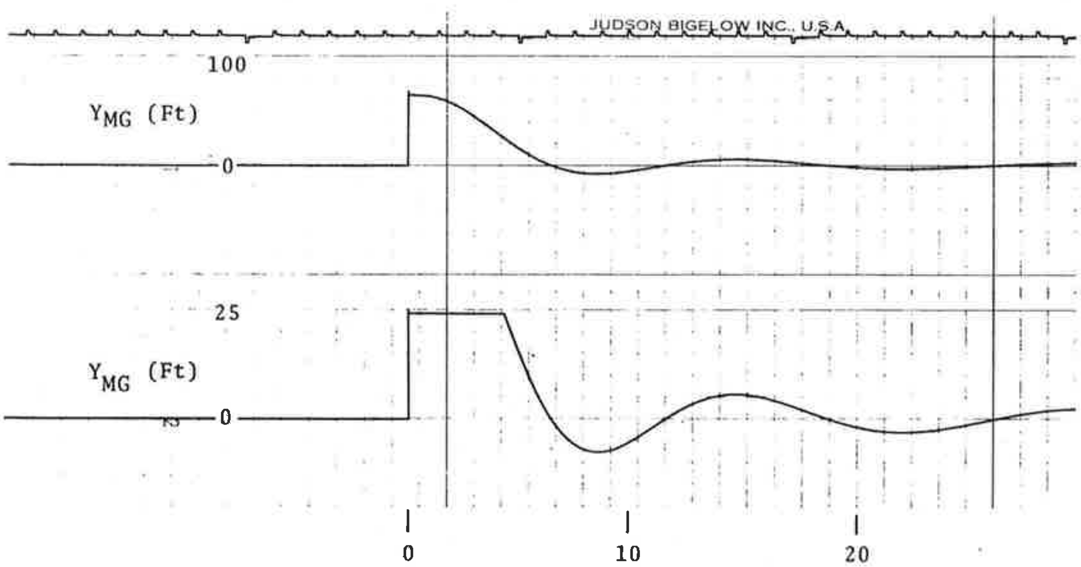
SIMULATION MODEL R_i = 9100 Ft. V_i = 236.5 Ft/Sec

Figure D-1 Main Gear Lateral Position Responses for Initial Lateral Position of 65 ft.



TIME (SECONDS)

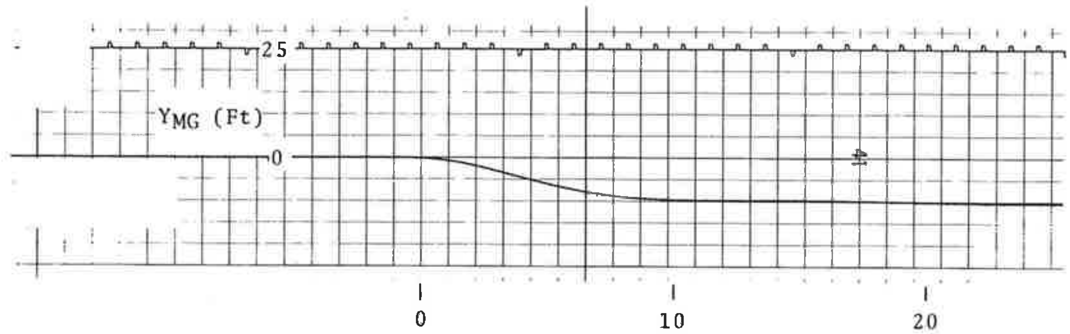
ANALYSIS MODEL R = 6700 Ft, V = 236.5 Ft/Sec



TIME (SECONDS)

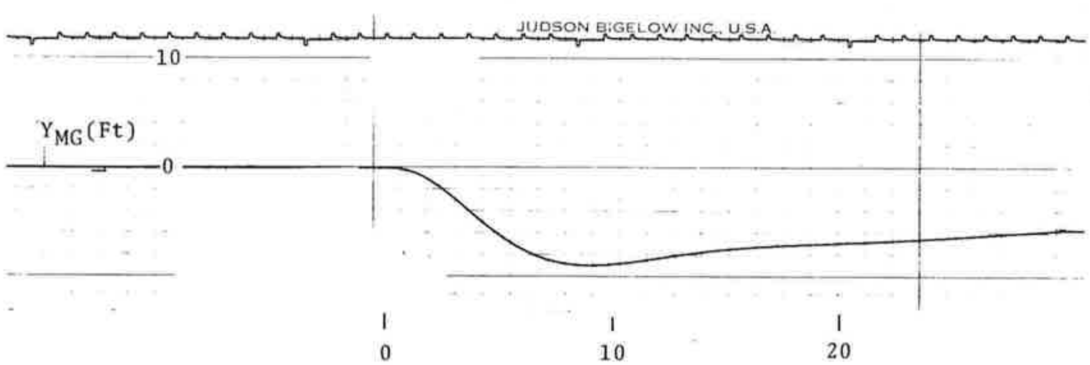
SIMULATION MODEL R_i = 6700 Ft, V_i = 236.5 Ft/Sec

Figure D-2 Main Gear Lateral Position Responses for an Initial Lateral Position of 65 ft.



TIME (SECONDS)

ANALYSIS MODEL R = 9100 Ft. V = 236.5 Ft/Sec



TIME (SECONDS)

SIMULATION MODEL Ri = 9100 Ft. V_i = 236.5 Ft/Sec

Figure D-3 Main Gear Lateral Position Responses for a Step Localizer Input of 5 Microamperes (.067 deg. or 11.6 ft. at R = 9100 ft.)

APPENDIX E

DERIVATION OF A LOCALIZER SIGNAL SPECIFICATION FOR SINUSOIDAL DISTURBANCES

This section derives a specification for sinusoidal localizer disturbances during ground rollout. Figure E-1 shows the rollout guidance system frequency response of the main gear lateral position with inputs from the localizer disturbance channel. The frequency response indicates the steady state response characteristics of the system when the input (in this case, the localizer disturbance) is a sine wave. The response is flat at low frequencies, attenuated at high frequencies and has no predominant exciting frequency. Hence, low frequency or bias disturbances produce the largest excursions from the runway centerline.

Since the performance criterion is defined in terms of the maximum lateral excursion, it is apparent that larger amplitude sine wave disturbances can be tolerated when the frequency of the disturbance is large. In fact (for a specified maximum lateral excursion) the maximum amplitude of the sine wave disturbance can be determined exactly from the attenuation factor of the frequency response. A specification can be developed accordingly as a function of the frequency of the disturbance.

The performance criterion of Section 5.0 requires that the maximum lateral excursion be less than 12 ft. With no attenuation effect (e.g. low frequency disturbance) the maximum permissable disturbance amplitude must be less than 5 microamperes. (This is based on the FAA standard localizer sensitivity of .43 microamperes/ft. at the runway threshold). With an attenuation factor of 2 (i.e. for a disturbance frequency of .56 rad/sec) the maximum permissable disturbance amplitude must be less than 10 microamperes. The complete localizer signal specification for sinusoidal disturbances is shown in Figure E-2 as a function of the frequency of the disturbance.

This specification was actually developed for a constant parameter rollout guidance system (i.e. R = 9100 ft. and V = 236.5 ft/sec). However, the specification was verified for the simulation model with the nominal localizer signal gain and for a disturbance

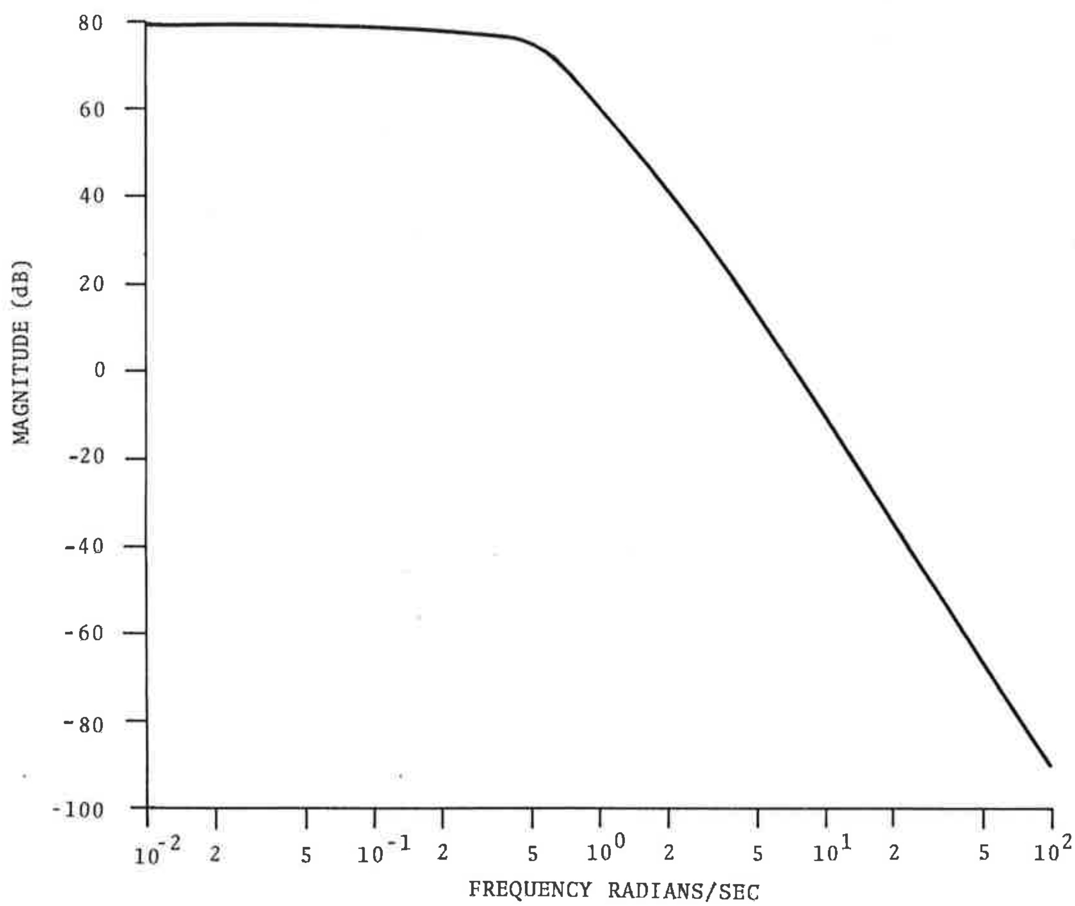


Figure E-1 Rollout Guidance System Frequency Response, R = 9100 ft., V = 236.5 ft./sec frequency of 1 rad/sec. These results are shown in Figures E-3 and E-4. Figure E-2 shows that the maximum permissable disturbance amplitude for a disturbance frequency of 1 rad/sec is 40 microamperes. As expected, this results in a maximum lateral position error of 12 ft (i.e. the performance criterion limit) when the aircraft lands at R_i = 9100 ft. The lateral position error slightly exceeds the performance criterion limit when the aircraft lands at R_i = 6700 ft. This is also expected due to the decreased damping effect of the rollout guidance system and does not invalidate the specification because the rollout guidance system at R_i = 6700 ft. is not as representative as one with a reduced localizer signal gain which would tend to reduce the lateral excursions. This is discussed further in Appendix C.

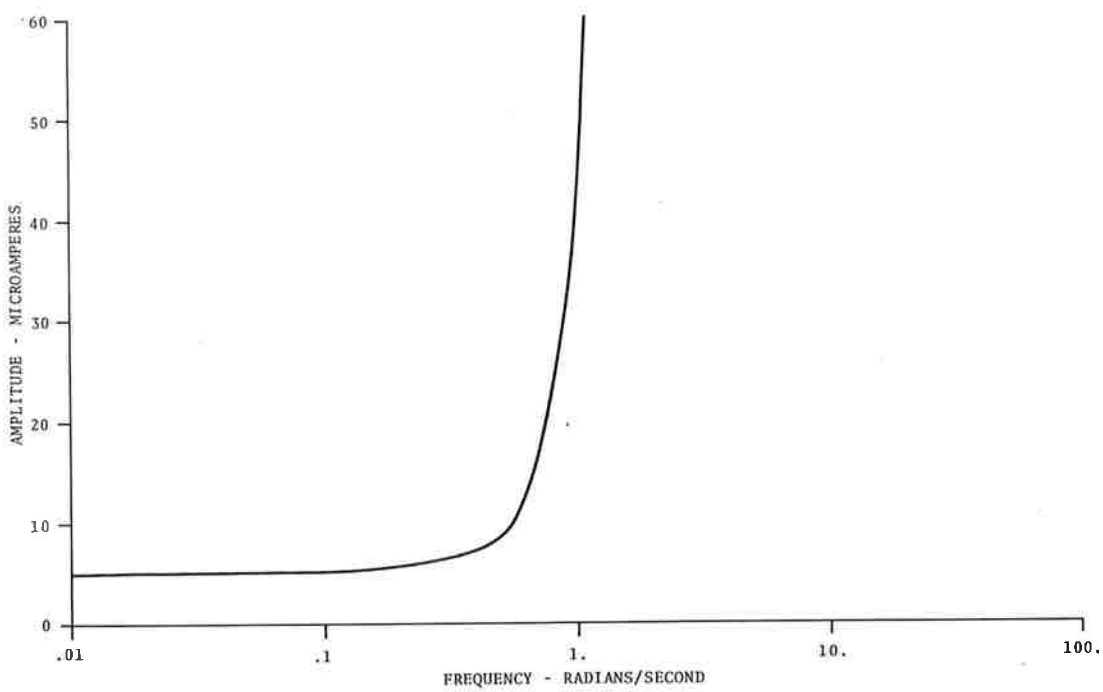


Figure E-2 Localizer Signal Specification for Sinusoidal Disturbances

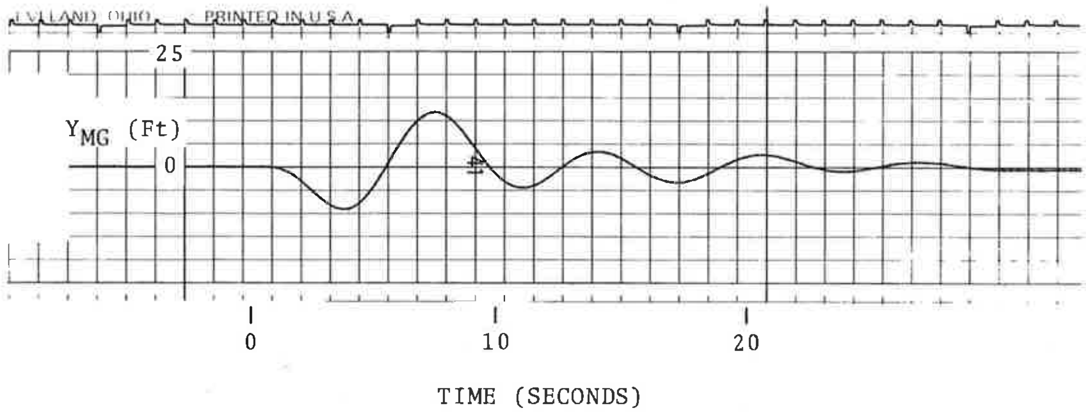


Figure E-3 Main Gear Lateral Response to Sinusoidal Localizer Disturbance with Amplitude of 40 microamperes and frequency of 1 radian/second (R_i = 9100 ft., V_i = 236.5 ft./sec)

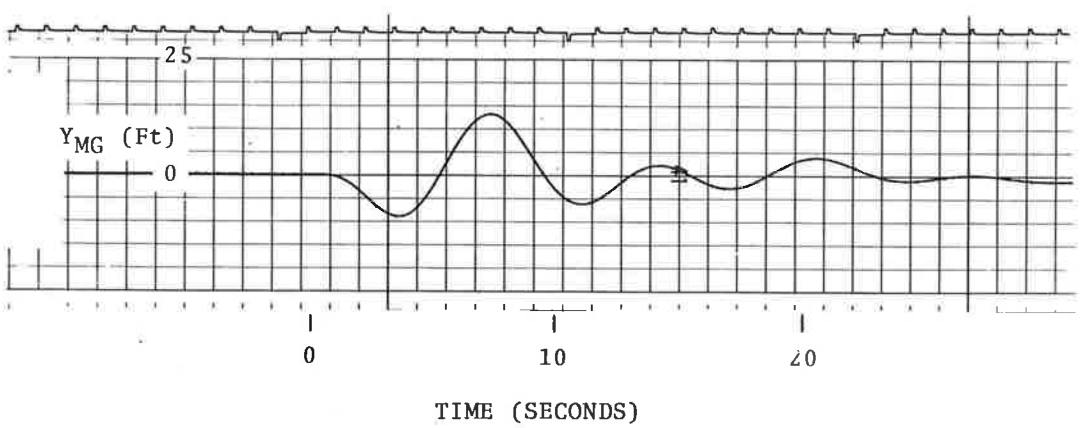


Figure E-4 Main Gear Lateral Response to Sinusoidal Localizer Disturbance with Amplitude of 40 microamperes and frequency of 1 radian/second (R_i = 6700 ft., V_i = 236.5 ft./sec)

APPENDIX F
DERIVATION OF A LOCALIZER SIGNAL SPECIFICATION FOR DISTURBANCES CHARACTERIZED BY WHITE NOISE PASSED THROUGH A FIRST ORDER FILTER

This section derives a specification for localizer disturbances during ground rollout that can be characterized by white noise passed through a first order filter. The specification is based on satisfying the performance criterion outlined in Section 5.0.

A statistical analysis was performed with the rollout guidance system (neglecting the receiver dynamics) to determine the root mean square RMS value of the main gear lateral position as a function of the RMS of the localizer disturbance and the noise filter break frequency. Figure F-1 presents the results in terms of the RMS ratio as a function of the noise filter break frequency. These results were determined using power spectral density methods and tabulated integrals.

It is obvious from Figure F-1 that the disturbance power concentrated at low frequencies has the dominant effect on the main gear lateral excursions. The RMS ratio is maximum and flat for small noise filter bandwidths because the rollout guidance system frequency response is also flat at low frequencies (see Appendix E) and all the localizer disturbance power is therefore uniformly passed through the system. The RMS ratio decreases with noise filter bandwidth because the localizer disturbance power becomes distributed over higher frequencies compared to the system bandwidth and the system thus effectively filters out the higher frequency power.

The effective bandwidth of the lateral position response is governed by the localizer disturbance bandwidth when the localizer disturbance bandwidth is small, and limited by the system bandwidth when the localizer disturbance bandwidth is large.

When the localizer disturbance break frequency and RMS level are .01 radian/second and 5 microamperes respectively the predicted RMS value of the main gear lateral position is 11.5 ft. If the

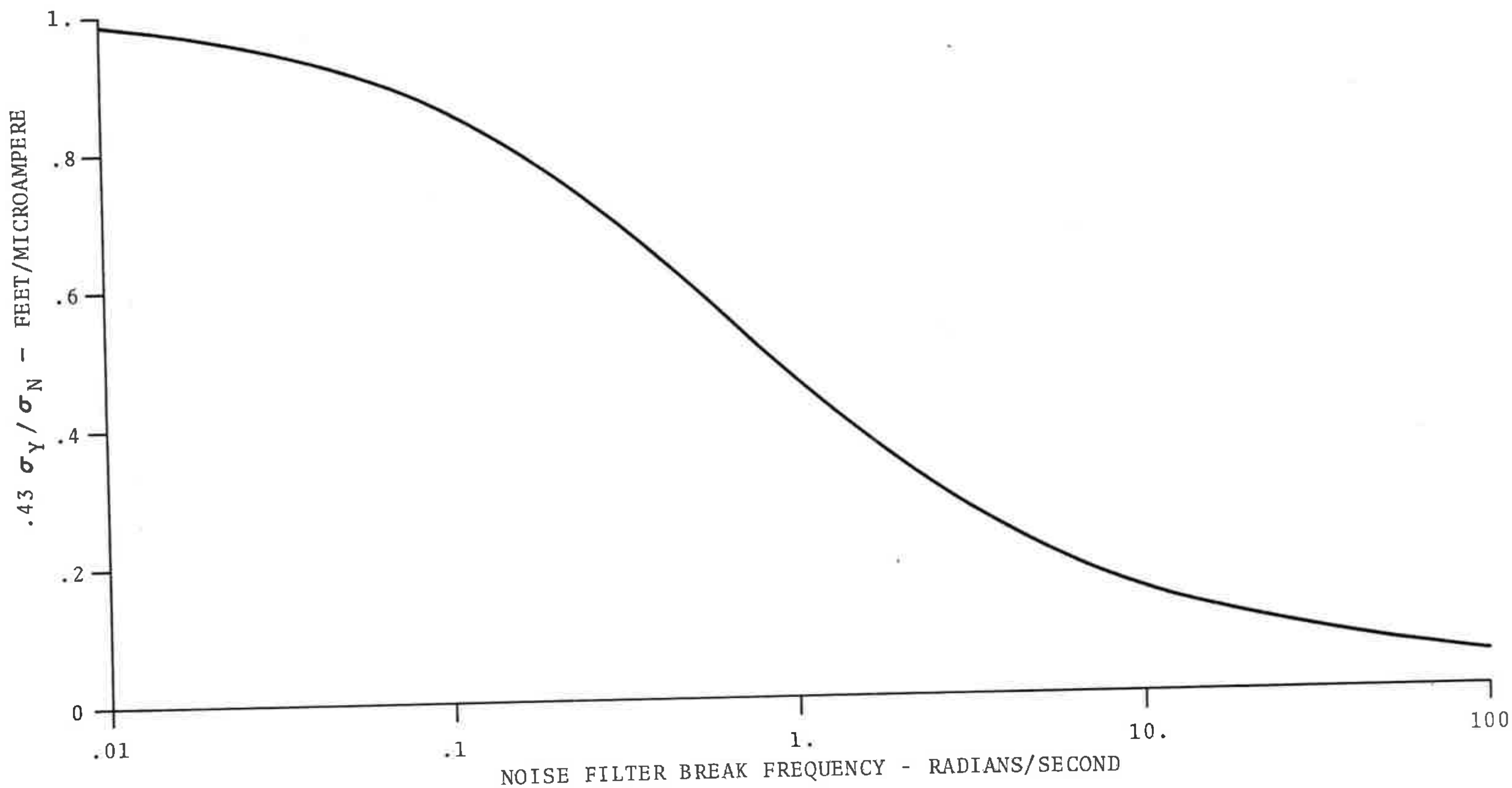


Figure F-1 RMS Ratio of Main Gear Lateral Position to Localizer Disturbance

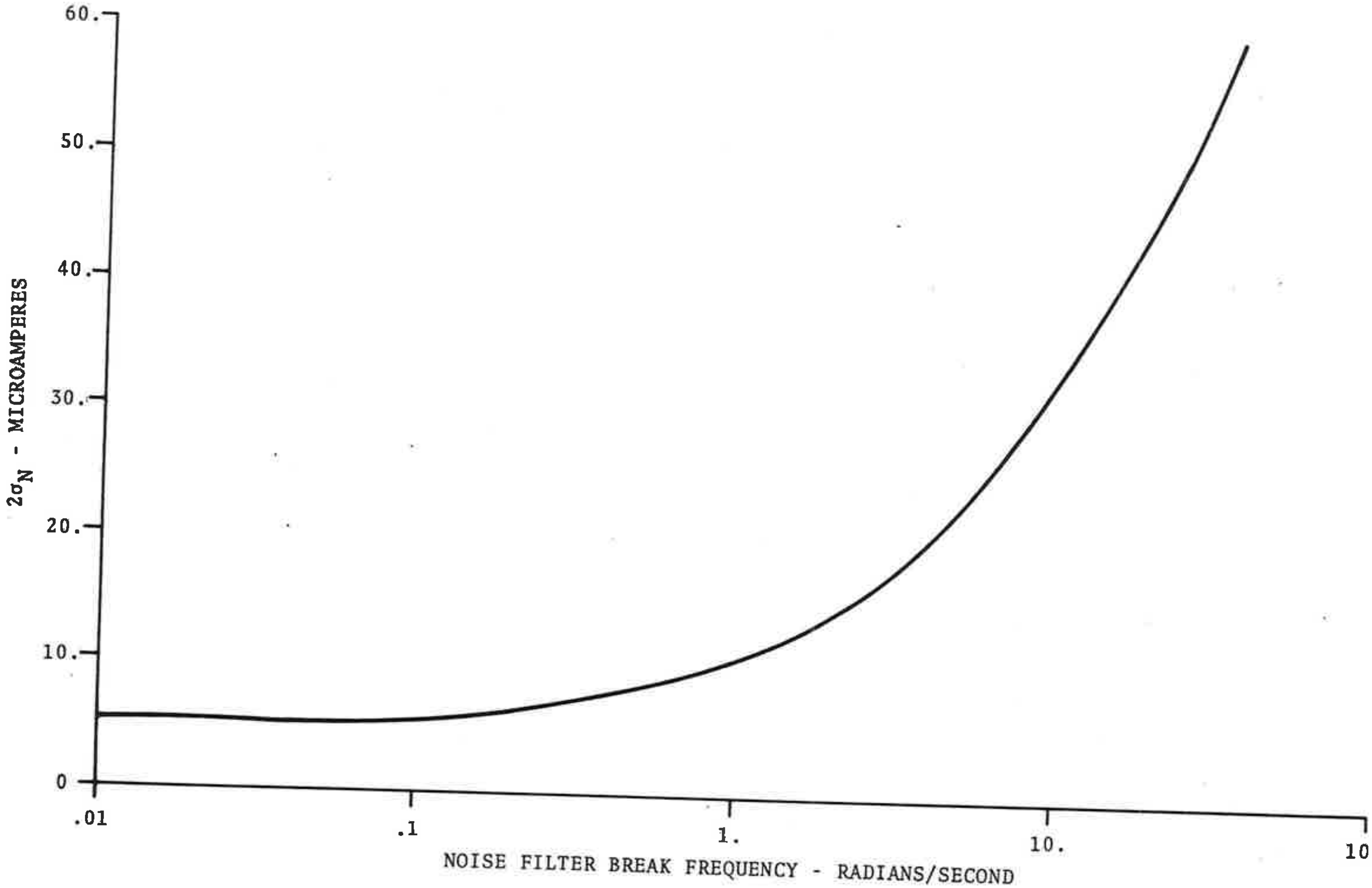


Figure F-2 Localizer Signal Specification for Disturbances Characterized by White Noise Passed through a First Order Filter localizer disturbance break frequency were .8 radian/second, the rollout guidance system could tolerate a localizer disturbance of 10 microamperes RMS, and still maintain the main gear lateral position within an RMS level of 12 ft. Since the performance criterion requires that the maximum lateral excursion be less than 12 ft. on a 95% probability basis, the maximum localizer disturbance can be determined from Figure F-1 on a 95% probability basis as a function of the noise filter break frequency. The resulting curve, shown in Figure F-2, is the localizer signal specification for disturbances characterized by white noise passed through a first order filter. For low noise filter bandwidths, the results approach the current ICAO specification. However, for larger noise filter bandwidths the resulting specification is significantly relaxed compared to the current specification. Again this is accounted for by the attenuating effect of the rollout guidance system.

The specification was actually developed for a constant parameter rollout guidance system (i.e. R = 9100 ft., V = 236.5 ft./sec, K_N = 30 rad/rad). However, the specification was qualitatively verified for the simulation model for noise filter break frequencies of 1 radian/sec and 3 radians/sec. These results are shown in Figures F-3 thru F-10. Note that the lateral response remains within the performance criterion even when the aircraft lands well down the runway (i.e. R_i = 6700 ft.). This is shown in Figure F-3 for a noise filter break frequency of 1 radian/sec. The decreased damping effect of the rollout guidance system for this particular case did not significantly alter the main gear lateral response.

That the lateral response did not exceed the 12 ft. criterion in any of the above cases may be explained by the fact that the receiver dynamics was not included in the derivation of the localizer signal specification which makes the derived specification somewhat conservative.

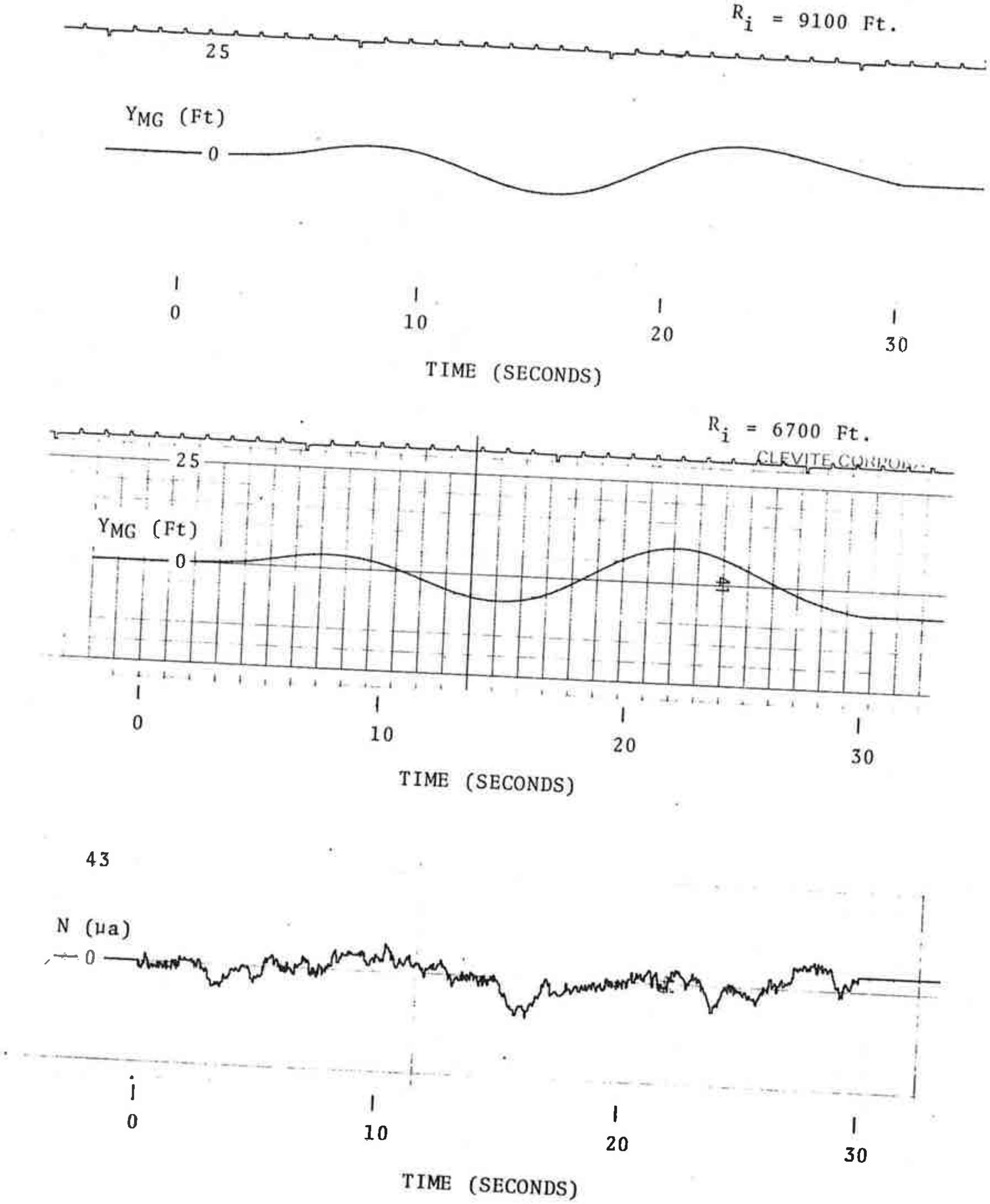
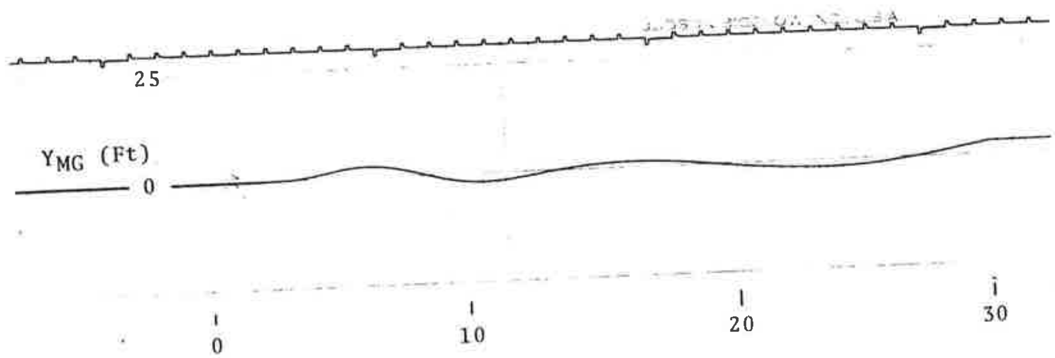


Figure F-3 Main Gear Lateral Response to White Noise passed through a First Order Filter with a break frequency of 1 radian/second, $2\ \sigma_N$ = 10.5 microamperes, V_i = 236.5 ft./sec



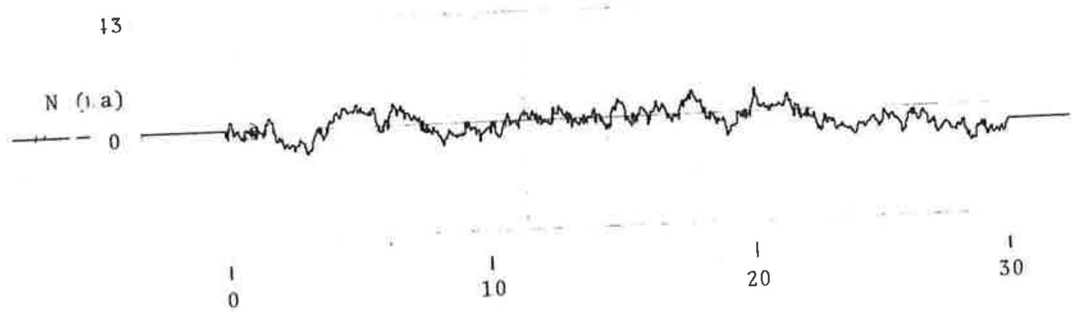
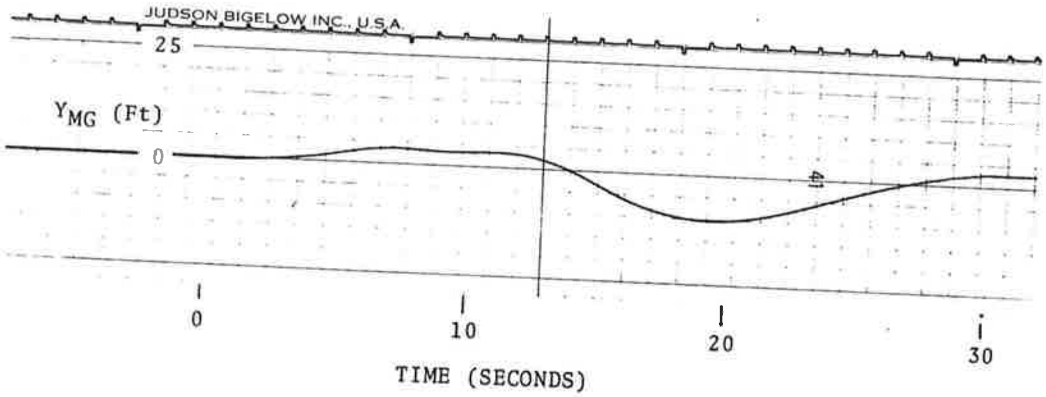


Figure F-4 Main Gear Lateral Response to White Noise passed through a First Order Filter with break frequency of 1 radian/second, 2 σ_N = 9.8 microamperes R_i = 9100 ft., V_i = 236.5 ft./sec



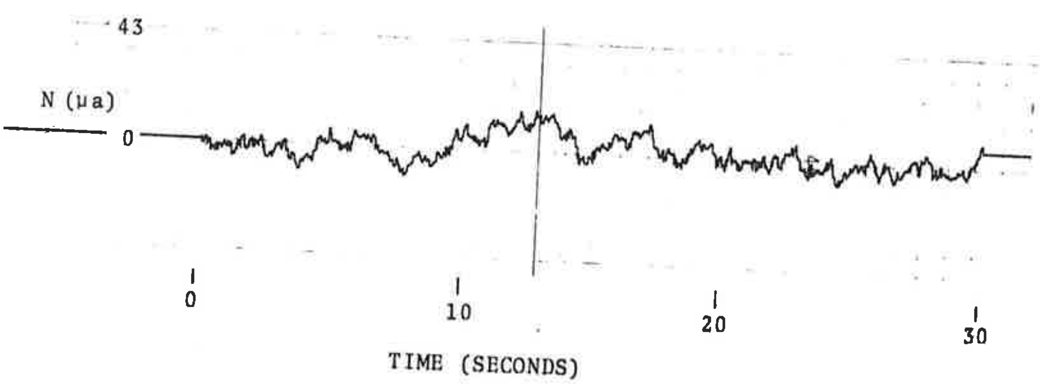
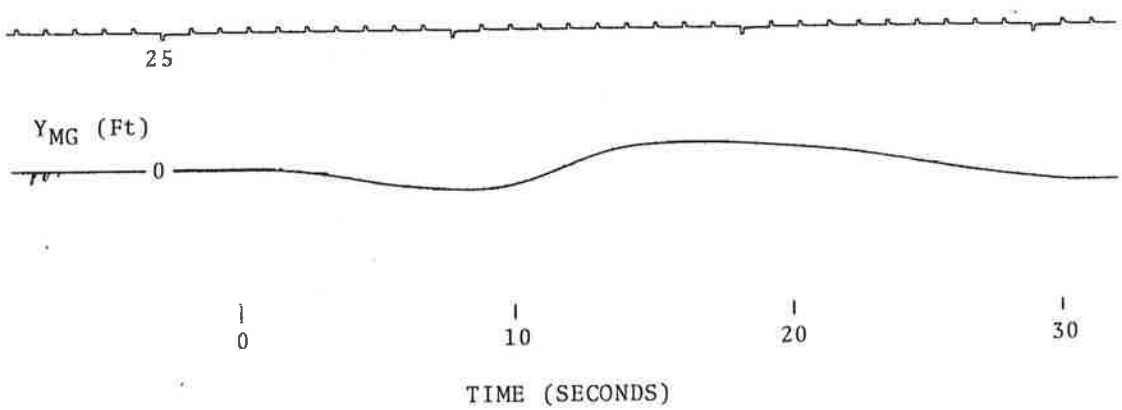


Figure F-5 Main Gear Lateral Response to White Noise passed through a First Order Filter with break frequency of 1 radian/second, 2 σ_N = 10.6 microamperes, R_i = 9100 ft., V_i = 236.5 ft./sec



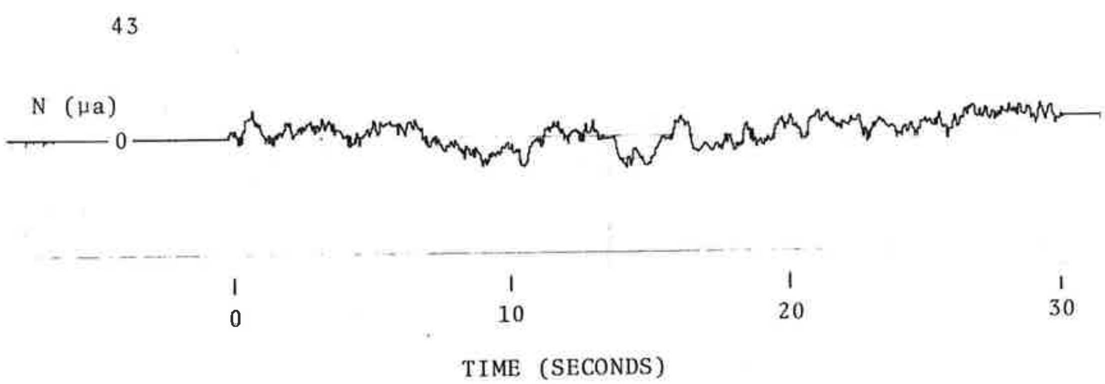


Figure F-6 Main Gear Lateral Response to White Noise passed through a First Order Filter with break frequency of 1 radian/second, 2 σ_N = 9.7 microamperes, R_i = 9100 ft., V_i = 236.5 ft./sec

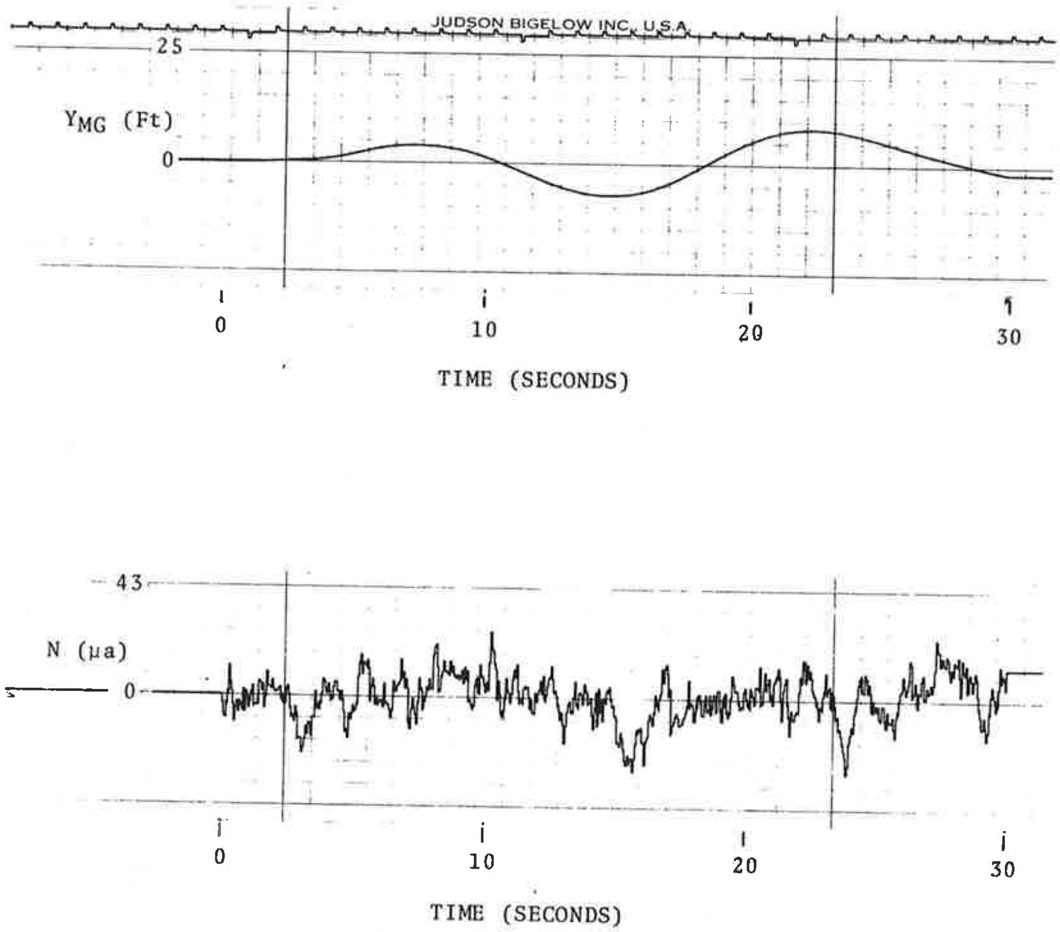
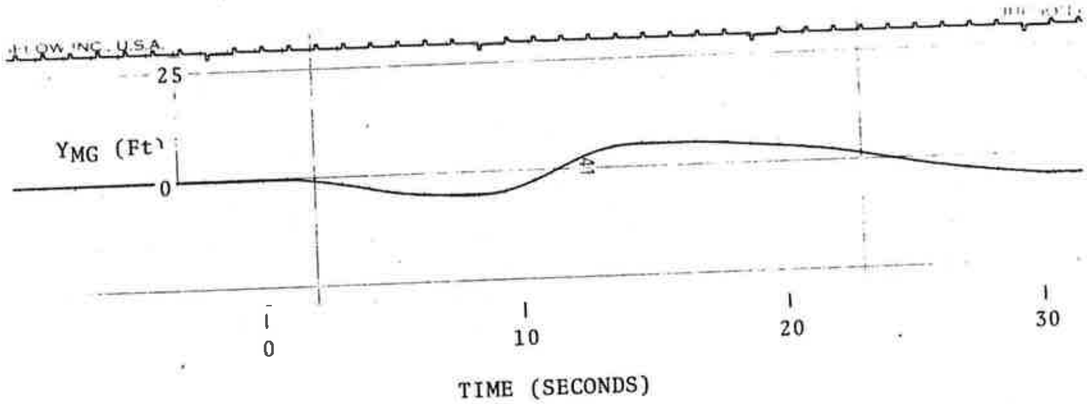


Figure F-7 Main Gear Lateral Response to White Noise passed through a First Order Filter with break frequency of 3 radians/second, 2 σ_N = 18.1 microamperes, R_i = 9100 ft., V_i = 236.5 ft./sec



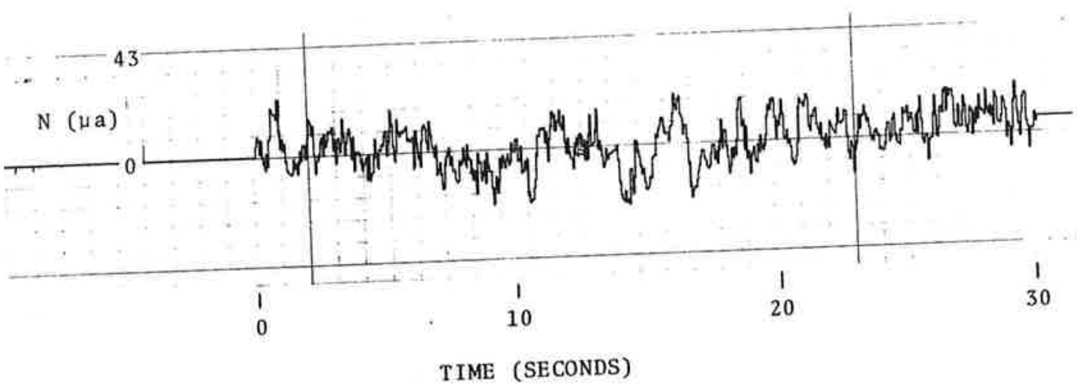
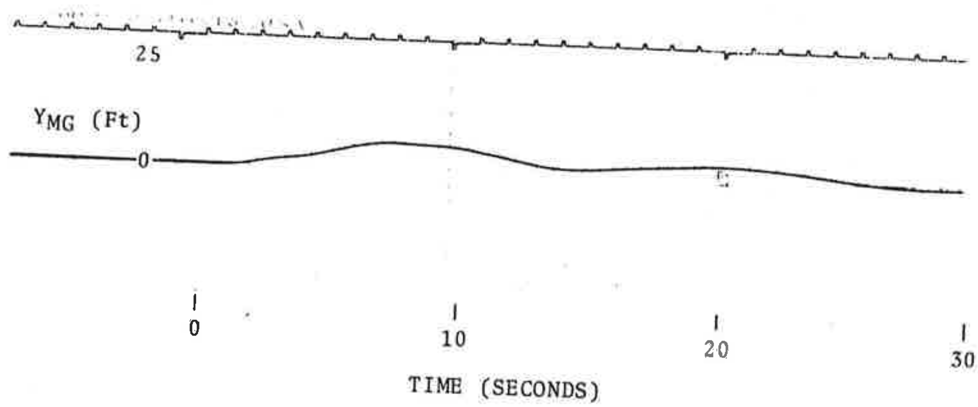


Figure F-8 Main Gear Lateral Response to White Noise passed through a First Order Filter with break frequency of 3 radians/second 2 σ_N = 17.3 microamperes, R_i = 9100 ft., V_i = 236.5 ft./sec



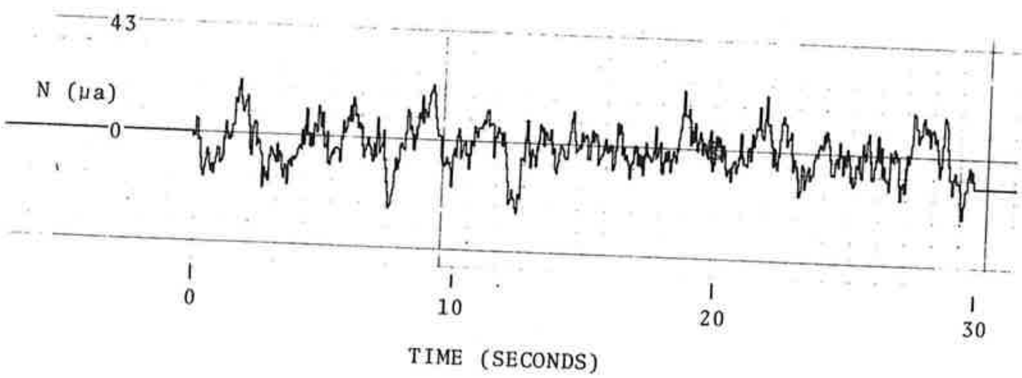


Figure F-9 Main Gear Lateral Response to White Noise passed through a First Order Filter with break frequency of 3 radians/second, 2 σ_N = 17.7 microamperes; R_i = 9100 ft. V_i = 236.5 ft./sec

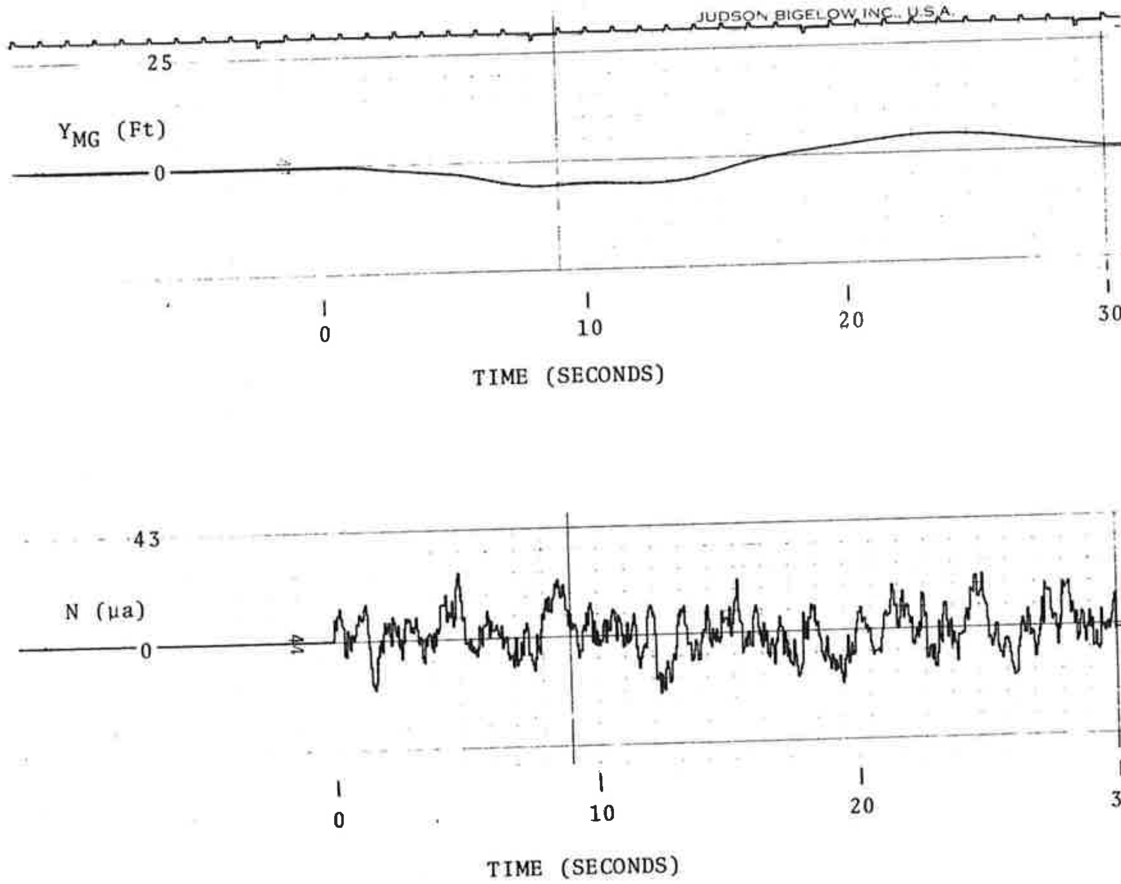


Figure F-10 Main Gear Lateral Response to White Noise passed through a First Order Filter with break frequency of 3 radians/second, 2 σ_N = 17.9 microamperes, R_i = 9100 ft., V_i = 236.5 ft./sec

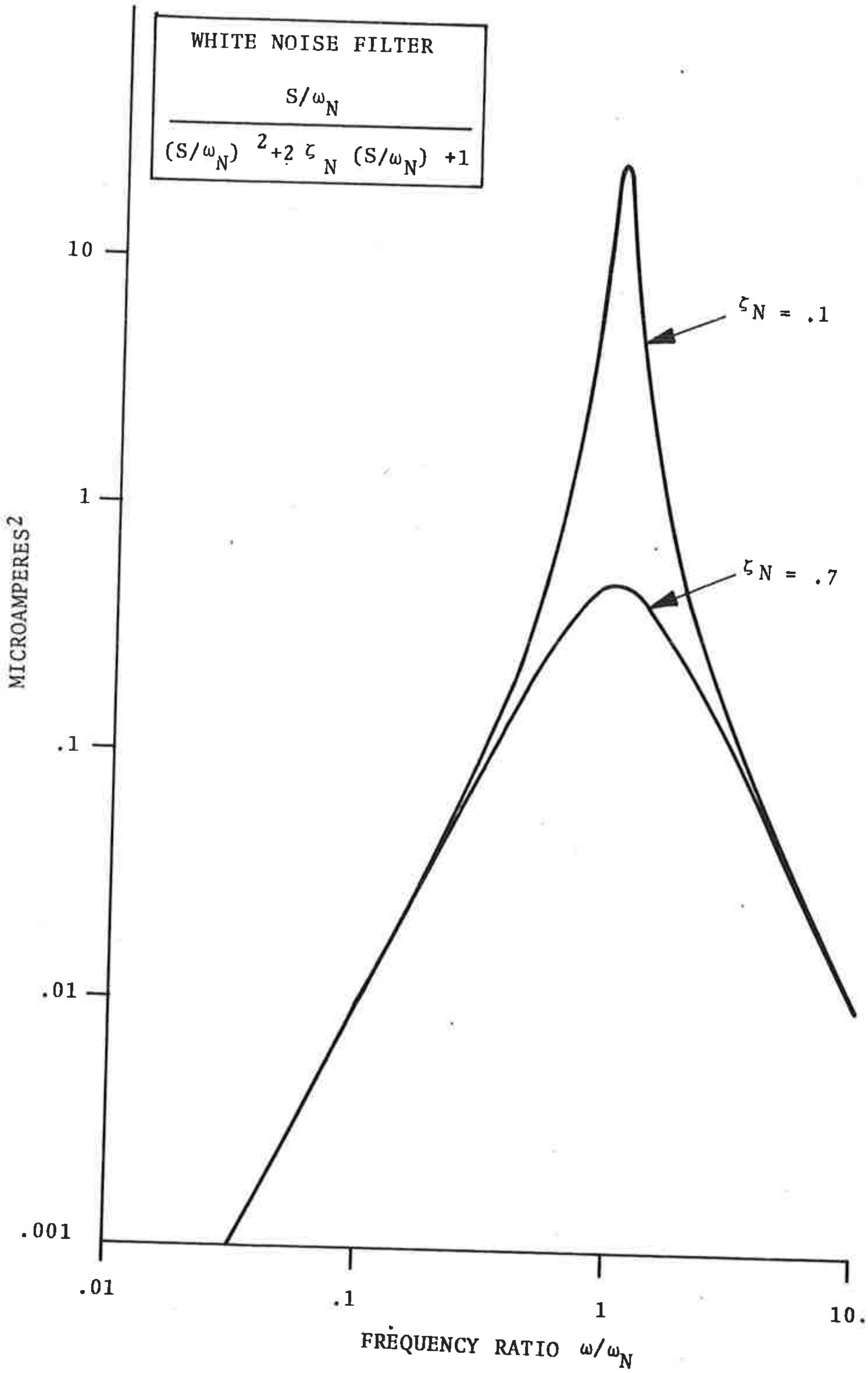


Figure G-1 Power Spectral Density Curves for Unity White Noise Power Input

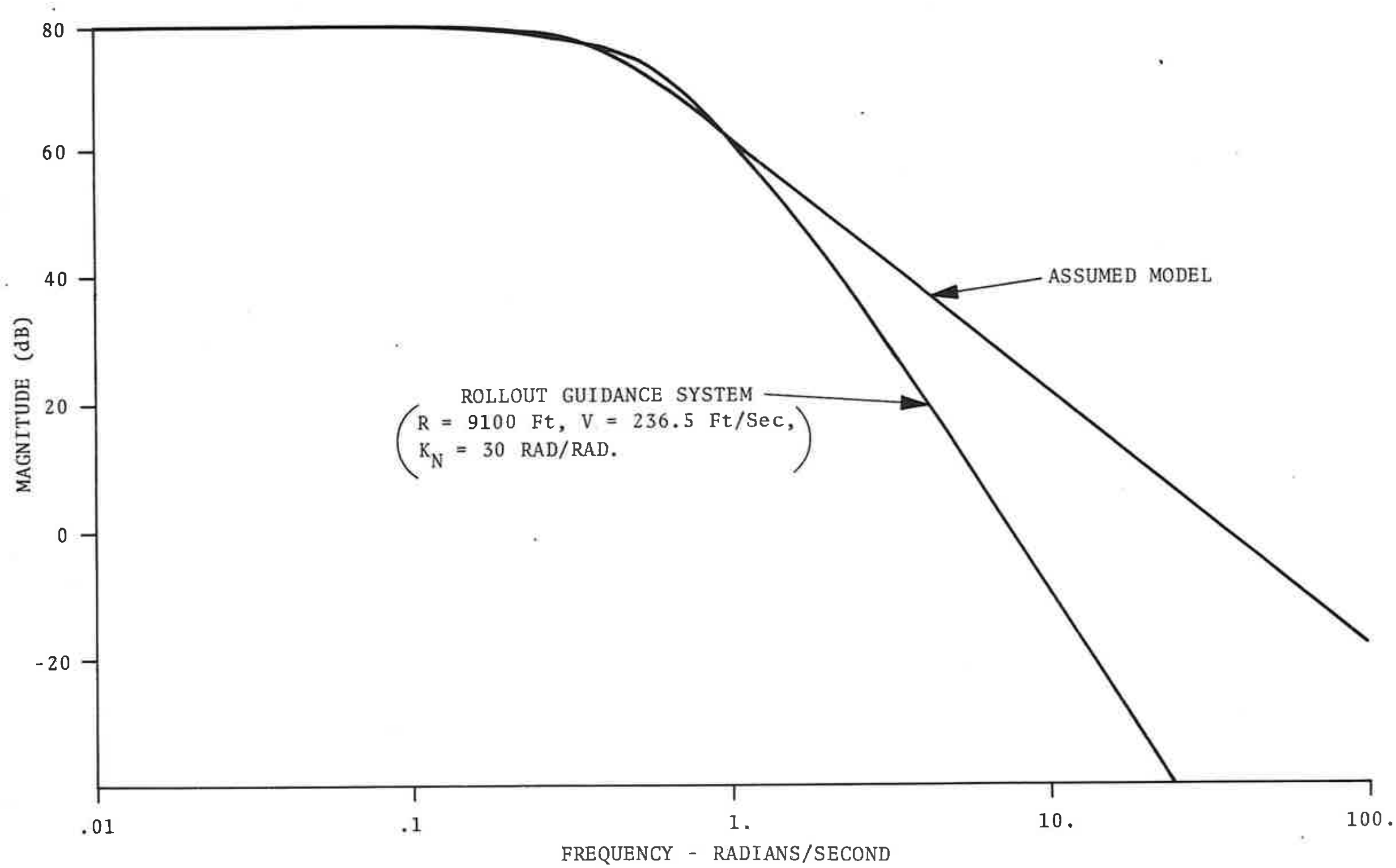


Figure G-2 Comparison of Frequency Responses

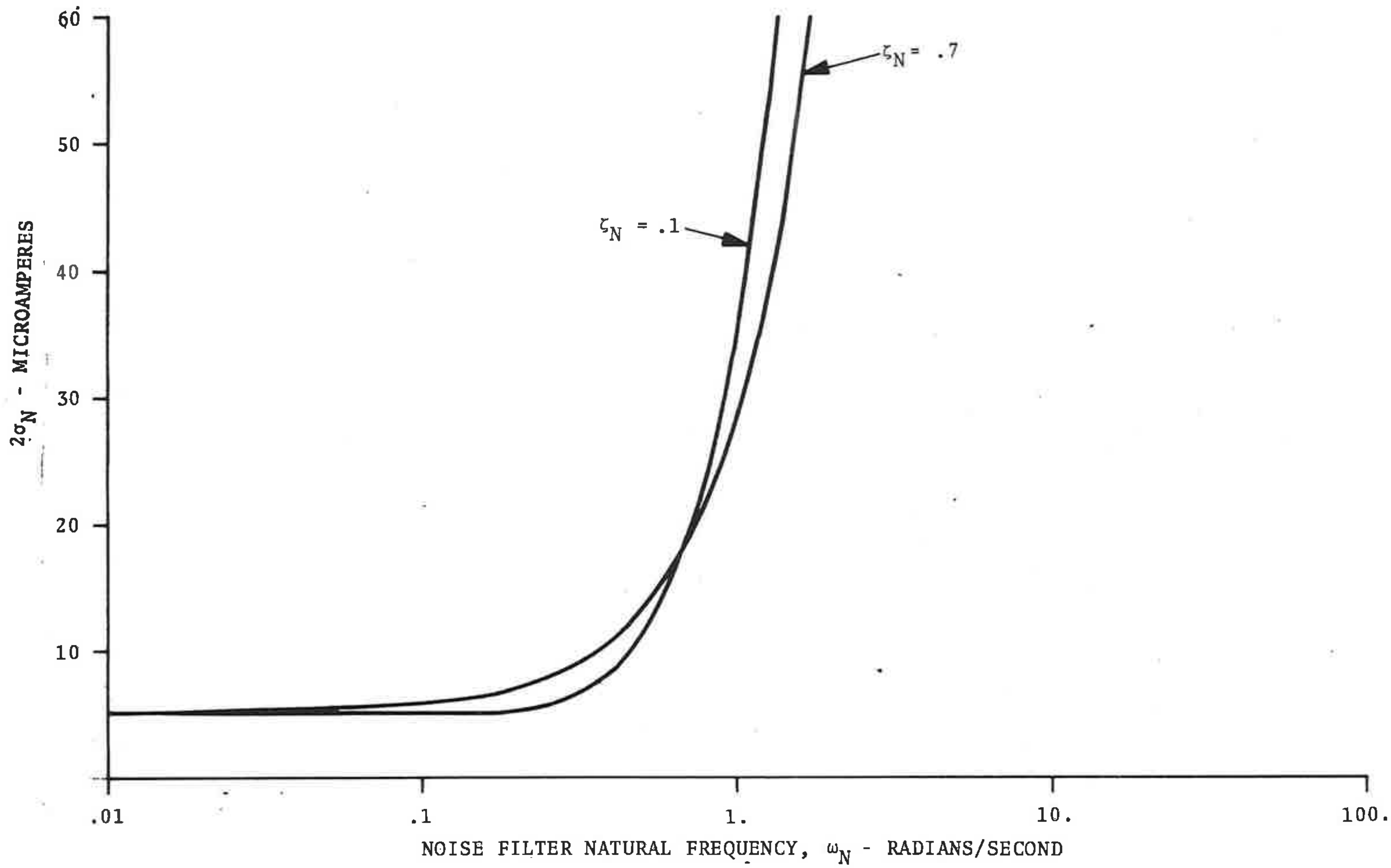


Figure G-3 Localizer Signal Specification for Disturbances Characterized by White Noise Passed through a Second Order Filter with Low Frequency Washout

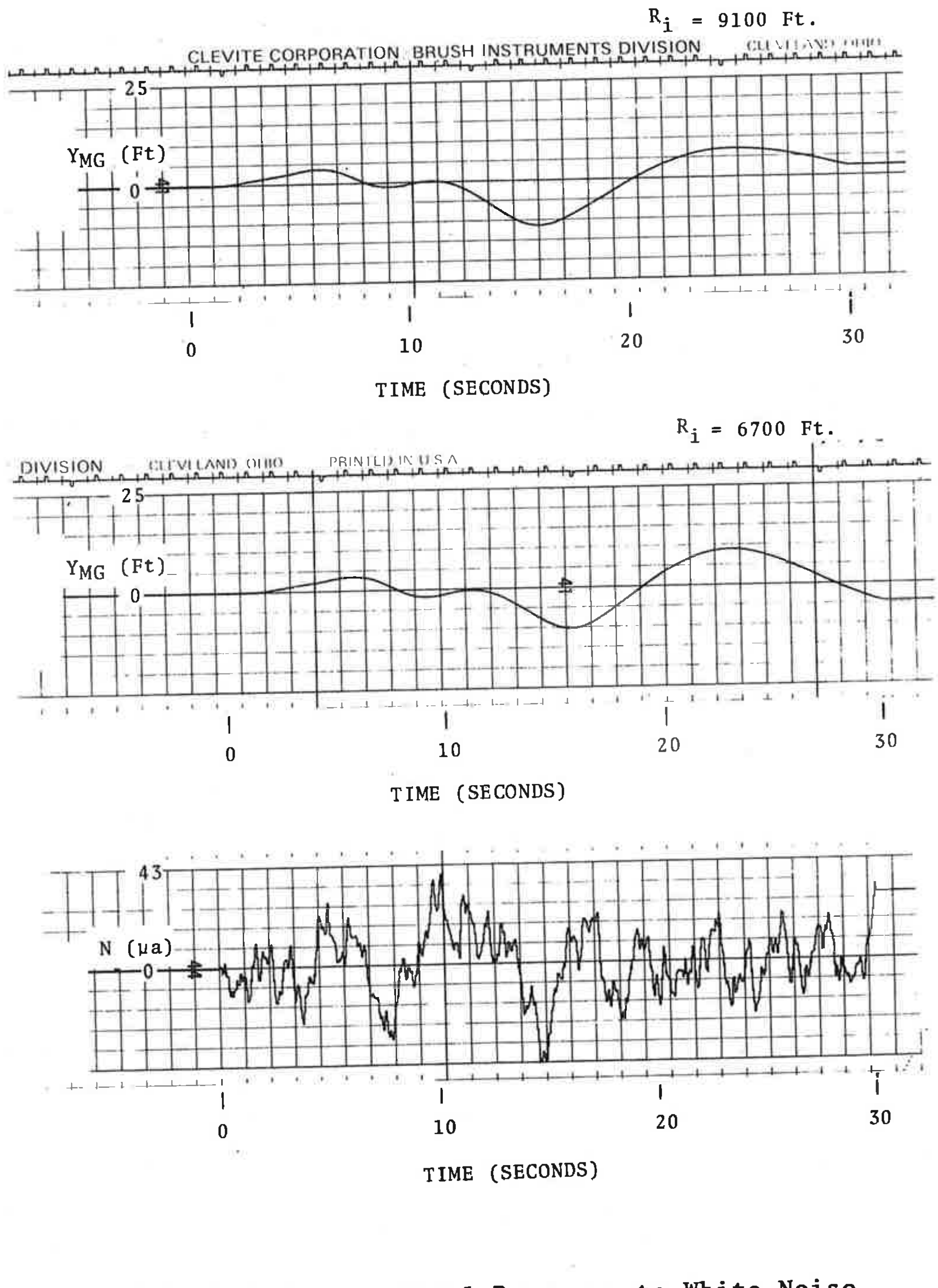


Figure G-4 Main Gear Lateral Response to White Noise passed through a Second Order Filter with Low Frequency Washout $2\ \sigma_N$ = 28 microamperes, ω_N = 1 radian/second, ζ_N = .7, V_i = 236.5 ft./sec characteristics over this runway increment are unacceptable.

Case B Consider the same case as above except that the measurement was taken over a runway increment near the localizer transmitter, where a relaxation factor of four can be applied. The maximum allowance bend amplitude (two standard deviation) from Figure 9-1 is now 40 microamperes. The allowable RMS value is therefore 20 microamperes and the signal characteristics over this runway increment are acceptable.

Case C The localizer signal near the runway threshold is a sine wave with a frequency of one radian per second and an amplitude of 25 microamperes (50 microamperes peak to peak). The maximum allowance bend amplitude from Figure 9-1 is about 40 microamperes. The signal characteristics near the runway threshold are therefore acceptable.

For a given localizer signal, it is also possible to determine the minimum aircraft speed at each runway increment, that will satisfy the appropriate localizer signal specification. The procedure for determining the minimum aircraft speed is essentially the same as that outlined above for determining the acceptability of a localizer signal. The measured localizer signal is simply processed at different tape speeds (representing different aircraft landing speeds) and studied separately until the appropriate specification is satisfied. The specification is then assured for any higher landing speeds because higher landing speeds widen the localizer signal spectrum, thereby relaxing the specification requirement while the measured localizer signal RMS value remains unchanged.

Since actual localizer signals cannot be precisely represented by white noise passed through a first order filter or second order filter with low frequency washout, a technique for applying the specification to each runway increment is developed below. The amplitude specification of Figure 8-1 was first transformed into power spectral density requirements and is shown in

Figures H-2 and H-3. These power spectral density requirements or boundaries were derived from the maximum allowance bend amplitude specification and the power spectral density profiles for white noise passed through a first order filter and white noise passed through a second order filter with low frequency washout. The boundaries are higher in the low frequency regime because of the density effect (i.e., a constant amplitude specification transforms into an increasing density requirement for narrower frequency bounds). The boundaries in the high frequency regime of Figure H-2 essentially approach a constant level because the density effect is offset by the increasing amplitude specification. The boundaries in the high frequency regime of Figure H-3 are higher because the increasing amplitude specification predominates over the density effect.

Application of the specification now requires only a simple power spectral density measurement of the localizer distrubance signal. Classification of the signal is not required. The localizer signal is acceptable if its power spectral density is contained within any single one of the power spectral density boundaries. For example, consider the three power spectral densities of different localizer signals shown in Figure H-4. (Figure H-4 is a reproduction of H-2 with three examples of localizer power spectral density measurements added for this explanation.) Assume the signals were measured over a runway increment near the runway threshold. Since power spectral densities A and C are contained within specific power spectral density boundaries the localizer signals associated with these densities are acceptable. Power spectral density B, however, is not contained within any single one of the power spectral density boundaries and the localizer signal associated with this density is unacceptable. The closer the measured power spectral density is to any of the power spectral density boundaries, the closer the localizer signal is to a signal for which the amplitude specification was derived (i.e., white noise passed through a first order filter or second order filter with low frequency washout). Thus, containment within any single boundary assures conservative results. On the other hand, a power

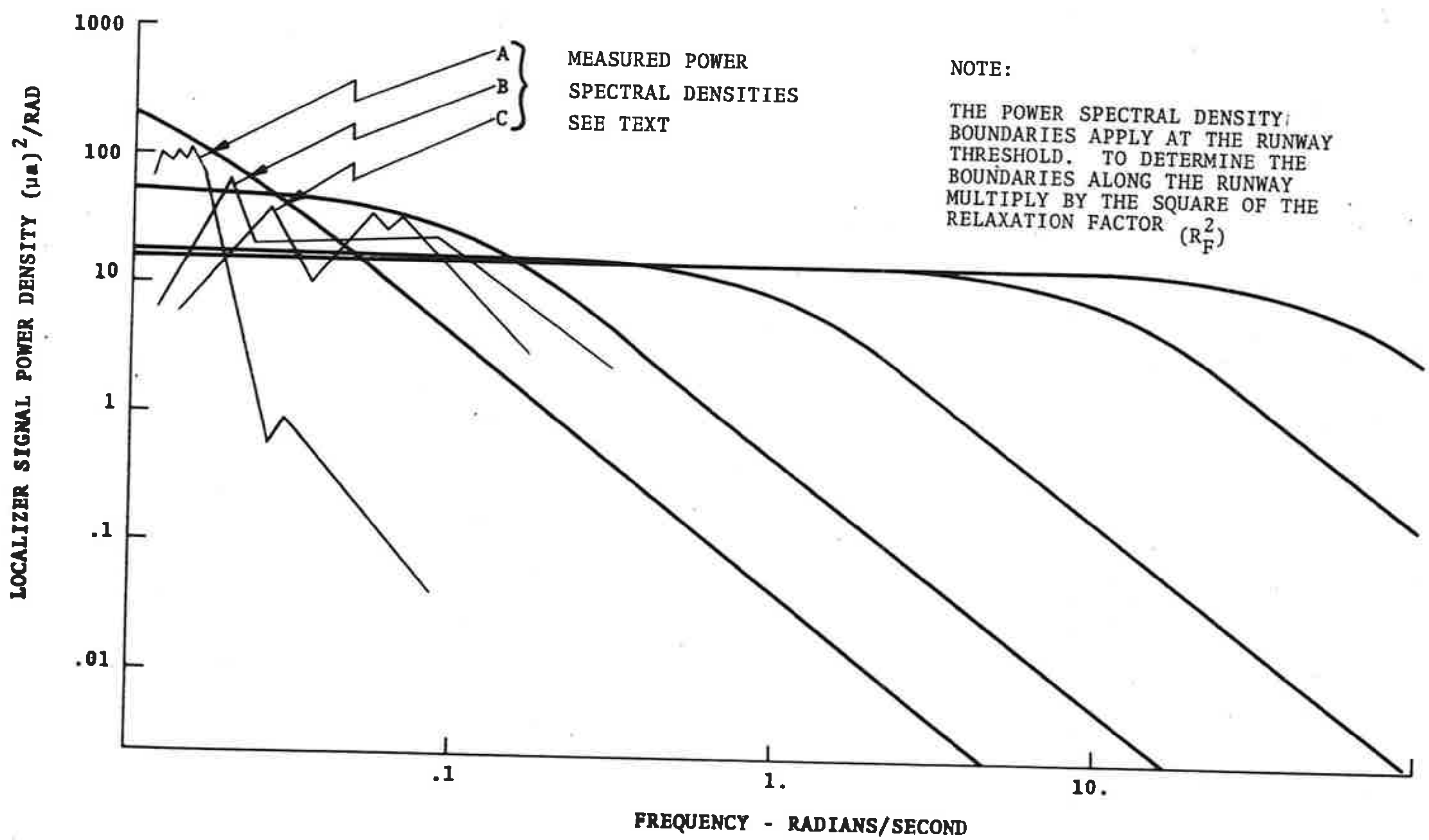


Figure H-4. Measured Power Spectral Densities

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