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West Lafayette, Indiana 47907

MEMO: Informal
Subject: Analysis of NLR Configurations Using OCM for Pilot Modeling
From: M.H. Drajeske
To: D.K. Schmidt

INTRODUCTION

The purpose of this memo is to present a summary of the results obtained from an analytic handling qualities analysis of the rate-command/attitude-hold aircraft configurations originally presented in an NLR report by Mooij[1]. Pilot/vehicle performance is evaluated using an optimal control technique for pilot modeling. Numerical and graphical results for a closed-loop frequency-domain analysis are presented and discussed and comparisons with experimental results are made. Finally, the results from this study are compared with those from another study that dealt with similar configurations[2].

NLR CONFIGURATIONS

The aircraft configurations studied by Mooij were variations of a medium-weight, twin-engine jet transport (a modified Foker F28/Mk6000) with a rate-command/attitude-hold control system for both pitch and roll. Two aircraft and a total of 12 configurations were studied. The theta-to-stick and gamma-to-stick transfer functions for the 12 configurations are presented in Appendix I. As shown in Table 1, the 12 configurations constitute three groups: E,F and G. Further details concerning the aircraft configurations and control system implementation are contained in Chapter 7 of [1].

Parameter varied	Configu-ration	n_α (g/rad)	Equivalent transfer function parameters: ω_q (rad/s)	ζ_q	τ_q (s)	T_q (s)	ME
short-period frequency	E-1	↑	0.68	0.78	1.72	↑	↑
	E-2		0.75	0.74	1.67		
	E-3	4.71	0.94	0.66	1.37	0.07	0
	E-4		1.12	0.63	1.15		
	E-5*	↓	1.31	0.62	0.96	↓	↓
numerator time constant	E-5*	↑	1.31	0.62	0.96	↑	↑
	F-3	4.71	1.27	0.61	1.45	0.07	0
	F-2		1.24	0.62	2.56		
	F-1	↓	1.23	0.63	5.26	↓	↓
manoeuvre enhancement	G-1	↑	1.30	0.62	0.93	↑	0
	G-2	3.41	1.31	0.62	0.93	0.07	0.45
	G-3		1.32	0.62	0.92		0.70
	G-4	↓	1.33	0.62	0.92	↓	1.00

Table 1
NLR Configuration Sets

CRITICAL TASK MODELING

Two separate tasks were modeled in this analysis: (1) The precise control of attitude (i.e., attitude tracking) and (2) The precise control of flight path (i.e., flight-path tracking). The modeling of the attitude and flight-path tracking tasks are discussed in detail in [3] and [4] respectively. The multi-loop nature of the flight-path tracking task is reflected by the block diagram in Fig.1. The describing functions P_{γ_e},P_γ and P_θ in Fig.1 are estimated via the OCM. Using block diagram manipulation, one may reduce Fig.1 to Fig.2 and obtain the equivalent single-loop pilot describing function, P_{eq}.

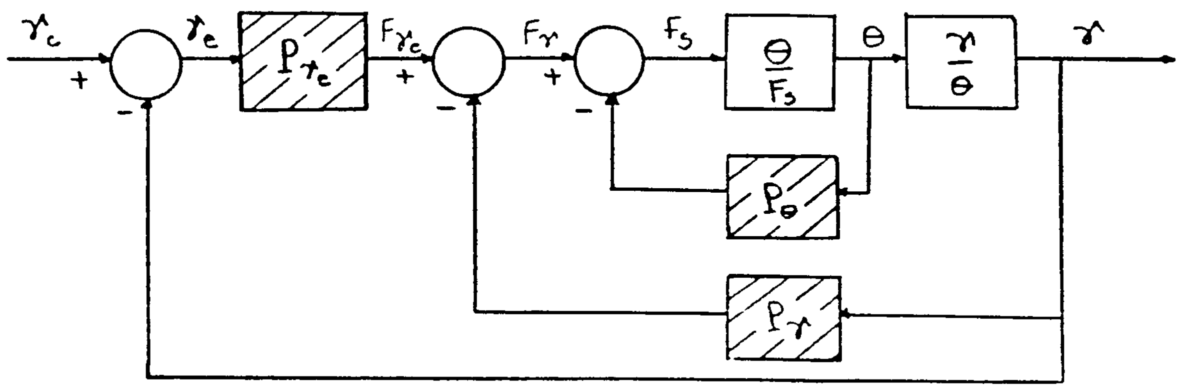


Figure 1 : Flight-Path Tracking Task

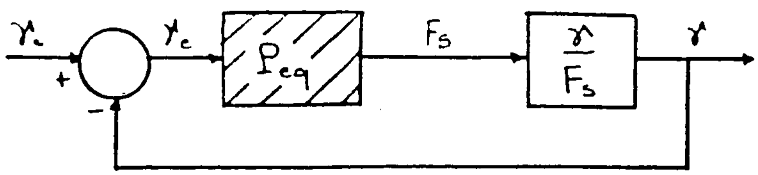


Figure 2 : Equivalent Flight-Path Tracking Task

Similarly, the nature of the precision attitude tracking task is reflected by the block diagram in Fig.3. In this case, P_{θ_e} and P_θ may be combined in order to find a single-loop equivalent pilot function as shown in Fig.4. The equations for the above manipulations are presented in Appendix II.

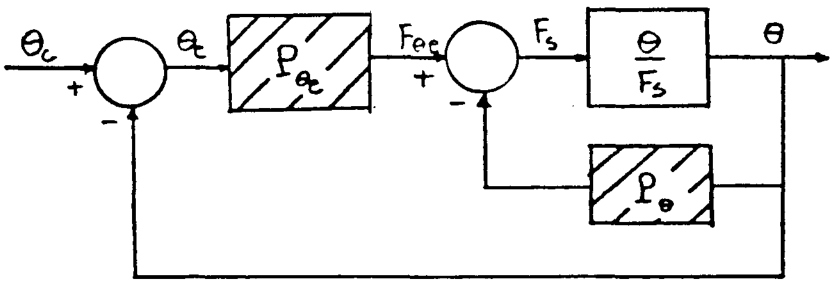


Figure 3 : Attitude Tracking Task

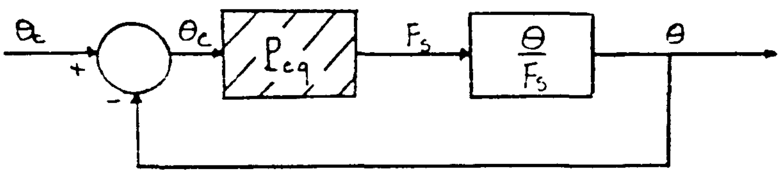


Figure 4 : Equivalent Attitude Tracking Task

PILOT MODELING USING AN OCM

The pilot-related parameters used in the OCM for the flight-path and the attitude tracking tasks are presented in Tables 2 and 4 respectively. The values selected for τ,the pilot's observation delay, and τ_N, the pilot's neuromuscular lag time constant, were chosen to represent the human operator in his most aggressive mode. This is done in order to expose handling qualities *cliffs* in the various configurations by modeling the pilot's most aggressive control techniques[4]. The rationale behind the selection of the other parameters is discussed in [3] and [4]. Sample input files for the local implementation of the OCM code (PIREP) are presented in Appendix III.

RESULTS

Presented in Appendix V are the graphical results of the frequency domain analysis of the flight-path and attitude tracking tasks. Included are representations of the pilot functions P_{γ_e},P_{θ_e},P_γ and P_θ as well as the equivalent single-loop pilot function P_{eq}. Open-loop and closed-loop Bode plots for all 12 configurations are also presented. Quantities such as crossover frequency, therefore, can be determined directly from these plots.

A number of key quantities (ref. fig.2 and 4) for both the flight-path and attitude tracking tasks are summarized in tables 3 and 5 respectively. The following definitions are used:

ω_c	crossover frequency - the frequency at which the magnitude of the open-loop pilot/vehicle system equals 0 dB
$\measuredangle P_{eq}\vert_{\omega_c}$	phase angle of the equivalent pilot function P_{eq} at the crossover frequency
$\measuredangle P_{eq}\vert_{lowfreq}$	phase angle of P_{eq} at lower frequencies
Bw	bandwidth - the frequency at which the closed-loop pilot/vehicle response has phase = -90 deg
$\measuredangle NS$	pilot phase compensation for the attitude tracking task adjusted to be comparable to a quantity discussed by Neal-Smith $\measuredangle NS = \measuredangle P_{eq}\vert_{Bw} + 57.3\,\tau\,Bw + \tan^{-1}(\tau_N\,Bw)$
$\left\vert \frac{\theta}{\theta_c} \right\vert_{max}$	maximum magnitude of the closed-loop pilot/vehicle response for the attitude tracking task
σ_{γ_e}	predicted rms gamma error
σ_{θ_e}	predicted rms theta error
$\sigma_{\dot{F}_s}$	predicted rms stick rate
TOTAL COST	value of OCM objective function

Table 2 : Pilot Model Parameters

Pilot Model Parameters - γ tracking	
Parameter	Value
Observation Vector	$\vec{y}_p^T = [\gamma_e , \dot{\gamma}_e , \gamma , \dot{\gamma} , \theta , \dot{\theta}]$
Objective Function Weights	$q_i = [1, 0, 0, 0, 0, 0]$ $r_{F_s} = 0$, $g_{\dot{F}_s}$ to yield τ_N
Observation Thresholds	$T_{\gamma_e}, T_\gamma, T_\theta = 0.05$ deg $T_{\dot{\gamma}_e}, T_{\dot{\gamma}}, T_{\dot{\theta}} = 0.18$ deg/sec
Observation Noise Ratio	-20 dB All Observed Variables
Fractional Attention	$f_i = 0.3333$ All Observed Variables
Observation Delay	$\tau = 0.2$ sec
Neuromuscular Lag	$\tau_N = 0.2$ sec
Motor Noise Variance	-25 dB
Control Input	F_s (Stick Force in lbs.)
Command Signal (n=white noise)	$\theta_c/n = .25/(s^2 + .5s + .25)$ $\gamma_c/\theta_c = .5/(s + .5)$

Table 3 : Performance Measures for Flight-Path Tracking Task

Config.	Pilot Rating (gnd/flt)	ω_c (rad/sec)	$\measuredangle P_{eq}\vert_{\omega_c}$ (deg)	$\measuredangle P_{eq}\vert_{low\ freq}$ (deg)	σ_{γ_e} (deg)	$\sigma_{\dot{F}_s}$ (lbs/sec)	Total Cost
E-1	8.00/ -	1.800	57.19	61.20	.4843	21.77	.3544
E-2	5.17/5.67	1.819	55.63	58.43	.4743	19.07	.3399
E-3	4.00/ -	1.858	53.31	55.16	.4562	15.18	.3140
E-4	3.00/ -	1.892	46.66	54.07	.4414	13.29	.2933
E-5	2.33/3.67	1.922	40.09	53.72	.4287	12.17	.2764
F-3	3.33/ -	1.967	36.06	50.07	.4099	9.43	.2528
F-2	4.33/ -	1.971	36.12	50.02	.4081	5.71	.2506
F-1	6.33/7.67	2.077	23.69	29.86	.3740	3.37	.2094
G-1	5.67/6.00	1.935	38.09	52.88	.3897	15.17	.2384
G-2	4.17/ -	2.342	-53.24	48.62	.3410	7.85	.1719
G-3	4.00/5.33	2.348	-59.71	45.53	.3455	5.02	.1707
G-4	3.00/ -	2.344	-61.07	43.20	.3502	3.84	.1740

Table 4 : Pilot Model Parameters

Pilot Model Parameters - θ tracking	
Parameter	Value
Observation Vector	$\vec{y}_p^T = [\theta_e, \dot{\theta}_e, \theta, \dot{\theta}]$
Objective Function Weights	$q_i = [1, 0, 0, 0]$ $r_{F_s} = 0$, $g_{\dot{F}_s}$ to yield τ_N
Observation Thresholds	$T_{\theta_e}, T_\theta = 0.05$ deg $T_{\dot{\theta}_e}, T_{\dot{\theta}} = 0.18$ deg/sec
Observation Noise Ratio	-20 dB All Observed Variables
Fractional Attention	$f_i = 0.5$ All Observed Variables
Observation Delay	$\tau = 0.2$ sec
Neuromuscular Lag	$\tau_N = 0.2$ sec
Motor Noise Variance	-25 dB
Control Input	F_s (Stick Force in lbs.)
Command Signal (n=white noise)	$\theta_c/n = .25/(s^2 + .5s + .25)$

Table 5 : Performance Measures for Attitude Tracking Task

Config.	ω_c (rad/sec)	$\measuredangle P_{eq}\vert_{\omega_c}$ (deg)	$\measuredangle NS$ (deg)	$\left\vert\frac{\theta}{\theta_c}\right\vert_{max}$ (dB)	σ_{θ_e} (deg)	$\sigma_{\dot{F}_s}$ (lbs/sec)	Total Cost
E-1	1.737	26.21	69.04	4.155	1.186	15.83	1.832
E-2	1.747	24.86	68.22	4.188	1.179	13.85	1.806
E-3	1.774	21.13	66.05	4.265	1.163	11.08	1.751
E-4	1.804	16.29	62.99	4.320	1.146	9.68	1.697
E-5	1.829	11.54	59.82	4.354	1.132	8.92	1.654
F-3	1.872	6.03	55.98	4.391	1.107	7.00	1.578
F-2	1.928	0.64	52.79	4.480	1.076	4.71	1.488
F-1	1.939	-4.30	48.90	4.465	1.071	2.42	1.478
G-1	1.810	12.63	60.40	4.335	1.143	8.93	1.687
G-2	1.814	12.18	59.99	4.335	1.141	8.86	1.681
G-3	1.817	11.57	59.54	4.335	1.139	8.80	1.674
G-4	1.821	11.09	59.15	4.335	1.137	8.73	1.668

DISCUSSION

Using the data presented, one should be able to address the following questions:

1. Are there correlations between model-based performance measures and experimental pilot ratings, and if so, are these correlations comparable to the results presented in [3] and [4].

2. Do the results of the attitude-tracking task offer any additional insight beyond that gained via the flight-path tracking task results.

3. How do the results for the NLR configurations compare with the results for the TIFS configurations as presented in [2].

When analyzing the model-based performance metrics for the flight-path tracking task, a number of trends were expected. Anderson and Schmidt[4] have shown previously that in the flared landing task, a strong correlation exists between pilot rating and achievable bandwidth (or crossover frequency), required pilot phase compensation, rms gamma error, and total cost. Comparing these quantities for the E configuration set in Figs.5-8, we note that there is strong correlation between experimental and model-based performance metrics within this subset of the configurations.

Pilot workload (and thereby pilot rating) has been shown to correlate with the pilot phase compensation required. Pilot phase compensation here refers to the phase angle of the equivalent single-loop pilot function, P_{eq}, at crossover. In Fig.6 we see that there is a consistent trend for configurations E-1 to E-5. Configuration E-5 has the best pilot rating (CH 2.33) and the lowest pilot phase required (40 deg). Likewise, configuration E-1 has the worst pilot rating (CH 8.0) and the highest pilot phase required (57 deg).

A model-based measure of pilot/vehicle performance is the rms gamma-error computed by the OCM. Fig.7 shows the correlation between pilot rating and rms gamma-error for the E configuration set. In addition, *total cost* is a model-based measure that has correlated with pilot rating in previous studies[5]. Fig.8 shows the correlation between total cost and pilot rating for the E configuration set.

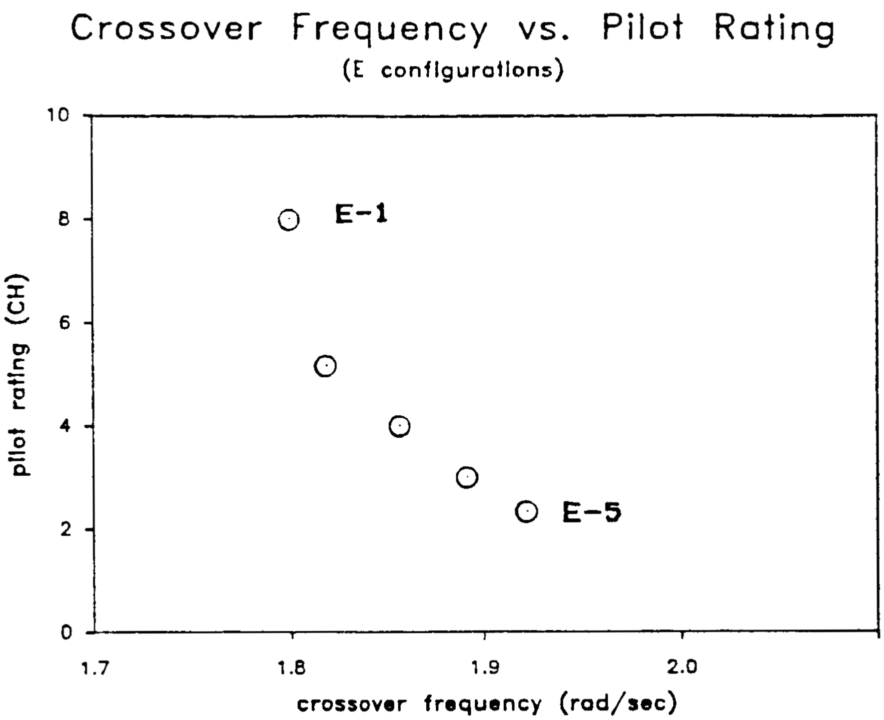


Figure 5

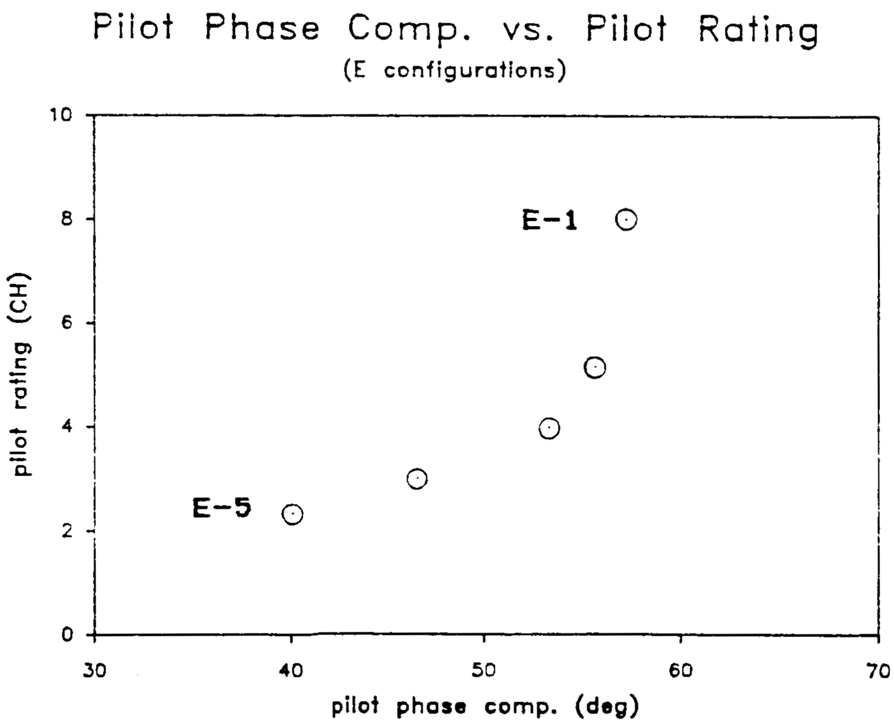


Figure 6

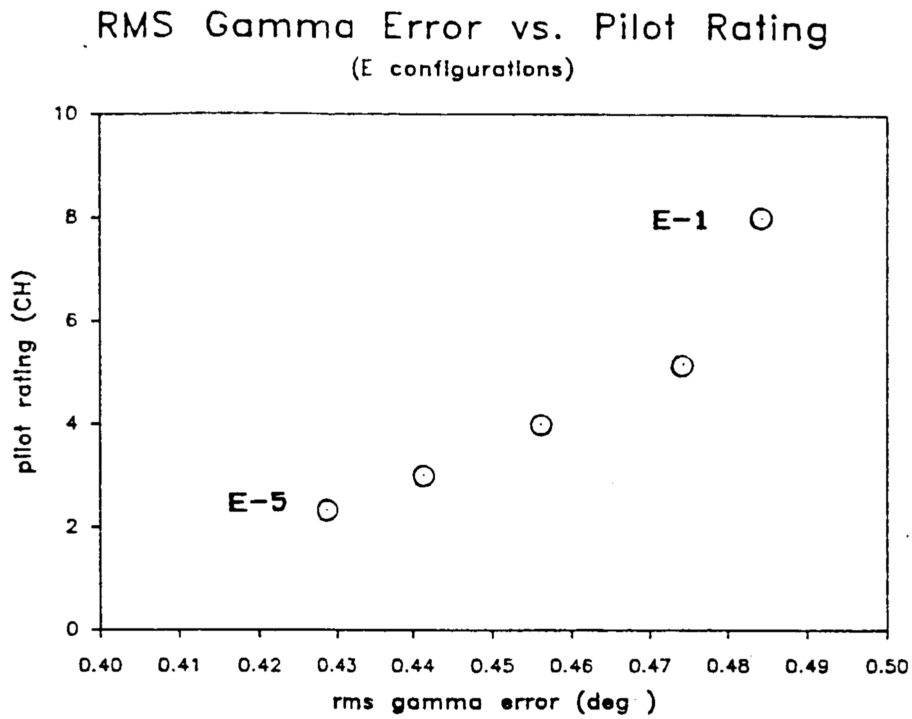


Figure 7

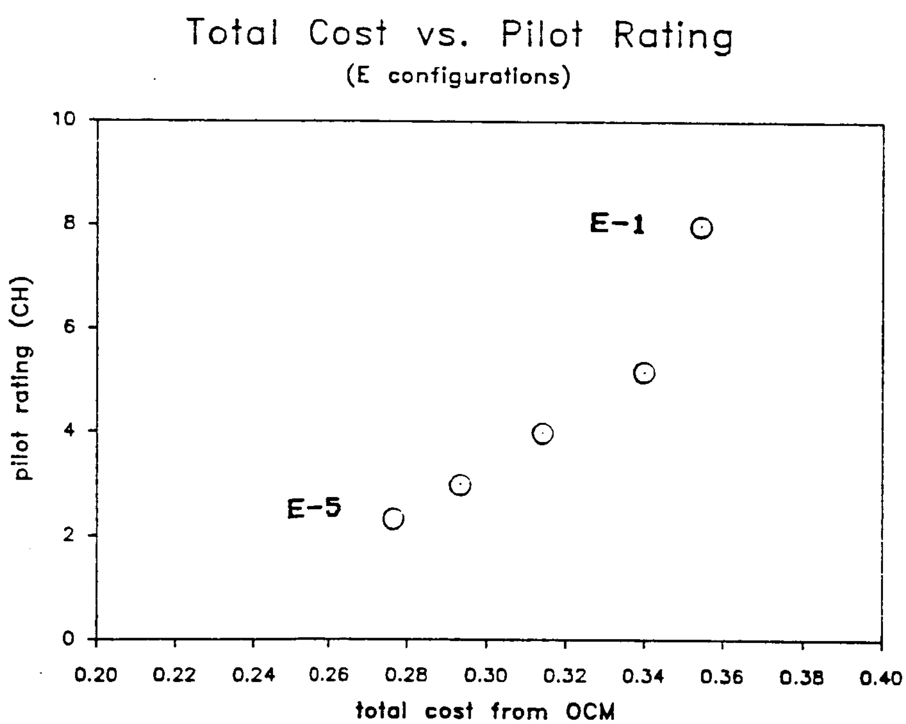


Figure 8

While the model-based measures for the E configuration set correlated well with experimental pilot rating, such is not the case across all of the configuration sets. It would be exceptional if we could find a single model-based performance metric that always correlated with pilot rating in a predictable manner. However in this case, because of the lack of consistent correlations over all configurations studied, we need to take a closer look at the configuration dynamics in the attempt to explain the subjective pilot ratings.

Bode Analysis

In the attempt to explain the experimental pilot ratings for configuration sets F and G, the vehicle-alone dynamics (namely γ/F_s and θ/F_s) for configuration sets E,F and G are now considered. Vehicle transfer functions are derived and presented in Appendix I. Bode plots for γ/F_s and θ/F_s are presented in Figs.9-14.

For good closed-loop stability margins in a tracking system, the desired *shape* of the open-loop frequency response in the crossover region is well known (i.e. constant slope of -20 dB/decade and constant -90 deg phase). Assume that the critical task for a pilot in the approach and flared landing task is the precise control of flight-path angle (or sink rate). If this is indeed the case, we would expect to find the configurations that have a γ/F_s frequency response more like K/s in the region of crossover to also be rated better by the pilots. Note that crossover frequency for all configurations studied is below 2 rad/sec. From Figs.10,12 and 14 we find that the γ/F_s frequency responses that appear more *K/s-like* in the critical frequency range (0.5-2.0 rad/sec) invariably correspond to the better rated configurations. More specifically, those configurations with (γ/F_s)-phase tending to be more uniformly equal to -90 deg in the critical frequency range also tend to be rated better.

Comparison of NLR and TIFS Analyses

A pilot/vehicle analysis of pitch-rate command aircraft configurations in an approach and landing task was also conducted by Wendel[2]. In Wendel's analysis, 26 configurations, originally studied using Calspan's Total Inflight Simulator (TIFS) were evaluated using the OCM for pilot modeling. Of those 26 configurations, six had dynamics free of any added dynamics due to pre-filters,etc. A quick comparison of results from the two analyses is made here in an attempt to find some sort of consistency between studies.

The 5 pitch-rate command configurations from Wendel's TIFS study having dynamics comparable to the NLR configurations discussed are presented in Table 6. Configuration 7-1 is also included in this comparison for it represents an aircraft with *conventional* dynamics. The θ/F_s and γ/F_s transfer functions for the 6 configurations presented in Table 6 are presented in Appendix IV. Model-based metrics for the flight-path tracking task are summarized in Table 7. Configuration 7-1, which has the best pilot rating out of the 6, has a very small value for required pilot phase compensation ($P_{eq}|_{\omega_c} = 7$ deg). Configuration 7-1 also has the largest crossover frequency ($\omega_c = 1.90$ rad/sec). Presented in Fig.16 are the frequency responses for γ/F_s for configurations 1-1,2-1 and 7-1. Note that the shape of the Bode plots for configurations 1-1 and 2-1 in the region of crossover are very similar, as are their respective pilot ratings (CH=6). Configuration 7-1, looking much more like K/s in the region of crossover (0.5-2.0 rad/sec), earns a much better pilot rating (CH=2.75)!

Table 6 : TIFS Configuration Sets

Config.	$\omega_{n_{sp}}$	ζ_{sp}	$1/\tau_{\theta 2}$	λ_2'	ω_{n_p}	ζ_p
1-1	2.79	0.8	0.38	0.44	-	-
1-2	2.76	0.8	0.72	0.82	-	-
1-3	2.73	0.8	1.00	1.19	-	-
2-1	1.78	0.6	0.38	0.50	-	-
2-2	1.75	0.6	0.72	0.93	-	-
7-1	2.84	0.8	0.72	-	0.16	0.01

Table 7 : Performance Measures for Flight-Path Tracking Task for Comparable TIFS Configurations

Config.	Pilot Rating	ω_c (rad/sec)	$\measuredangle P_{eq}|_{\omega_c}$ (deg)	Bw (rad/sec)
1-1	6.00	1.65	39.2	1.86
1-2	6.83	1.85	24.0	1.96
1-3	5.33	1.80	16.2	1.96
2-1	6.50	1.65	60.0	1.79
2-2	3.75	1.65	43.8	1.82
7-1	2.75	1.90	7.0	2.06

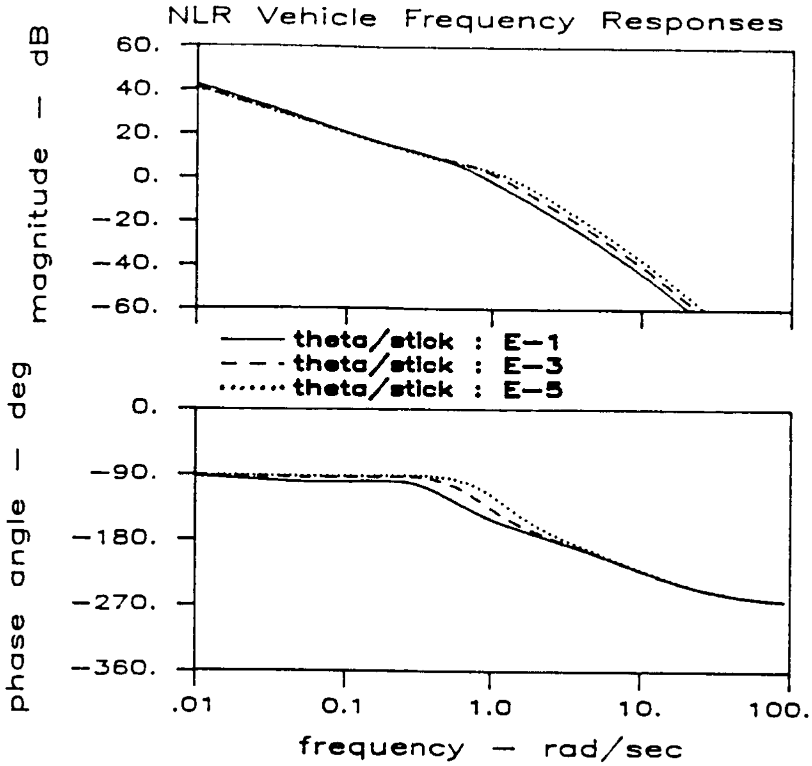


Figure 9

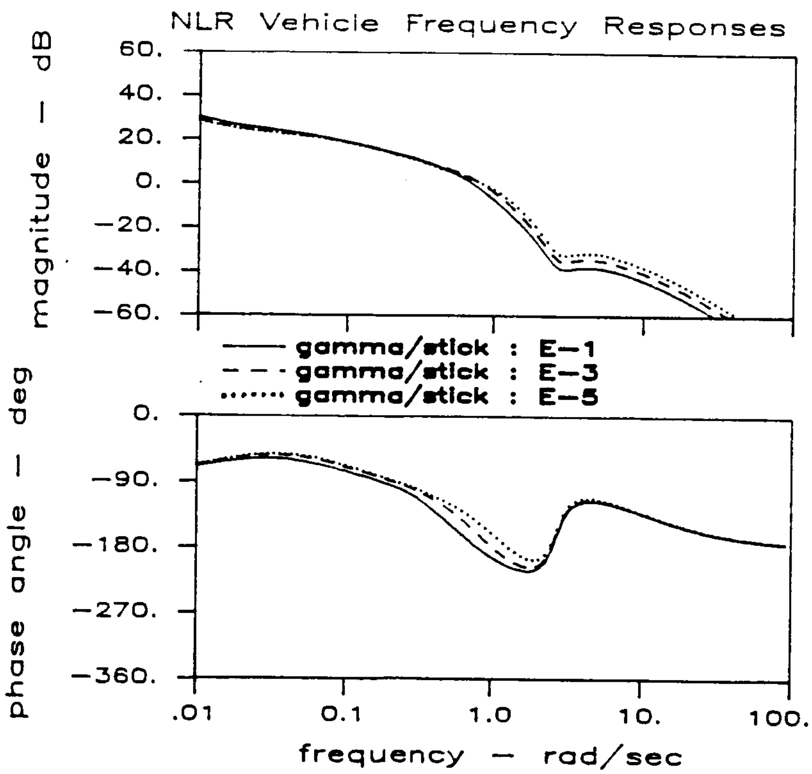
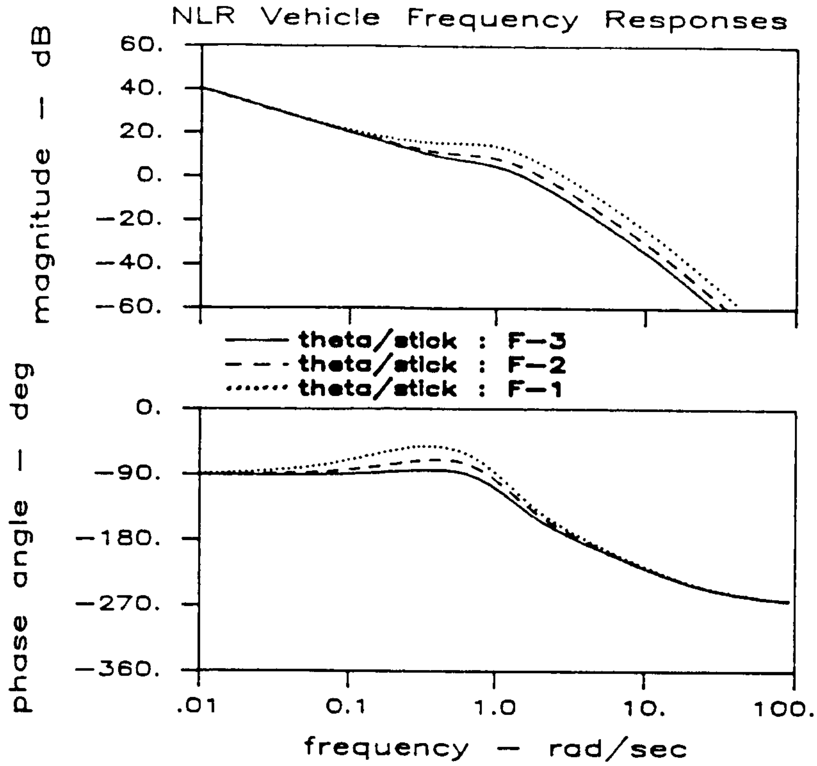


Figure 10



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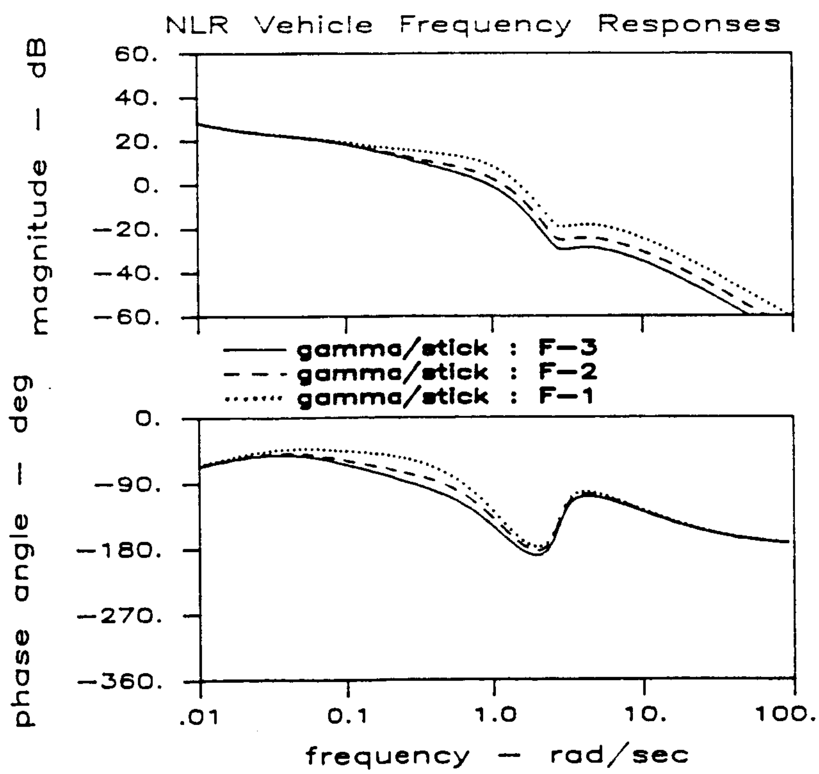

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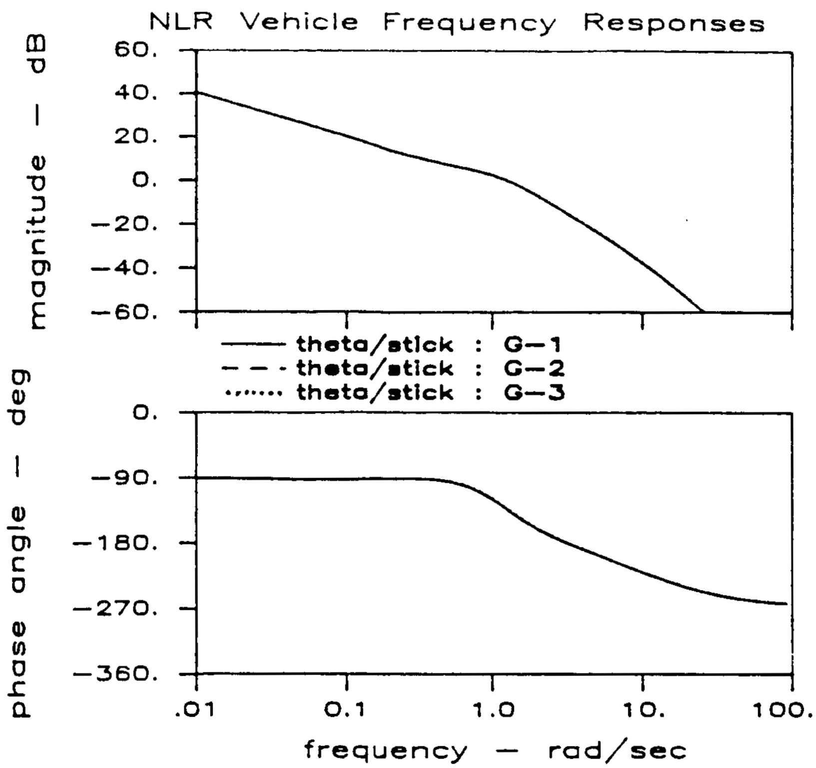

Figure 13

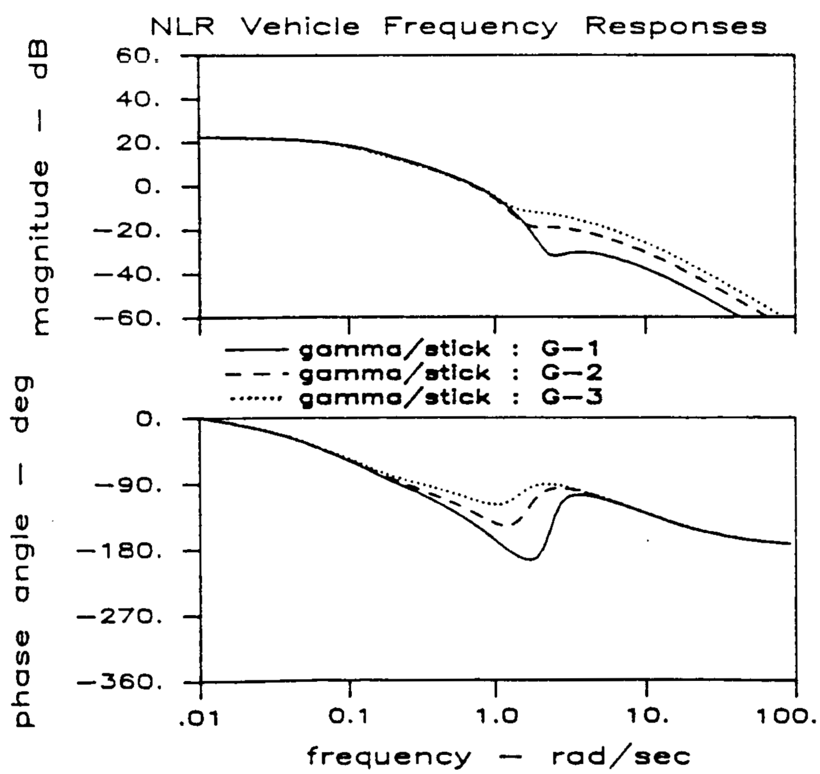

Figure 14

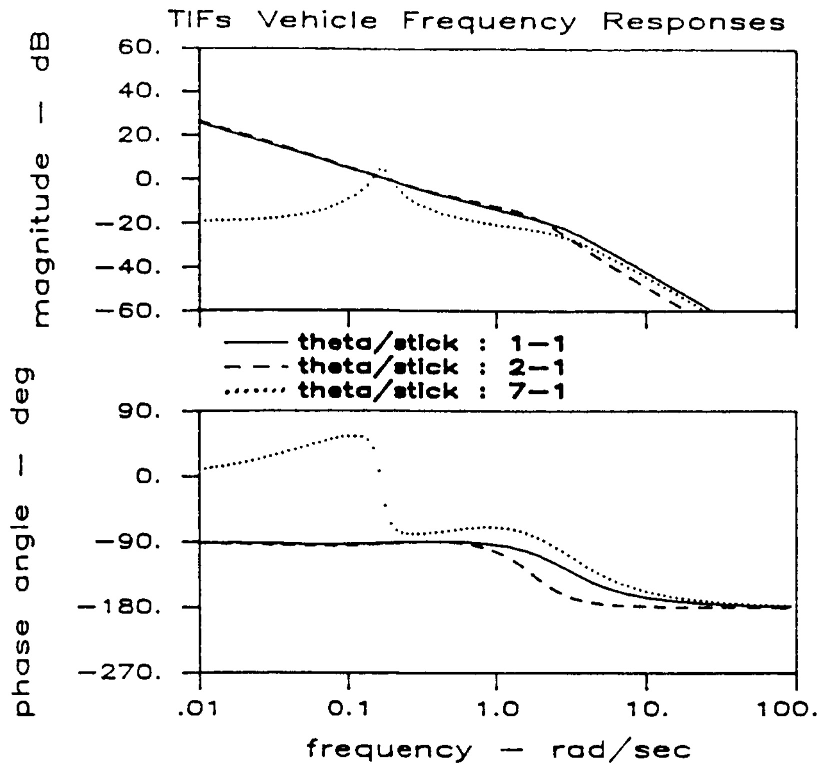

Figure 15

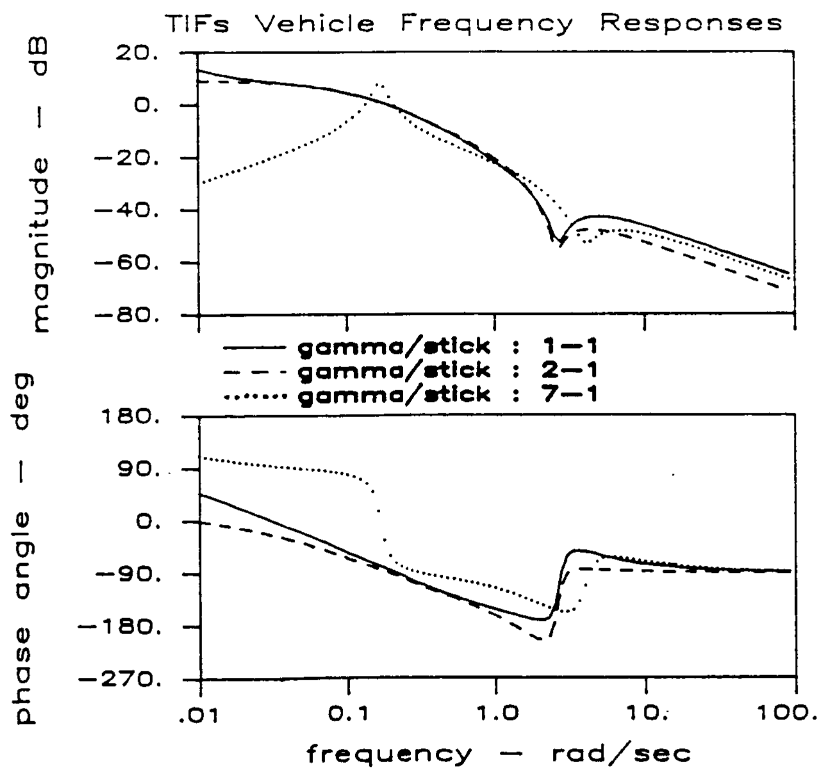

Figure 16

Attitude Tracking Analysis

Up to this point, very little has been said about the analysis of the attitude tracking task. Certainly for an aircraft to have acceptable performance in an outer-loop such as flight-path (refer to Fig.1), it must first have good inner-loop, attitude dynamics. This is the reason for conducting an attitude tracking analysis - to insure that the configuration under study has good attitude dynamics before beginning the flight-path analysis. Another reason for conducting an OCM analysis of the attitude tracking task might be that attitude tracking has been argued by some to be the *critical* task.

Yet, as stated earlier, it is hypothesized that the critical task for approach and landing is the precise control of flight-path angle. If this hypotheses is true, one should expect to find correlation between experimental pilot ratings and model-based metrics from the **flight-path** tracking analysis. Having shown through this study that there is a strong correlation between the γ/F_s frequency response in the region of crossover and experimental pilot rating offers evidence that precise control of flight-path is indeed the critical task. For this reason, it is more sensible to draw conclusions based upon the results from the flight-path analysis and not the attitude analysis.

CONCLUSION

This informal memo was written in order to summarize the results of an analytic handling qualities analysis of the rate-command, attitude-hold aircraft configurations originally presented in an NLR report by Mooij. While the discussion contained is rather limited in scope, there were a few key ideas that were brought forward:

1. Model-based performance metrics, such as required pilot phase compensation, appear to correlate well with experimentally obtained pilot ratings **within** a configuration class, but not necessarily over all classes. This was true for both the TIFS database as well as for the NLR study.

2. Vehicle configurations that exhibit K/s behavior in the flight-path response, especially in the frequency range 0.5-2.0 rad/sec, elicit better pilot ratings in the landing task.

3. For the approach and landing task, the OCM analysis of the attitude tracking task, while a necessary step in the complete analysis procedure, does not seem to offer as much insight as the OCM analysis of of the flight-path tracking task. This offers evidence for the hypotheses that the *critical task* for a pilot in the approach and landing task is the precise control of flight-path.

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[5] Hess, R., " *Prediction of Pilot Opinion Rating Using an Optimal Pilot Model*," Human Factors, Vol.19, Oct. 1977, pp. 459-475.

APPENDIX I

Vehicle Transfer Functions for NLR Configurations

Configuration E-1 *

```
------------------------------------------------------------------------
                            Theta/stick E-1
(    9.490     )S** 3          ( -0.8310E-01) + J(        0.       )
(    11.21     )S** 2          ( -0.3920    ) + J(        0.       )
(    3.492     )S** 1          ( -0.7060    ) + J(        0.       )
(   0.2183     )

(    1.000     )S** 6          ( -0.5780E-01) + J(        0.       )
(    11.39     )S** 5          (   -1.100   ) + J(        0.       )
(    20.12     )S** 4          (   -10.00   ) + J(        0.       )
(    12.17     )S** 3          ( -0.3682    ) + J(   0.3600        )
(    3.555     )S** 2          ( -0.3682    ) + J(  -0.3600        )
(   0.1686     )S** 1          (     0.     ) + J(        0.       )
(      0.      )
                            Gamma/stick E-1
(   0.9667     )S** 4          ( -0.1660E-01) + J(        0.       )
(    1.394     )S** 3          ( -0.3920    ) + J(        0.       )
(    7.564     )S** 2          ( -0.5168    ) + J(    2.670        )
(    2.928     )S** 1          ( -0.5168    ) + J(   -2.670        )
(   0.4652E-01)

(    1.000     )S** 6          ( -0.5780E-01) + J(        0.       )
(    11.39     )S** 5          (   -1.100   ) + J(        0.       )
(    20.12     )S** 4          (   -10.00   ) + J(        0.       )
(    12.17     )S** 3          ( -0.3682    ) + J(   0.3600        )
(    3.555     )S** 2          ( -0.3682    ) + J(  -0.3600        )
(   0.1686     )S** 1          (     0.     ) + J(        0.       )
(      0.      )
```

Configuration E-2

```
------------------------------------------------------------------------
                            Theta/stick E-2
(    11.00     )S** 3          ( -0.8310E-01) + J(        0.       )
(    13.77     )S** 2          ( -0.4630    ) + J(        0.       )
(    4.664     )S** 1          ( -0.7060    ) + J(        0.       )
(   0.2988     )

(    1.000     )S** 6          (     0.     ) + J(        0.       )
(    11.99     )S** 5          ( -0.6450E-01) + J(        0.       )
(    21.29     )S** 4          (   -1.080   ) + J(        0.       )
(    14.39     )S** 3          (   -10.00   ) + J(        0.       )
(    4.679     )S** 2          ( -0.4226    ) + J(   0.4203        )
(   0.2475     )S** 1          ( -0.4226    ) + J(  -0.4203        )
(      0.      )
                            Gamma/stick E-2
(    1.119     )S** 4          ( -0.1660E-01) + J(        0.       )
(    1.693     )S** 3          ( -0.4630    ) + J(        0.       )
(    8.339     )S** 2          ( -0.5168    ) + J(    2.670        )
(    3.978     )S** 1          ( -0.5168    ) + J(   -2.670        )
(   0.6361E-01)

(    1.000     )S** 6          (     0.     ) + J(        0.       )
(    11.99     )S** 5          ( -0.6450E-01) + J(        0.       )
(    21.29     )S** 4          (   -1.080   ) + J(        0.       )
(    14.37     )S** 3          (   -10.00   ) + J(        0.       )
(    4.679     )S** 2          ( -0.4226    ) + J(   0.4203        )
(   0.2475     )S** 1          ( -0.4226    ) + J(  -0.4203        )
(      0.      )
------------------------------------------------------------------------
```

* refer to last page of Appendix I for derivation

```
Configuration E-3
----------------------------------------------------------
                        Theta/stick E-3
(     14.20      )S** 3          ( -0.8310E-01) + J(      0.      )
(     19.97      )S** 2          ( -0.6170    ) + J(      0.      )
(     7.747      )S** 1          ( -0.7060    ) + J(      0.      )
(   0.5140       )

(     1.000      )S** 6          ( -0.7240E-01) + J(      0.      )
(     12.19      )S** 5          ( -0.9870    ) + J(      0.      )
(     23.81      )S** 4          (   -10.00   ) + J(      0.      )
(     19.94      )S** 3          ( -0.5651    ) + J(  0.5733      )
(     7.719      )S** 2          ( -0.5651    ) + J( -0.5733      )
(   0.4631       )S** 1          (      0.    ) + J(      0.      )
(       0.       )
                        Gamma/stick E-3
(     1.441      )S** 4          ( -0.1660E-01) + J(      0.      )
(     2.402      )S** 3          ( -0.6170    ) + J(      0.      )
(     11.62      )S** 2          ( -0.5168    ) + J(   2.670      )
(     6.768      )S** 1          ( -0.5168    ) + J(  -2.670      )
(   0.1092       )

(     1.000      )S** 6          ( -0.7240E-01) + J(      0.      )
(     12.19      )S** 5          ( -0.9870    ) + J(      0.      )
(     23.81      )S** 4          (   -10.00   ) + J(      0.      )
(     19.94      )S** 3          ( -0.5651    ) + J(  0.5733      )
(     7.719      )S** 2          ( -0.5651    ) + J( -0.5733      )
(   0.4631       )S** 1          (      0.    ) + J(      0.      )
(       0.       )
Configuration E-4
----------------------------------------------------------
                        Theta/stick E-4
(     17.00      )S** 3          ( -0.8310E-01) + J(      0.      )
(     25.91      )S** 2          ( -0.7060    ) + J(      0.      )
(     10.86      )S** 1          ( -0.7350    ) + J(      0.      )
(   0.7331       )

(     1.000      )S** 6          (      0.    ) + J(      0.      )
(     12.39      )S** 5          ( -0.7560E-01) + J(      0.      )
(     26.38      )S** 4          ( -0.9030    ) + J(      0.      )
(     25.60      )S** 3          (   -10.00   ) + J(      0.      )
(     10.82      )S** 2          ( -0.7070    ) + J(  0.7072      )
(   0.6827       )S** 1          ( -0.7070    ) + J( -0.7072      )
(       0.       )
                        Gamma/stick E-4
(     1.719      )S** 4          ( -0.1660E-01) + J(      0.      )
(     3.069      )S** 3          ( -0.7350    ) + J(      0.      )
(     14.07      )S** 2          ( -0.5168    ) + J(   2.670      )
(     9.577      )S** 1          ( -0.5168    ) + J(  -2.670      )
(   0.1551       )

(     1.000      )S** 6          (      0.    ) + J(      0.      )
(     12.39      )S** 5          ( -0.7560E-01) + J(      0.      )
(     26.38      )S** 4          ( -0.9030    ) + J(      0.      )
(     25.60      )S** 3          (   -10.00   ) + J(      0.      )
(     10.82      )S** 2          ( -0.7070    ) + J(  0.7072      )
(   0.6827       )S** 1          ( -0.7070    ) + J( -0.7072      )
(       0.       )
----------------------------------------------------------
```

Configuration E-5

```
--------------------------------------------------------------------
                    Theta/stick E-5
(    19.20     )S** 3          ( -0.8310E-01) + J(       0.      )
(    31.85     )S** 2          ( -0.7060    ) + J(       0.      )
(    14.31     )S** 1          ( -0.8700    ) + J(       0.      )
(   0.9800     )

(    1.000     )S** 6          ( -0.7750E-01) + J(       0.      )
(    12.59     )S** 5          ( -0.8380    ) + J(       0.      )
(    28.97     )S** 4          (   -10.00   ) + J(       0.      )
(    31.83     )S** 3          ( -0.8388    ) + J(   0.8581      )
(    14.37     )S** 2          ( -0.8388    ) + J(  -0.8581      )
(   0.9352     )S** 1          (      0.    ) + J(       0.      )
(       0.     )
                    Gamma/stick E-5
(    1.951     )S** 4          ( -0.1660E-01) + J(       0.      )
(    3.746     )S** 3          ( -0.8700    ) + J(       0.      )
(    16.25     )S** 2          ( -0.5168    ) + J(    2.670      )
(    12.82     )S** 1          ( -0.5168    ) + J(   -2.670      )
(   0.2084     )

(    1.000     )S** 6          ( -0.7750E-01) + J(       0.      )
(    12.59     )S** 5          ( -0.8380    ) + J(       0.      )
(    28.97     )S** 4          (   -10.00   ) + J(       0.      )
(    31.83     )S** 3          ( -0.8388    ) + J(   0.8581      )
(    14.37     )S** 2          ( -0.8388    ) + J(  -0.8581      )
(   0.9352     )S** 1          (      0.    ) + J(       0.      )
(       0.     )
```

Configuration F-3

```
--------------------------------------------------------------------
                    Theta/stick F-3
(    26.90     )S** 3          ( -0.8310E-01) + J(       0.      )
(    37.93     )S** 2          ( -0.6210    ) + J(       0.      )
(    14.76     )S** 1          ( -0.7060    ) + J(       0.      )
(   0.9801     )

(    1.000     )S** 6          (      0.    ) + J(       0.      )
(    12.59     )S** 5          ( -0.7750E-01) + J(       0.      )
(    28.97     )S** 4          ( -0.8380    ) + J(       0.      )
(    31.83     )S** 3          (   -10.00   ) + J(       0.      )
(    14.37     )S** 2          ( -0.8388    ) + J(   0.8581      )
(   0.9352     )S** 1          ( -0.8388    ) + J(  -0.8581      )
(       0.     )
                    Gamma/stick F-3
(    2.730     )S** 4          ( -0.1660E-01) + J(       0.      )
(    4.562     )S** 3          ( -0.6210    ) + J(       0.      )
(    22.02     )S** 2          ( -0.5168    ) + J(    2.670      )
(    12.90     )S** 1          ( -0.5168    ) + J(   -2.670      )
(   0.2081     )

(    1.000     )S** 6          (      0.    ) + J(       0.      )
(    12.59     )S** 5          ( -0.7750E-01) + J(       0.      )
(    28.97     )S** 4          ( -0.8380    ) + J(       0.      )
(    31.83     )S** 3          (   -10.00   ) + J(       0.      )
(    14.37     )S** 2          ( -0.8388    ) + J(   0.8581      )
(   0.9352     )S** 1          ( -0.8388    ) + J(  -0.8581      )
(       0.     )
--------------------------------------------------------------------
```

Configuration F-2

```
------------------------------------------------------------------------
                      Theta/stick F-2
(    44.80     )S** 3        ( -0.8310E-01) + J(       0.       )
(    52.02     )S** 2        ( -0.3720    ) + J(       0.       )
(    15.78     )S** 1        ( -0.7060    ) + J(       0.       )
(   0.9777     )

(    1.000     )S** 6        ( -0.7750E-01) + J(       0.       )
(    12.59     )S** 5        ( -0.8380    ) + J(       0.       )
(    28.97     )S** 4        (  -10.00    ) + J(       0.       )
(    31.83     )S** 3        ( -0.8388    ) + J(   0.8581       )
(    14.37     )S** 2        ( -0.8388    ) + J(  -0.8581       )
(   0.9352     )S** 1        (     0.     ) + J(       0.       )
(      0.      )
                      Gamma/stick F-2
(    4.547     )S** 4        ( -0.1660E-01) + J(       0.       )
(    6.467     )S** 3        ( -0.3720    ) + J(       0.       )
(    35.48     )S** 2        ( -0.5168    ) + J(    2.670       )
(    13.10     )S** 1        ( -0.5168    ) + J(   -2.670       )
(   0.2077     )

(    1.000     )S** 6        ( -0.7750E-01) + J(       0.       )
(    12.59     )S** 5        ( -0.8380    ) + J(       0.       )
(    28.97     )S** 4        (  -10.00    ) + J(       0.       )
(    31.83     )S** 3        ( -0.8388    ) + J(   0.8581       )
(    14.37     )S** 2        ( -0.8388    ) + J(  -0.8581       )
(   0.9352     )S** 1        (     0.     ) + J(       0.       )
(      0.      )
```

Configuration F-1

```
------------------------------------------------------------------------
                      Theta/stick F-1
(    89.90     )S** 3        ( -0.8310E-01) + J(       0.       )
(    87.66     )S** 2        ( -0.1860    ) + J(       0.       )
(    18.47     )S** 1        ( -0.7060    ) + J(       0.       )
(   0.9810     )

(    1.000     )S** 6        ( -0.7750E-01) + J(       0.       )
(    12.59     )S** 5        ( -0.8380    ) + J(       0.       )
(    28.97     )S** 4        (  -10.00    ) + J(       0.       )
(    31.83     )S** 3        ( -0.8388    ) + J(   0.8581       )
(    14.37     )S** 2        ( -0.8388    ) + J(  -0.8581       )
(   0.9352     )S** 1        (     0.     ) + J(       0.       )
(      0.      )
                      Gamma/stick F-1
(    9.130     )S** 4        ( -0.1660E-01) + J(       0.       )
(    11.29     )S** 3        ( -0.1860    ) + J(       0.       )
(    69.47     )S** 2        ( -0.5168    ) + J(    2.670       )
(    13.71     )S** 1        ( -0.5168    ) + J(   -2.670       )
(   0.2085     )

(    1.000     )S** 6        ( -0.7750E-01) + J(       0.       )
(    12.59     )S** 5        ( -0.8380    ) + J(       0.       )
(    28.97     )S** 4        (  -10.00    ) + J(       0.       )
(    31.83     )S** 3        ( -0.8388    ) + J(   0.8581       )
(    14.37     )S** 2        ( -0.8388    ) + J(  -0.8581       )
(   0.9352     )S** 1        (     0.     ) + J(       0.       )
(      0.      )
------------------------------------------------------------------------
```

Configuration G-1

```
------------------------------------------------------------------
                         Theta/stick G-1
(    18.50      )S** 3            ( -0.9100E-01) + J(       0.      )
(    26.36      )S** 2            ( -0.4940    ) + J(       0.      )
(    9.923      )S** 1            ( -0.8400    ) + J(       0.      )
(  0.6986       )

(    1.000      )S** 6            ( -0.8350E-01) + J(       0.      )
(    12.31      )S** 5            ( -0.5520    ) + J(       0.      )
(    25.59      )S** 4            (   -10.00   ) + J(       0.      )
(    26.22      )S** 3            ( -0.8354    ) + J(  0.8475       )
(    9.835      )S** 2            ( -0.8354    ) + J( -0.8475       )
(   0.6527      )S** 1            (       0.   ) + J(       0.      )
(       0.      )

                         Gamma/stick G-1
(    1.880      )S** 4            (  0.1470E-02) + J(       0.      )
(    3.031      )S** 3            ( -0.8400    ) + J(       0.      )
(    11.43      )S** 2            ( -0.3868    ) + J(   2.298       )
(    8.559      )S** 1            ( -0.3868    ) + J(  -2.298       )
(  -0.1261E-01)

(    1.000      )S** 6            ( -0.8350E-01) + J(       0.      )
(    12.31      )S** 5            ( -0.5520    ) + J(       0.      )
(    25.59      )S** 4            (   -10.00   ) + J(       0.      )
(    26.22      )S** 3            ( -0.8354    ) + J(  0.8475       )
(    9.835      )S** 2            ( -0.8354    ) + J( -0.8475       )
(   0.6527      )S** 1            (       0.   ) + J(       0.      )
(       0.      )
------------------------------------------------------------------
```

Configuration G-2

```
----------------------------------------------------------------------
                        Theta/stick G-2
(    18.80      )S** 4          ( -0.9110E-01) + J(        0.       )
(    30.06      )S** 3          ( -0.1980    ) + J(        0.       )
(    15.21      )S** 2          ( -0.5250    ) + J(        0.       )
(    2.684      )S** 1          ( -0.7850    ) + J(        0.       )
(  0.1398       )

(    1.000      )S** 7          ( -0.8350E-01) + J(        0.       )
(    12.51      )S** 6          ( -0.2000    ) + J(        0.       )
(    28.05      )S** 5          ( -0.5520    ) + J(        0.       )
(    31.33      )S** 4          (  -10.00    ) + J(        0.       )
(    15.08      )S** 3          ( -0.8354    ) + J(   0.8475       )
(    2.620      )S** 2          ( -0.8354    ) + J(  -0.8475       )
(  0.1305       )S** 1          (      0.    ) + J(        0.       )
(       0.      )

                        Gamma/stick G-2
(    4.332      )S** 5          (  0.1470E-02) + J(        0.       )
(    7.681      )S** 4          ( -0.2190    ) + J(        0.       )
(    15.82      )S** 3          ( -0.6580    ) + J(        0.       )
(    10.88      )S** 2          ( -0.4488    ) + J(    1.588       )
(    1.684      )S** 1          ( -0.4488    ) + J(   -1.588       )
( -0.2499E-02)

(    1.000      )S** 7          ( -0.8350E-01) + J(        0.       )
(    12.51      )S** 6          ( -0.2000    ) + J(        0.       )
(    28.05      )S** 5          ( -0.5520    ) + J(        0.       )
(    31.33      )S** 4          (  -10.00    ) + J(        0.       )
(    15.08      )S** 3          ( -0.8354    ) + J(   0.8475       )
(    2.620      )S** 2          ( -0.8354    ) + J(  -0.8475       )
(  0.1305       )S** 1          (      0.    ) + J(        0.       )
(       0.      )
----------------------------------------------------------------------
```

Configuration G-3

```
------------------------------------------------------------------------
                          Theta/stick G-3
(    19.10     )S** 4        ( -0.9310E-01) + J(        0.       )
(    30.01     )S** 3        ( -0.1960    ) + J(        0.       )
(    15.22     )S** 2        ( -0.5860    ) + J(        0.       )
(    2.699     )S** 1        ( -0.6960    ) + J(        0.       )
(   0.1421     )

(    1.000     )S** 7        ( -0.8350E-01) + J(        0.       )
(    12.51     )S** 6        ( -0.2000    ) + J(        0.       )
(    28.05     )S** 5        ( -0.5520    ) + J(        0.       )
(    31.33     )S** 4        (  -10.00    ) + J(        0.       )
(    15.08     )S** 3        ( -0.8354    ) + J(   0.8475       )
(    2.620     )S** 2        ( -0.8354    ) + J(  -0.8475       )
(   0.1305     )S** 1        (       0.   ) + J(        0.       )
(       0.     )

                          Gamma/stick G-3
(    7.098     )S** 5        (  0.1470E-02) + J(        0.       )
(    12.48     )S** 4        ( -0.2590    ) + J(        0.       )
(    20.26     )S** 3        ( -0.4600    ) + J(        0.       )
(    11.00     )S** 2        ( -0.5203    ) + J(    1.311       )
(    1.666     )S** 1        ( -0.5203    ) + J(   -1.311       )
(  -0.2473E-02)

(    1.000     )S** 7        ( -0.8350E-01) + J(        0.       )
(    12.51     )S** 6        ( -0.2000    ) + J(        0.       )
(    28.05     )S** 5        ( -0.5520    ) + J(        0.       )
(    31.33     )S** 4        (  -10.00    ) + J(        0.       )
(    15.08     )S** 3        ( -0.8354    ) + J(   0.8475       )
(    2.620     )S** 2        ( -0.8354    ) + J(  -0.8475       )
(   0.1305     )S** 1        (       0.   ) + J(        0.       )
(       0.     )
------------------------------------------------------------------------
```

Configuration G-4

```
------------------------------------------------------------------
                        Theta/stick G-4
(    19.40      )S** 4        ( -0.9140E-01) + J(       0.      )
(    29.98      )S** 3        ( -0.1940    ) + J(       0.      )
(    15.19      )S** 2        ( -0.6300    ) + J(  0.9420E-01)
(    2.680      )S** 1        ( -0.6300    ) + J( -0.9420E-01)
(   0.1396      )

(    1.000      )S** 7        ( -0.8350E-01) + J(       0.      )
(    12.51      )S** 6        ( -0.2000    ) + J(       0.      )
(    28.05      )S** 5        ( -0.5520    ) + J(       0.      )
(    31.33      )S** 4        (   -10.00   ) + J(       0.      )
(    15.08      )S** 3        ( -0.8354    ) + J(  0.8475      )
(    2.620      )S** 2        ( -0.8354    ) + J( -0.8475      )
(   0.1305      )S** 1        (      0.    ) + J(       0.      )
(        0.     )

                        Gamma/stick G-4
(    9.578      )S** 5        (  0.1470E-02) + J(       0.      )
(    16.89      )S** 4        ( -0.3072    ) + J(  0.9310E-01)
(    24.43      )S** 3        ( -0.3072    ) + J( -0.9310E-01)
(    11.35      )S** 2        ( -0.5755    ) + J(   1.188      )
(    1.703      )S** 1        ( -0.5755    ) + J(  -1.188      )
( -0.2528E-02)

(    1.000      )S** 7        ( -0.8350E-01) + J(       0.      )
(    12.51      )S** 6        ( -0.2000    ) + J(       0.      )
(    28.05      )S** 5        ( -0.5520    ) + J(       0.      )
(    31.33      )S** 4        (   -10.00   ) + J(       0.      )
(    15.08      )S** 3        ( -0.8354    ) + J(  0.8475      )
(    2.620      )S** 2        ( -0.8354    ) + J( -0.8475      )
(   0.1305      )S** 1        (      0.    ) + J(       0.      )
(        0.     )
------------------------------------------------------------------
```

- DESIRE TO FIND $\theta/F_s\left[\frac{deg}{lb}\right]$ AND $\gamma/F_s\left[\frac{deg}{lb}\right]$:

1. TABLE 7.1 IN [1] HAS THE VEHICLE TRANSFER FUNCTIONS $q/q_c\left[\frac{deg/s}{deg/s}\right]$ AND $q_{zP}/q_c\left[\frac{m/s^2}{deg/s}\right]$.

2. FROM FIG'S 7.3 AND 7.12 IN [1] WE FIND

$$q_c/\delta_e \cong \frac{1\ deg/sec}{1\ deg}, \quad F_s/\delta_e \cong \frac{1\ lb_f}{1\ deg}$$

3. FOR θ/F_s TRANSFER FUNCTION

$$q/F_s = q/q_c \cdot q_c/\delta_e \cdot \delta_e/F_s \left[\frac{deg/sec}{lb}\right]$$

- $$\theta/F_s = 1/s \cdot q/F_s \left[\frac{deg}{lb}\right]$$

4. FOR γ/F_s TRANSFER FUNCTION

KINEMATIC RELATIONSHIP: $\dot{\gamma}_p = q_{zP}/U_0$ WHERE $_p$ SUBSCRIPT DENOTES QUANTITIES @ PILOT LOCATION

FROM PILOT BRIEFING CARDS: $U_0 = 210$ ft/sec

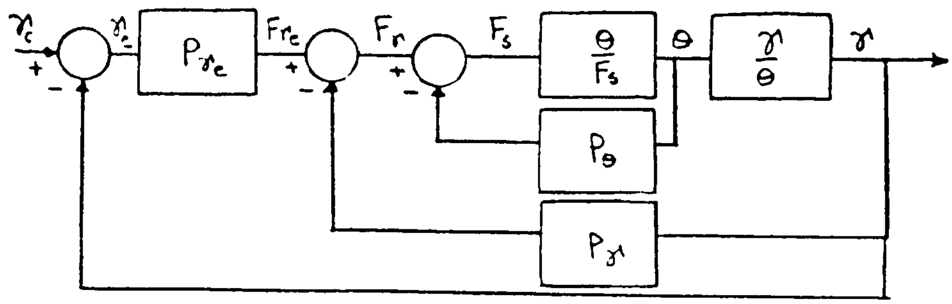
$$\dot{\gamma}_p/F_s = q_{zP}/q_c \cdot q_c/\delta_e \cdot \delta_e/F_s \cdot 1/U_0 \cdot \text{UNITS CONVERSION} \left[\frac{deg/sec}{lb}\right]$$

$$1/U_0 \cdot \text{UNITS CONV.} = \frac{1\ sec}{210\ ft} \cdot \frac{3.28084\ ft}{m} \cdot \frac{180°}{\pi\ rad} = .895135$$

$$\dot{\gamma}_p/F_s = .895135 \cdot q_{zP}/q_c \left[\frac{deg/sec}{lb}\right]$$

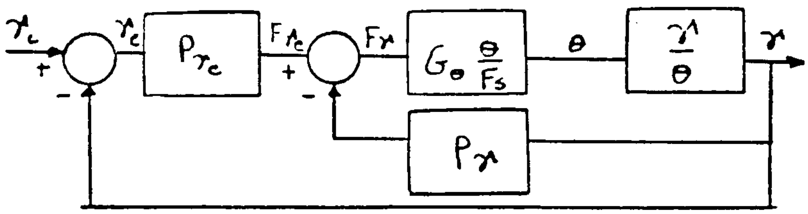
- $$\gamma_p/F_s = 1/s \cdot \dot{\gamma}_p/F_s \left[\frac{deg}{lb}\right]$$

GAMMA TRACKING TASK



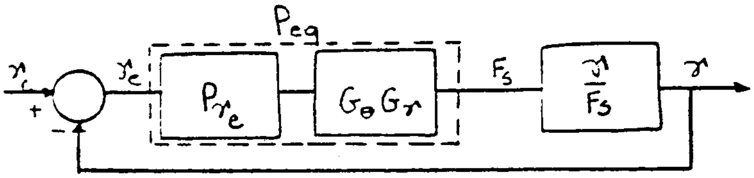
$$\theta = \frac{\theta}{F_s}\left(F_\gamma - P_\theta \theta\right)$$

$$\frac{\theta}{F_\gamma} = \frac{\theta / F_s}{\left[1 + P_\theta \, \theta / F_s\right]} \qquad \text{LET } G_\theta = \frac{1}{\left[1 + P_\theta \, \theta / F_s\right]}$$



$$\gamma = \frac{\gamma}{\theta}\left(G_\theta \frac{\theta}{F_s}\right) F_\gamma = \frac{\gamma}{\theta}\left(G_\theta \frac{\theta}{F_s}\right)\left[F_{\gamma_e} - P_\gamma \gamma\right]$$

$$\frac{\gamma}{F_{\gamma_e}} = \frac{\frac{\gamma}{\theta} G_\theta \frac{\theta}{F_s}}{\left[1 + \frac{\gamma}{\theta} G_\theta \frac{\theta}{F_s} P_\gamma\right]} = \frac{G_\theta \, \gamma / F_s}{\left[1 + G_\theta P_\gamma \, \gamma / F_s\right]} \qquad \text{LET } G_\gamma = \frac{1}{\left[1 + G_\theta P_\gamma \, \gamma / F_s\right]}$$



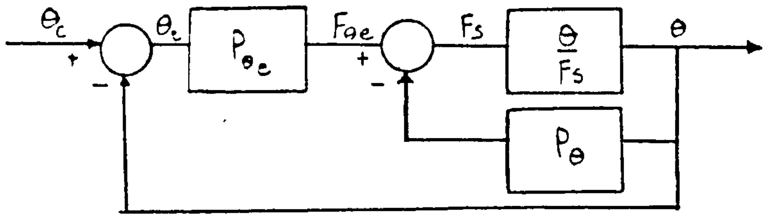
$$P_{eq} = P_{\gamma_e} G_\theta G_\gamma$$

$$\left.\frac{\gamma}{\gamma_c}\right|_{\text{OPEN LOOP}} = P_{eq} \frac{\gamma}{F_s}$$

$$\left.\frac{\gamma}{\gamma_c}\right|_{\text{CLOSED LOOP}} = \frac{P_{eq} \, \gamma / F_s}{\left[1 + P_{eq} \, \gamma / F_s\right]}$$

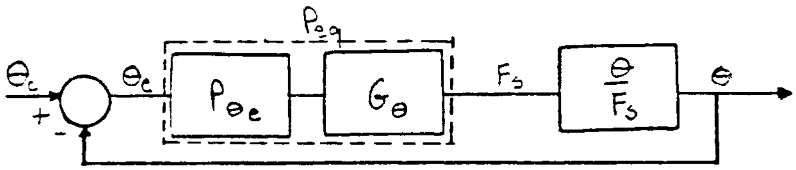
NOTE:
IN ORDER TO USE ABOVE SIGN CONVENTION AND EQUATIONS ONE NEEDS TO USE $+P_\gamma$, $+P_\theta$, AND $-P_{\gamma_e}$ WITH RESPECT TO THE NUMBERS PIREP IS PRODUCING.

THETA TRACKING TASK



$$\theta = \frac{\theta}{F_s}\left(F_{\theta e} - P_\theta\,\theta\right)$$

$$\frac{\theta}{F_{\theta e}} = \frac{\theta/F_s}{\left[1 + P_\theta\,\theta/F_s\right]} \qquad \text{LET} \quad G_\theta = \frac{1}{\left[1 + P_\theta\,\theta/F_s\right]}$$



$$\boxed{\begin{aligned} P_{eq} &= P_{\theta_e} G_\theta \\ \left.\frac{\theta}{\theta_c}\right|_{\text{OPEN LOOP}} &= P_{eq}\,\frac{\theta}{F_s} \\ \left.\frac{\theta}{\theta_c}\right|_{\text{CLOSED LOOP}} &= \frac{P_{eq}\,\theta/F_s}{\left[1 + P_{eq}\,\theta/F_s\right]} \end{aligned}}$$

NOTE:
IN ORDER TO USE ABOVE SIGN CONVENTION AND EQUATIONS ONE NEEDS TO USE $+P_\theta$ AND $-P_{\theta e}$ WITH RESPECT TO THE NUMBERS PREP IS PRODUCING.

APPENDIX III

OCM Input File for Config. E-1 Gamma Tracking Task

ORIGINAL PAGE IS
OF POOR QUALITY

```
NLR Configuration E-1 : Gamma Tracking
 $nam1 ktrg=2, icode=1, nx=9, nx1=3, nu=1, ny=6, nw=1,
 a(1,2)=1.,
 a(2,1)=-.25, a(2,2)=-.5,
 a(3,1)=.5, a(3,3)=-.5,
 a(4,4)=-11.89, a(4,5)=-20.12, a(4,6)=-12.17, a(4,7)=-3.555,
 a(4,8)=-.1686,
 a(5,4)=1., a(6,5)=1., a(7,6)=1., a(8,7)=1., a(9,8)=1.,
 b(4,1)=1.,
 c(1,3)=1., c(1,5)=-.9667, c(1,6)=-1.394, c(1,7)=-7.564,
 c(1,8)=-2.928, c(1,9)=-.04652,
 c(2,1)=.5, c(2,3)=-.5, c(2,4)=-.9667, c(2,5)=-1.394, c(2,6)=-7.564,
 c(2,7)=-2.928, c(2,8)=-.04652,
 c(3,5)=.9667, c(3,6)=1.394, c(3,7)=7.564, c(3,8)=2.928, c(3,9)=.04652,
 c(4,4)=.9667, c(4,5)=1.394, c(4,6)=7.564, c(4,7)=2.928, c(4,8)=.04652,
 c(5,6)=9.49, c(5,7)=11.21, c(5,8)=3.492, c(5,9)=.2183,
 c(6,5)=9.49, c(6,6)=11.21, c(6,7)=3.492, c(6,8)=.2183,
 e(2,1)=.25,
 qy(1)=1.,
 qr(1)=25.3e-05,
 t=.2,
 identu=2,
 vu(1)=-25.,
 identy=2,
 vy(1)=6*-20.,
 th(1)=.05,.13,.05,.13,.05,.13,
 w0(1)=64.,
 identa=0,
 attn(1)=6*.333333$
pilot response to gamma error
 $nam1 icode=10$
 $frqdat jx=2, mu=1, my1=1, my2=2$
pilot response to gamma
 $nam1 icode=10$
 $frqdat jx=2, mu=1, my1=3, my2=4$
pilot response to theta
 $nam1 icode=10$
 $frqdat jx=2, mu=1, my1=5, my2=6$
theta to stick
 $nam1 icode=10$
 $frqdat jx=4, mu=1, my1=5, my2=0$
q to stick
 $nam1 icode=10$
 $frqdat jx=4, mu=1, my1=6, my2=0$
gamma to stick
 $nam1 icode=10$
 $frqdat jx=4, mu=1, my1=3, my2=0$
gammadot to stick
 $nam1 icode=10$
 $frqdat jx=4, mu=1, my1=4, my2=0$
#eor
#eof
```

OCM Input File for Config. E-1 Theta Tracking Task

```
NLR Configuration E-1 : Theta Tracking
 $nam1 ktrg=2,icode=1,nx=8,nx1=2,nu=1,ny=4,nw=1,
 a(1,2)=1.,
 a(2,1)=-.25,a(2,2)=-.5,
 a(3,3)=-11.89,a(3,4)=-20.12,a(3,5)=-12.17,a(3,6)=-3.555,
 a(3,7)=-.1686,
 a(4,3)=1.,a(5,4)=1.,a(6,5)=1.,a(7,6)=1.,a(8,7)=1.,
 b(3,1)=1.,
 c(1,1)=1.,c(1,5)=-9.49,c(1,6)=-11.21,c(1,7)=-3.492,c(1,8)=-.2183,
 c(2,2)=1.,c(2,4)=-9.49,c(2,5)=-11.21,c(2,6)=-3.492,c(2,7)=-.2183,
 c(3,5)=9.49,c(3,6)=11.21,c(3,7)=3.492,c(3,8)=.2183,
 c(4,4)=9.49,c(4,5)=11.21,c(4,6)=3.492,c(4,7)=.2183,
 e(2,1)=.25,
 qy(1)=1.,
 qr(1)=16.98e-04,
 t=.2,
 identu=2,
 vu(1)=-25.,
 identy=2,
 vy(1)=4*-20.,
 th(1)=.05,.18,.05,.18,
 w0(1)=64.,
 identa=0,
 attn(1)=4*.5$
pilot response to theta error
 $nam1_icode=10$
 $frqdat jx=2,mu=1,my1=1,my2=2$
pilot response to theta
 $nam1 icode=10$
 $frqdat jx=2,mu=1,my1=3,my2=4$
theta to stick
 $nam1 icode=10$
 $frqdat jx=4,mu=1,my1=3,my2=0$
#eor
#eof
```

Configuration 1-1

```
                         Theta/stick 1-1
(  0.7700     )S** 3        ( -0.9360e-01) + J(      0.     )
(   1.905     )S** 2        ( -0.3807    ) + J(      0.     )
(  0.7579     )S** 1        (   -2.000   ) + J(      0.     )
(  0.5488e-01)

(   1.000     )S** 5        (      0.    ) + J(      0.     )
(   4.866     )S** 4        ( -0.8320e-01) + J(      0.     )
(   10.10     )S** 3        ( -0.4346    ) + J(      0.     )
(   4.203     )S** 2        (   -2.174   ) + J(   1.757     )
(  0.2825     )S** 1        (   -2.174   ) + J(  -1.757     )
(      0.     )

                        Gamma/stick 1-1
(  0.5230e-01)S** 4         (  0.1450e-01) + J(      0.     )
(  0.1248     )S** 3        (   -2.000   ) + J(      0.     )
(  0.4102     )S** 2        ( -0.2000    ) + J(   2.653     )
(  0.7344     )S** 1        ( -0.2000    ) + J(  -2.653     )
( -0.1074e-01)

(   1.000     )S** 5        (      0.    ) + J(      0.     )
(   4.866     )S** 4        ( -0.8320e-01) + J(      0.     )
(   10.10     )S** 3        ( -0.4346    ) + J(      0.     )
(   4.203     )S** 2        (   -2.174   ) + J(   1.757     )
(  0.2825     )S** 1        (   -2.174   ) + J(  -1.757     )
(      0.     )
```

Configuration 1-2

```
                        Theta/stick 1-2
(  0.7700     )S** 3        ( -0.5630e-01) + J(      0.     )
(   2.141     )S** 2        ( -0.7238    ) + J(      0.     )
(   1.234     )S** 1        (   -2.000   ) + J(      0.     )
(  0.6331e-01)

(   1.000     )S** 5        (      0.    ) + J(      0.     )
(   5.167     )S** 4        ( -0.5250e-01) + J(      0.     )
(   11.43     )S** 3        ( -0.8208    ) + J(      0.     )
(   6.855     )S** 2        (   -2.147   ) + J(   1.740     )
(  0.3291     )S** 1        (   -2.147   ) + J(  -1.740     )
(      0.     )

                        Gamma/stick 1-2
(  0.5230e-01)S** 4         (  0.1110e-02) + J(      0.     )
(  0.1648     )S** 3        (   -2.000   ) + J(      0.     )
(  0.7536     )S** 2        ( -0.5758    ) + J(   3.432     )
(   1.266     )S** 1        ( -0.5758    ) + J(  -3.432     )
( -0.1406e-02)

(   1.000     )S** 5        (      0.    ) + J(      0.     )
(   5.167     )S** 4        ( -0.5250e-01) + J(      0.     )
(   11.43     )S** 3        ( -0.8208    ) + J(      0.     )
(   6.855     )S** 2        (   -2.147   ) + J(   1.740     )
(  0.3291     )S** 1        (   -2.147   ) + J(  -1.740     )
(      0.     )
```

Configuration 1-3

Theta/stick 1-3

```
(  0.7700     )S** 3          ( -0.3850e-01) + J(        0.      )
(   2.362     )S** 2          (  -1.029    ) + J(        0.      )
(   1.674     )S** 1          (  -2.000    ) + J(        0.      )
(  0.6101e-01)

(   1.000     )S** 5          (      0.    ) + J(        0.      )
(   5.452     )S** 4          ( -0.3560e-01) + J(        0.      )
(   12.67     )S** 3          (  -1.190    ) + J(        0.      )
(   9.302     )S** 2          (  -2.113    ) + J(    1.726       )
(  0.3154     )S** 1          (  -2.113    ) + J(   -1.726       )
(      0.     )
```

Gamma/stick 1-3

```
(  0.5230e-01)S** 4           (  0.2230e-02) + J(        0.      )
(  0.2022     )S** 3          (  -2.000    ) + J(        0.      )
(   1.074     )S** 2          ( -0.9343    ) + J(    3.992       )
(   1.756     )S** 1          ( -0.9343    ) + J(   -3.992       )
( -0.3921e-02)

(   1.000     )S** 5          (      0.    ) + J(        0.      )
(   5.452     )S** 4          ( -0.3560e-01) + J(        0.      )
(   12.67     )S** 3          (  -1.190    ) + J(        0.      )
(   9.302     )S** 2          (  -2.113    ) + J(    1.726       )
(  0.3154     )S** 1          (  -2.113    ) + J(   -1.726       )
(      0.     )
```

Configuration 2-1

Theta/stick 2-1

```
(  0.3500     )S** 3          ( -0.9360e-01) + J(        0.      )
(  0.8660     )S** 2          ( -0.3807    ) + J(        0.      )
(  0.3445     )S** 1          (  -2.000    ) + J(        0.      )
(  0.2494e-01)

(   1.000     )S** 5          (      0.    ) + J(        0.      )
(   2.702     )S** 4          ( -0.7390e-01) + J(        0.      )
(   4.415     )S** 3          ( -0.4997    ) + J(        0.      )
(   1.890     )S** 2          (  -1.064    ) + J(    1.423       )
(  0.1166     )S** 1          (  -1.064    ) + J(   -1.423       )
(      0.     )
```

Gamma/stick 2-1

```
(  0.2435e-01)S** 4           (  0.1450e-02) + J(        0.      )
(  0.5770e-01)S** 3           (  -2.000    ) + J(        0.      )
(  0.1832     )S** 2          ( -0.1855    ) + J(    2.598       )
(  0.3301     )S** 1          ( -0.1855    ) + J(   -2.598       )
( -0.4791e-03)

(   1.000     )S** 5          (      0.    ) + J(        0.      )
(   2.702     )S** 4          ( -0.7390e-01) + J(        0.      )
(   4.415     )S** 3          ( -0.4997    ) + J(        0.      )
(   1.890     )S** 2          (  -1.064    ) + J(    1.423       )
(  0.1166     )S** 1          (  -1.064    ) + J(   -1.423       )
(      0.     )
```

Configuration 2-2

```
                          Theta/stick 2-2
(  0.3500    )S** 3         ( -0.5680e-01) + J(      0.     )
(  0.9732    )S** 2         ( -0.7238    ) + J(      0.     )
(  0.5608    )S** 1         (  -2.000    ) + J(      0.     )
(  0.2878e-01)

(   1.000    )S** 5         (     0.     ) + J(      0.     )
(   3.005    )S** 4         ( -0.4830e-01) + J(      0.     )
(   5.086    )S** 3         ( -0.9310    ) + J(      0.     )
(   3.085    )S** 2         (  -1.013    ) + J(   1.425     )
(  0.1375    )S** 1         (  -1.013    ) + J(  -1.425     )
(      0.    )

                          Gamma/stick 2-2
(  0.2435e-01)S** 3         (  -2.000    ) + J(      0.     )
(  0.7639e-01)S** 2         ( -0.5686    ) + J(   2.623     )
(  0.2308    )S** 1         ( -0.5686    ) + J(  -2.623     )
(  0.3508    )

(   1.000    )S** 4         ( -0.4830e-01) + J(      0.     )
(   3.005    )S** 3         ( -0.9310    ) + J(      0.     )
(   5.086    )S** 2         (  -1.013    ) + J(   1.425     )
(   3.085    )S** 1         (  -1.013    ) + J(  -1.425     )
(  0.1375    )
```

Configuration 7-1

```
                          Theta/stick 7-1
(  0.6200    )S** 2         ( -0.5470e-01) + J(      0.     )
(  0.4759    )S** 1         ( -0.7128    ) + J(      0.     )
(  0.2417e-01)

(   1.000    )S** 4         ( -0.1610e-01) + J(  0.1633     )
(   4.630    )S** 3         ( -0.1610e-01) + J( -0.1633     )
(   8.261    )S** 2         (  -2.324    ) + J(   1.638     )
(  0.3855    )S** 1         (  -2.324    ) + J(  -1.638     )
(  0.2177    )

                          Gamma/stick 7-1
(  0.4159e-01)S** 3         (  0.4000e-02) + J(      0.     )
(  0.4673e-01)S** 2         ( -0.5644    ) + J(   3.938     )
(  0.6580    )S** 1         ( -0.5644    ) + J(  -3.938     )
( -0.2633e-02)

(   1.000    )S** 4         ( -0.1610e-01) + J(  0.1633     )
(   4.630    )S** 3         ( -0.1610e-01) + J( -0.1633     )
(   8.261    )S** 2         (  -2.324    ) + J(   1.638     )
(  0.3855    )S** 1         (  -2.324    ) + J(  -1.638     )
(  0.2177    )
```

DESIRE TO FIND θ/F_s $[\frac{deg}{lb}]$ AND γ/F_s $[\frac{deg}{lb}]$:

1. APPENDIX A IN [2] CONTAINS THE FULL ORDER VEHICLE TF'S

   q/F_s $[\frac{deg/sec}{lb}]$ AND n_{zcg}/F_s $[\frac{g's}{lb}]$

2. REDUCE ORDER OF ABOVE TF'S FROM 11^{TH} TO 5^{TH} ORDER BY REMOVING POLE-ZERO CANCELLATIONS AND HIGHER ORDER MODEL FOLLOWING DYNAMICS. ADJUST DC GAIN APPROPRIATELY.

3. FOR θ/F_s TRANSFER FUNCTION

   $$\theta/F_s = 1/s \; q/F_s \quad [\frac{deg}{lb}]$$

4. FOR γ/F_s TRANSFER FUNCTION

   KINEMATIC RELATIONSHIP: $\dot{\gamma}_p = a_{zp}/U_0$, $a_{zp} = g \cdot n_{zcg} + l_p \ddot{\theta}$

   WHERE p SUBSCRIPT DENOTES QUANTITIES @ PILOT LOCATION

   $$\dot{\gamma}_p = (g \cdot \underset{g's}{n_{zcg}} + l_p \underset{deg/sec^2}{\ddot{\theta}})/U_0 \qquad U_0 = 200\ ft/sec \; , \; l_p = 34\ ft$$

   $$\dot{\gamma}_p = \frac{g}{U_0} \cdot \frac{180}{\pi} n_{zcg} + \frac{34.}{200.} \ddot{\theta} = 9.2246\,(n_{zcg} + .0184\,\ddot{\theta})$$

   $$\dot{\gamma}_p/F_s = 9.2246\,(n_{zcg}/F_s + .0184\,\ddot{\theta}/F_s) \quad [\frac{deg/sec}{lb}]$$

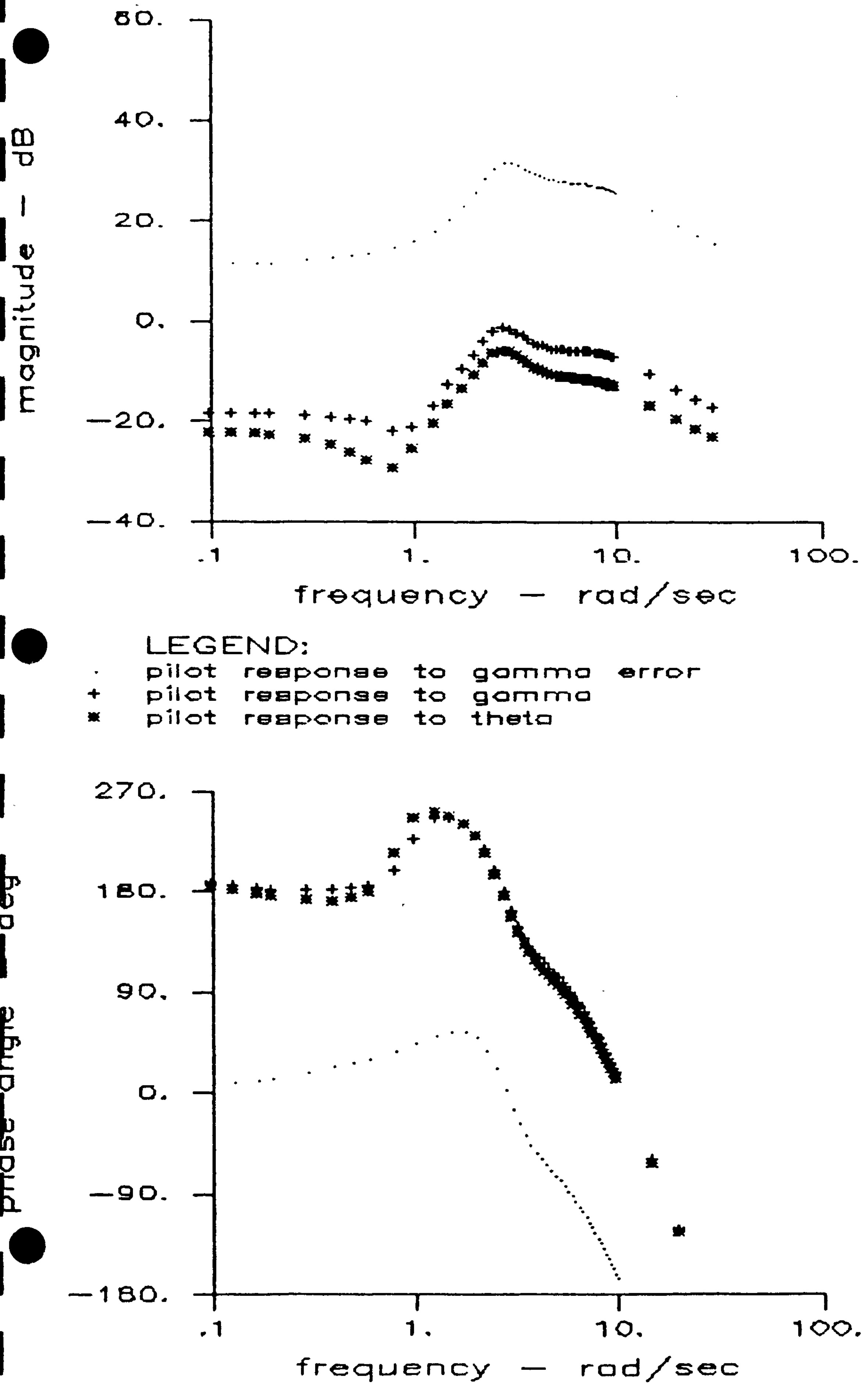
   $$\gamma_p/F_s = 1/s \cdot \dot{\gamma}_p/F_s \quad [\frac{deg}{lb}]$$

APPENDIX V

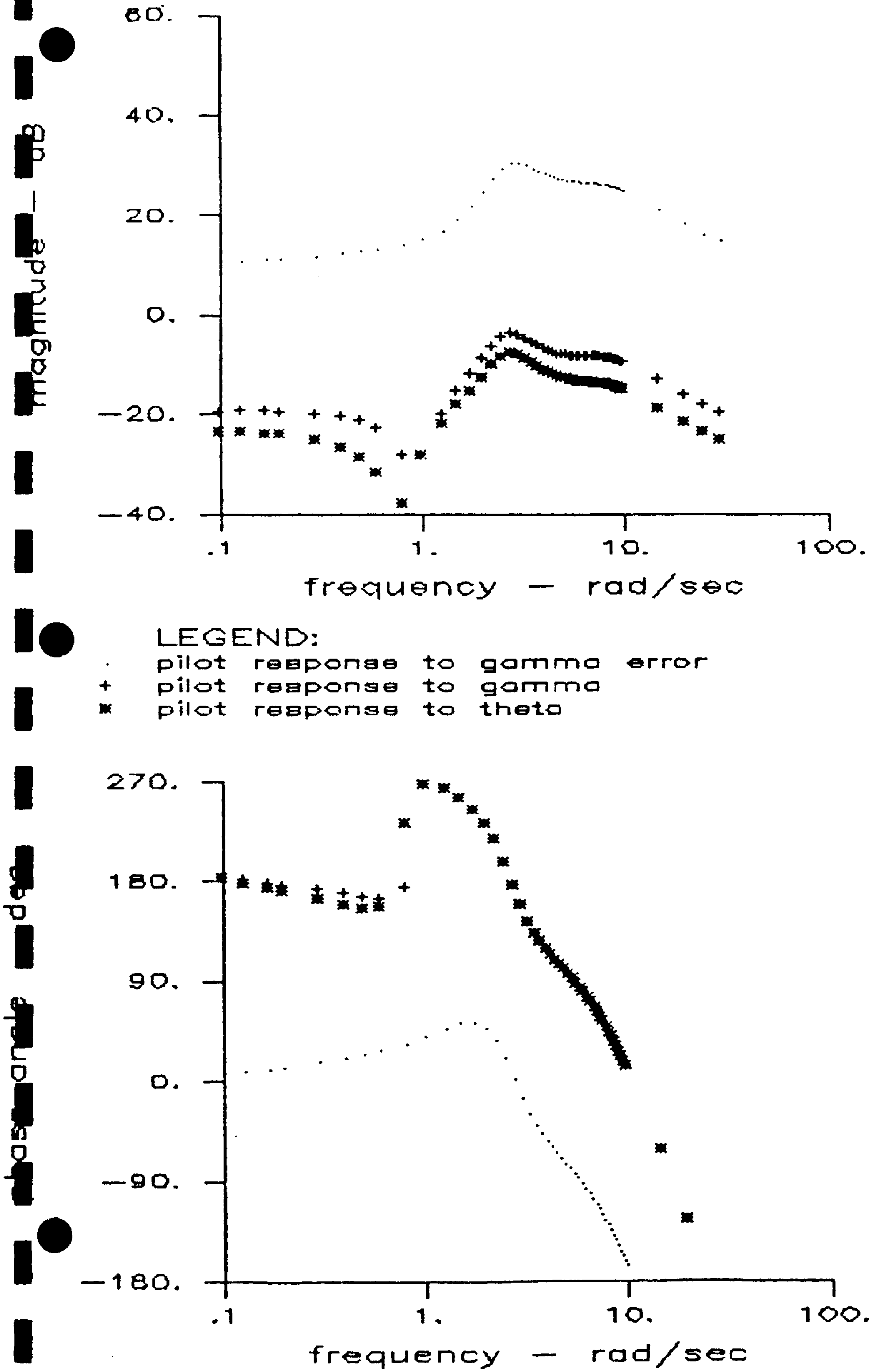
GAMMA TRACKING
- Pilot Responses
- Equivalent Single-Loop Pilot Function
- Gamma/Gamma Commanded, Open/Closed Loop

THETA TRACKING
- Pilot Responses
- Equivalent Single-Loop Pilot Function
- Theta/Theta Commanded, Open/Closed Loop

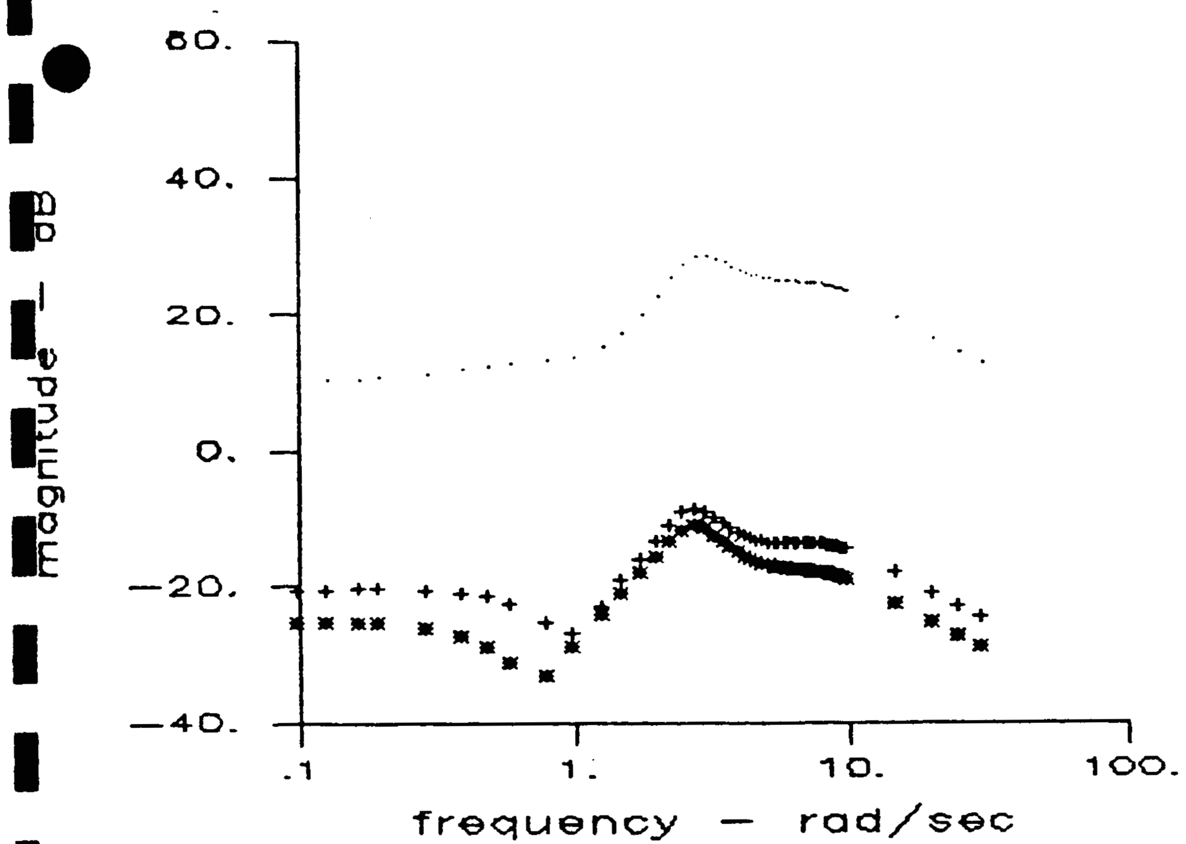
NLR Configuration E-1 : Gamma Tracking



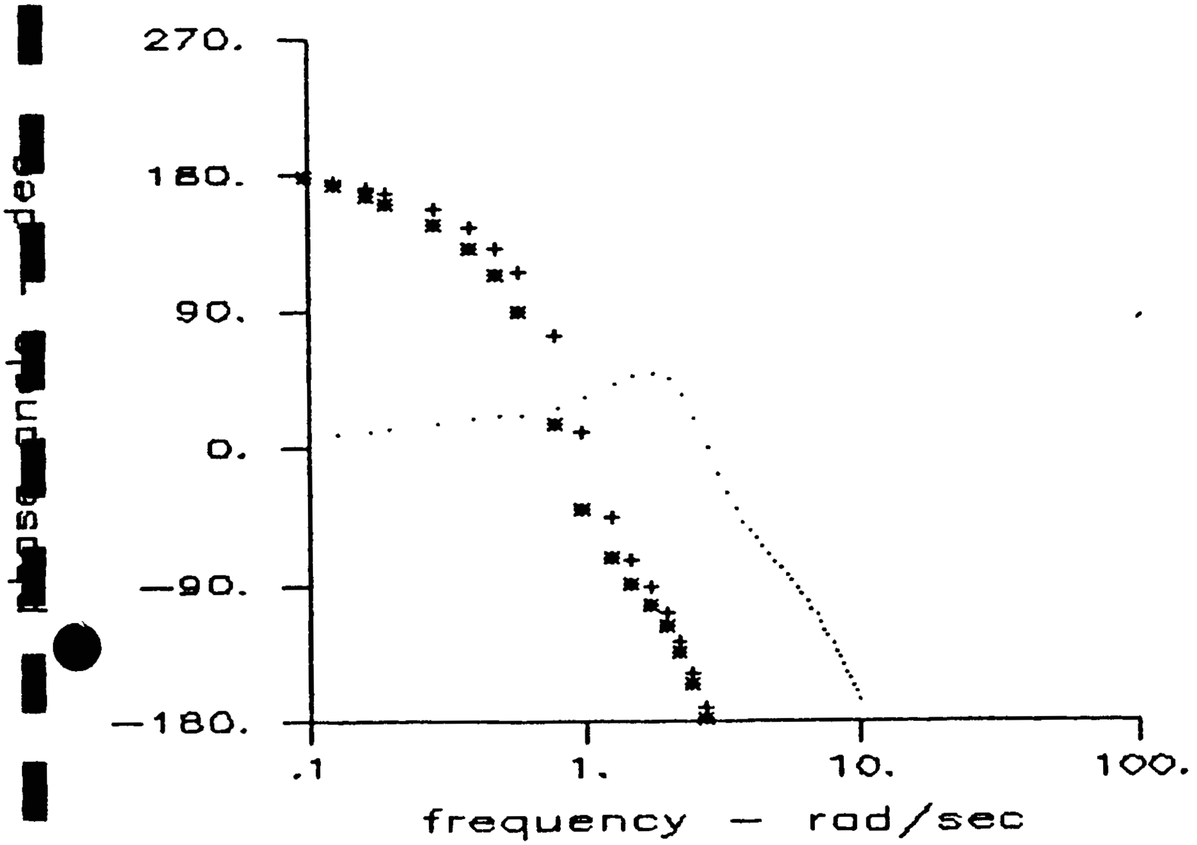
NLR Configuration E-2 : Gamma Tracking

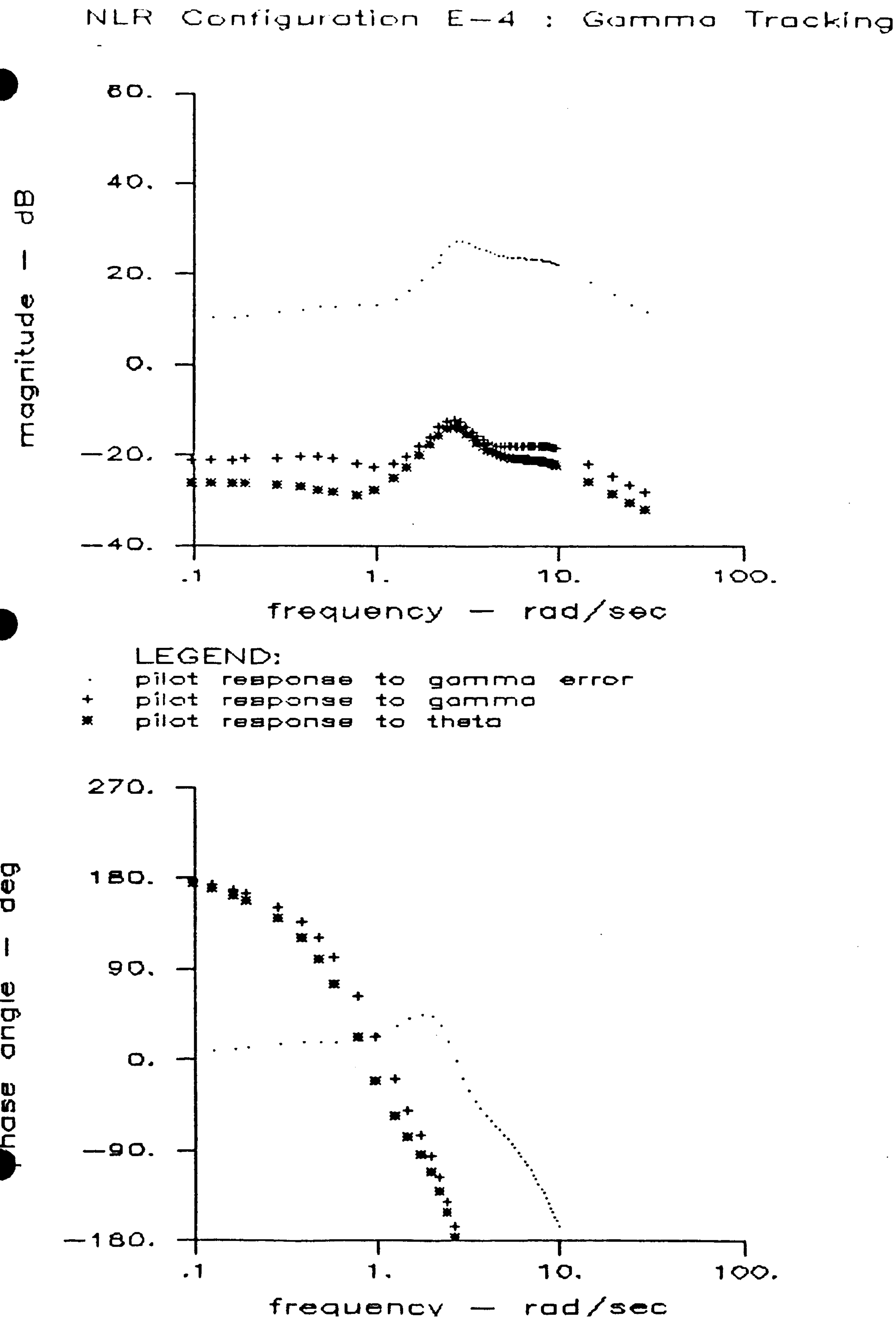


NLR Configuration E-3 : Gamma Tracking



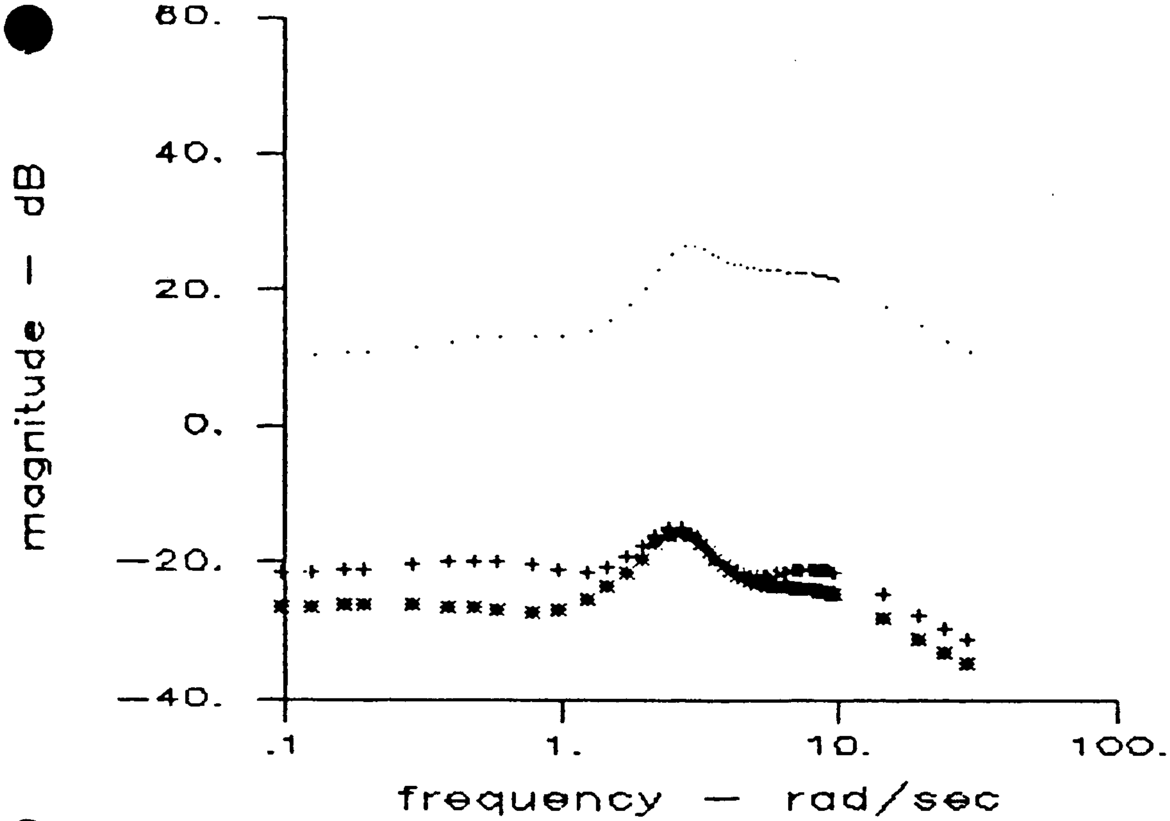
LEGEND:
· pilot response to gamma error
+ pilot response to gamma
* pilot response to theta



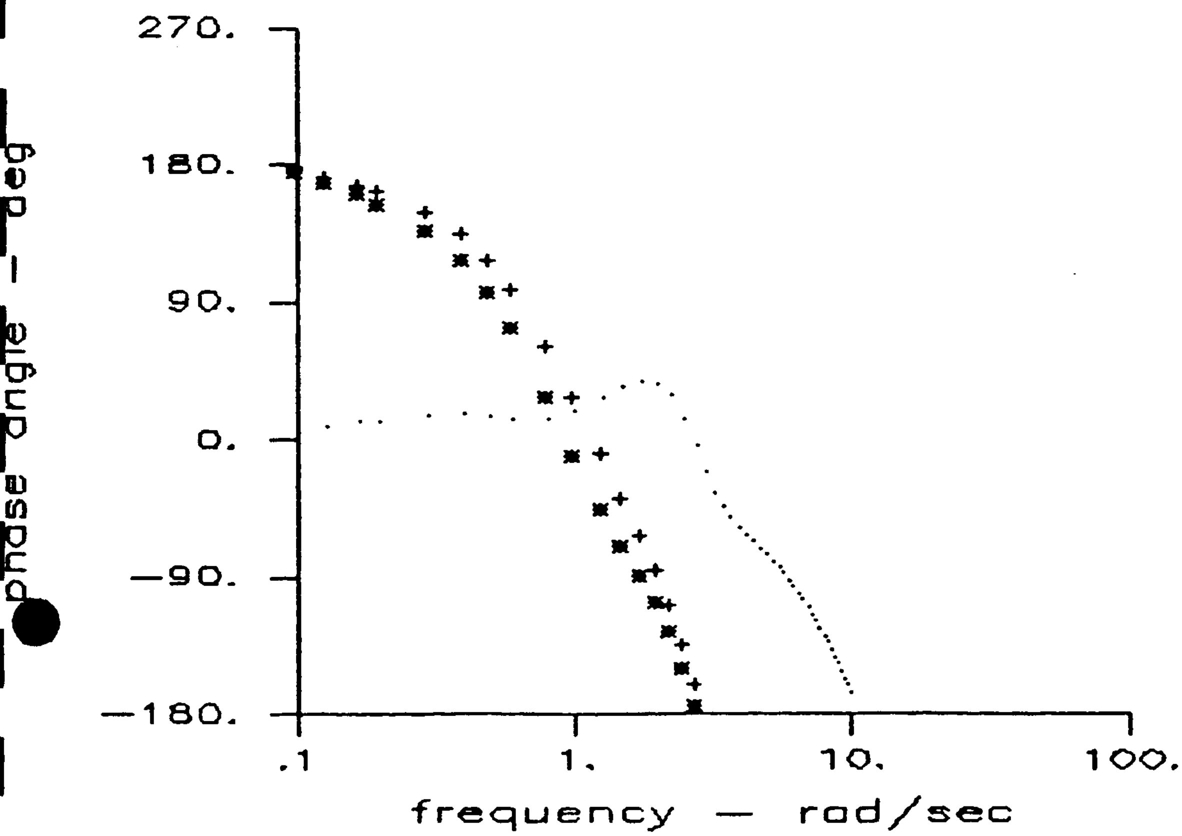


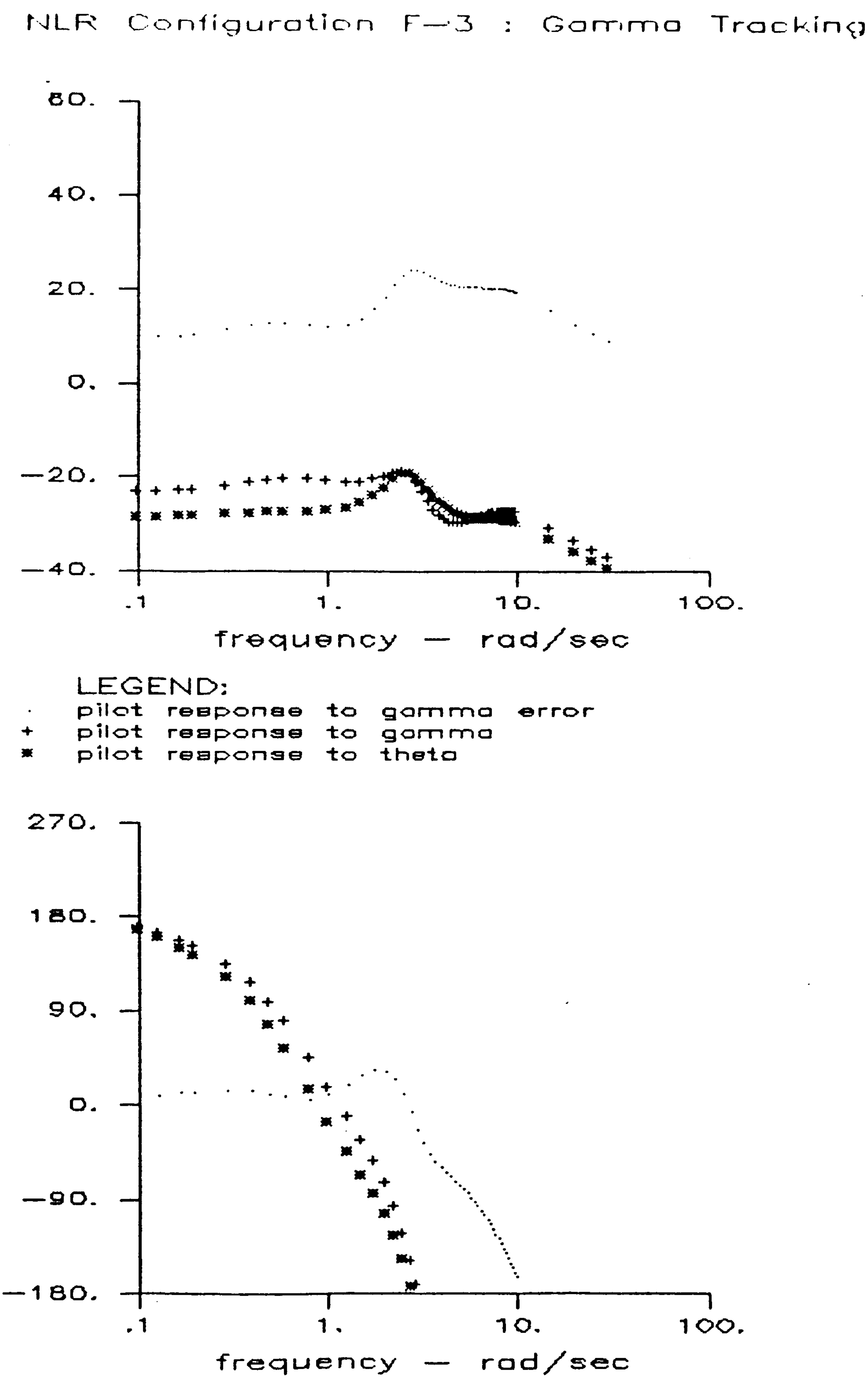
NLR Configuration E-4 : Gamma Tracking
80.
40.
20.
0.
-20.
-40.
magnitude - dB
.1
1.
10.
100.
frequency - rad/sec
LEGEND:
· pilot response to gamma error
+ pilot response to gamma
* pilot response to theta
270.
180.
90.
0.
-90.
-180.
phase angle - deg
.1
1.
10.
100.
frequency - rad/sec

NLR Configuration E-5 : Gamma Tracking

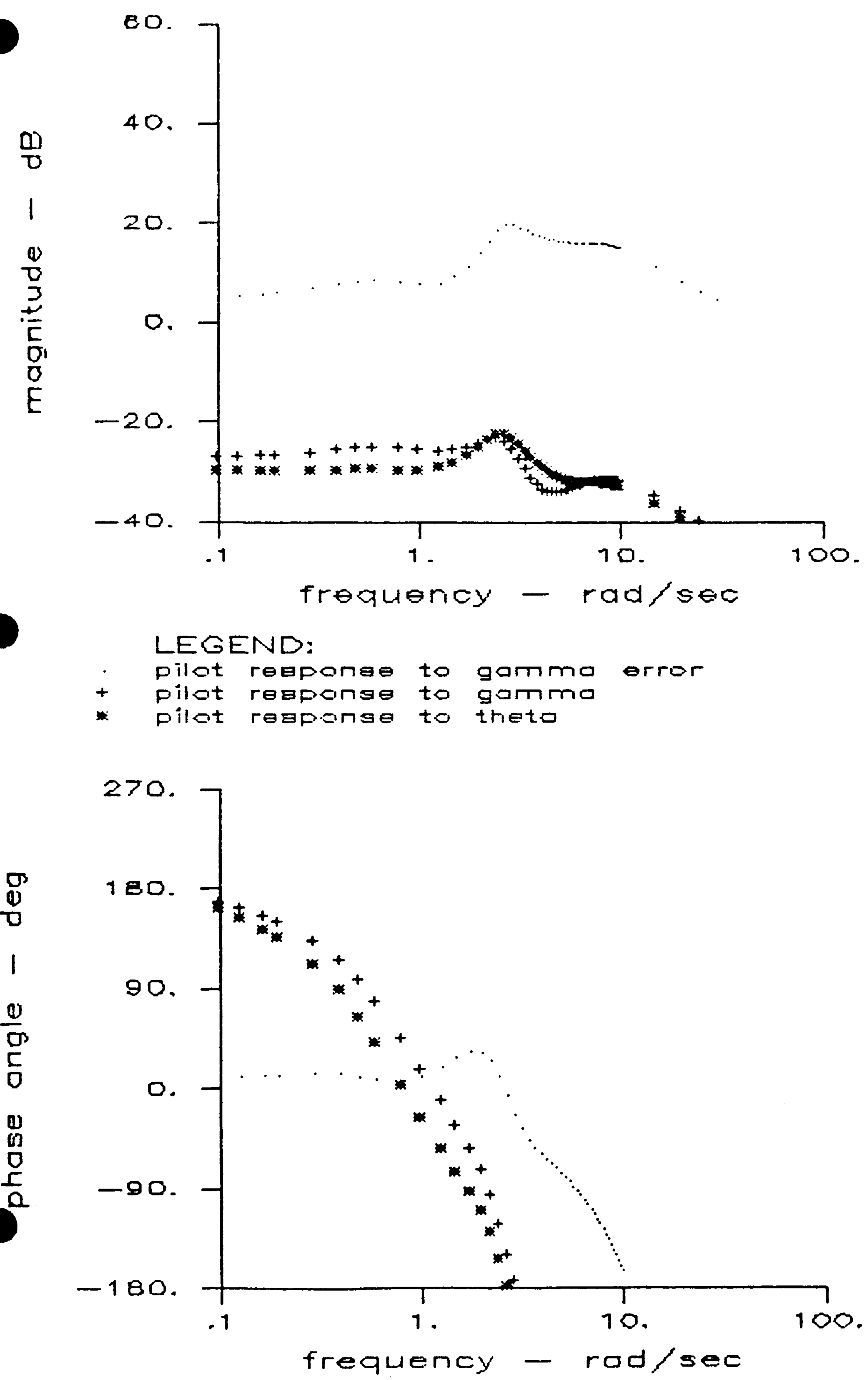


LEGEND:
· pilot response to gamma error
\+ pilot response to gamma
* pilot response to theta

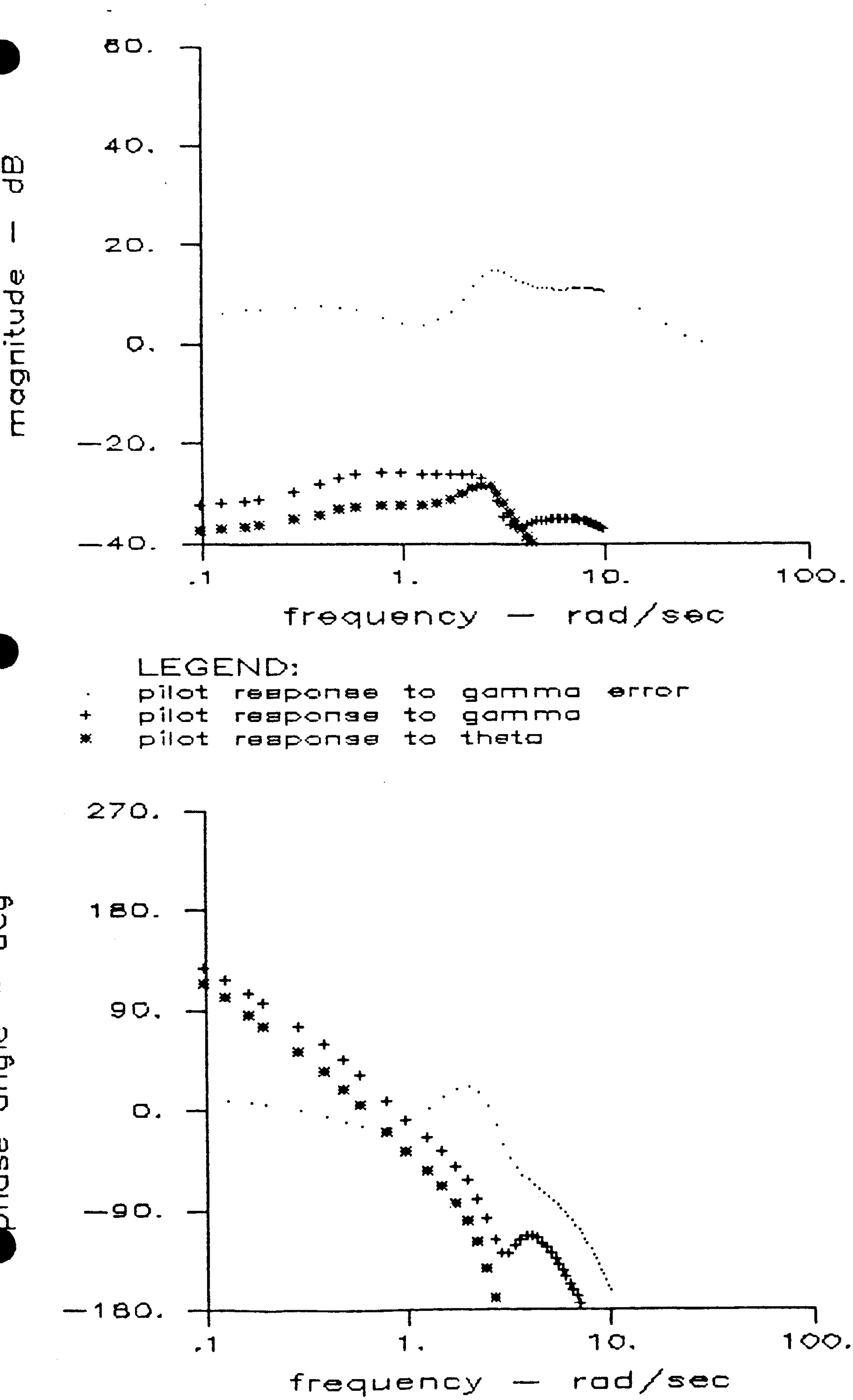


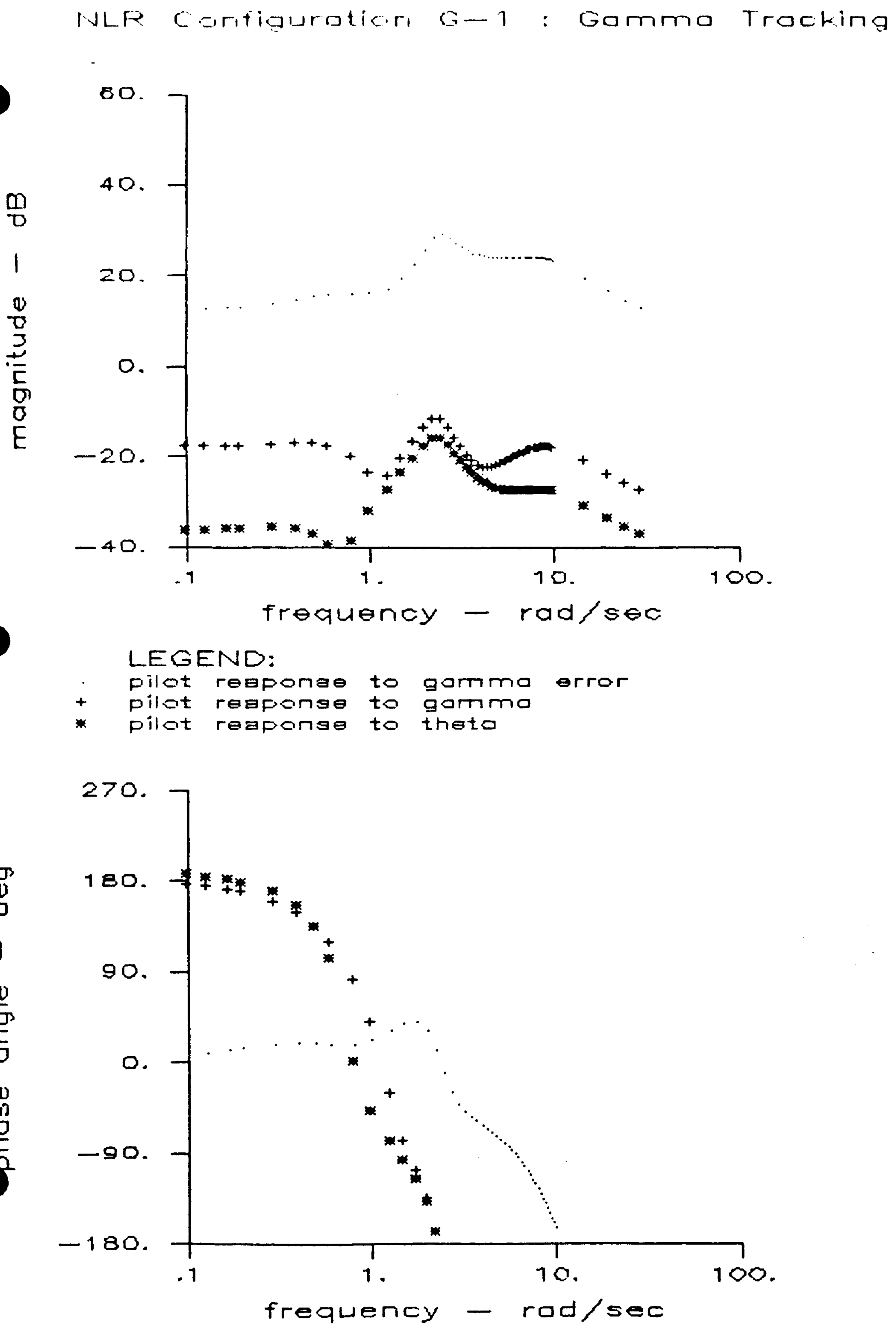

NLR Configuration F-3 : Gamma Tracking
magnitude — dB
60.
40.
20.
0.
-20.
-40.
.1
1.
10.
100.
frequency — rad/sec
LEGEND:
· pilot response to gamma error
+ pilot response to gamma
* pilot response to theta
phase angle — deg
270.
180.
90.
0.
-90.
-180.
.1
1.
10.
100.
frequency — rad/sec

NLR Configuration F-2 : Gamma Tracking



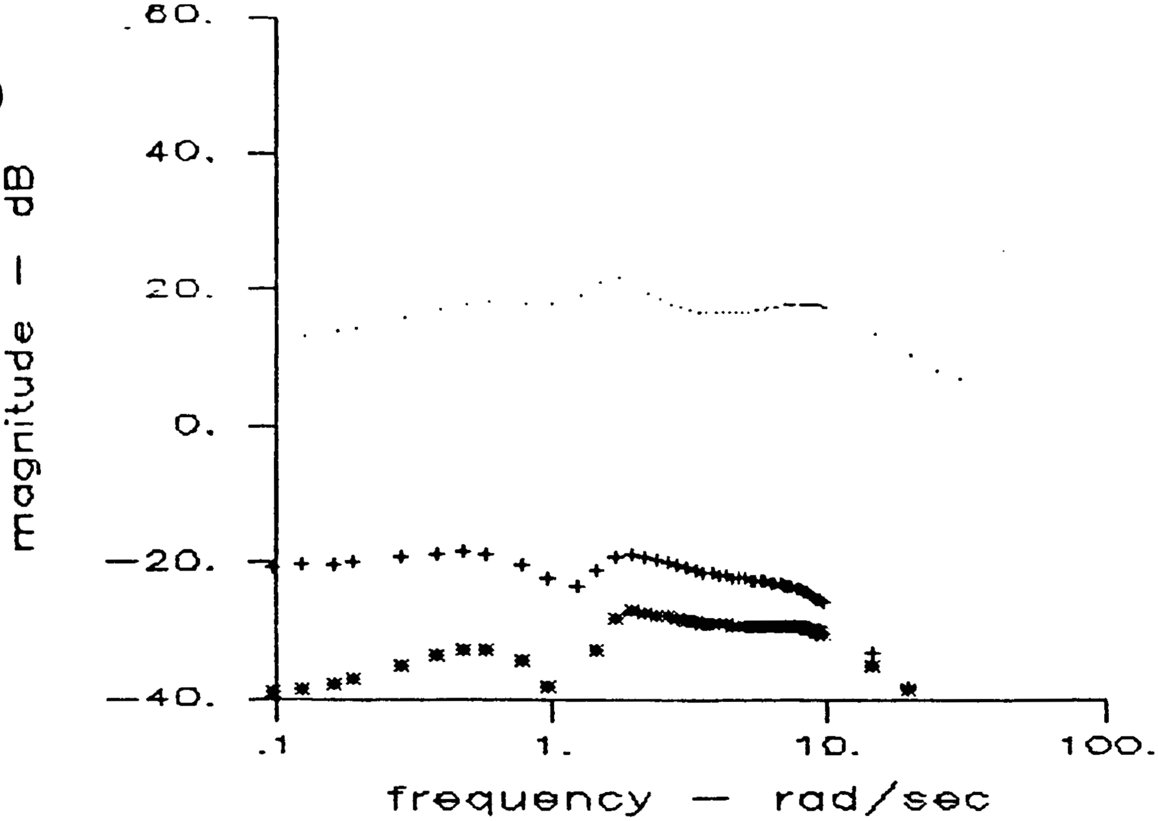
NLR Configuration F-1 : Gamma Tracking



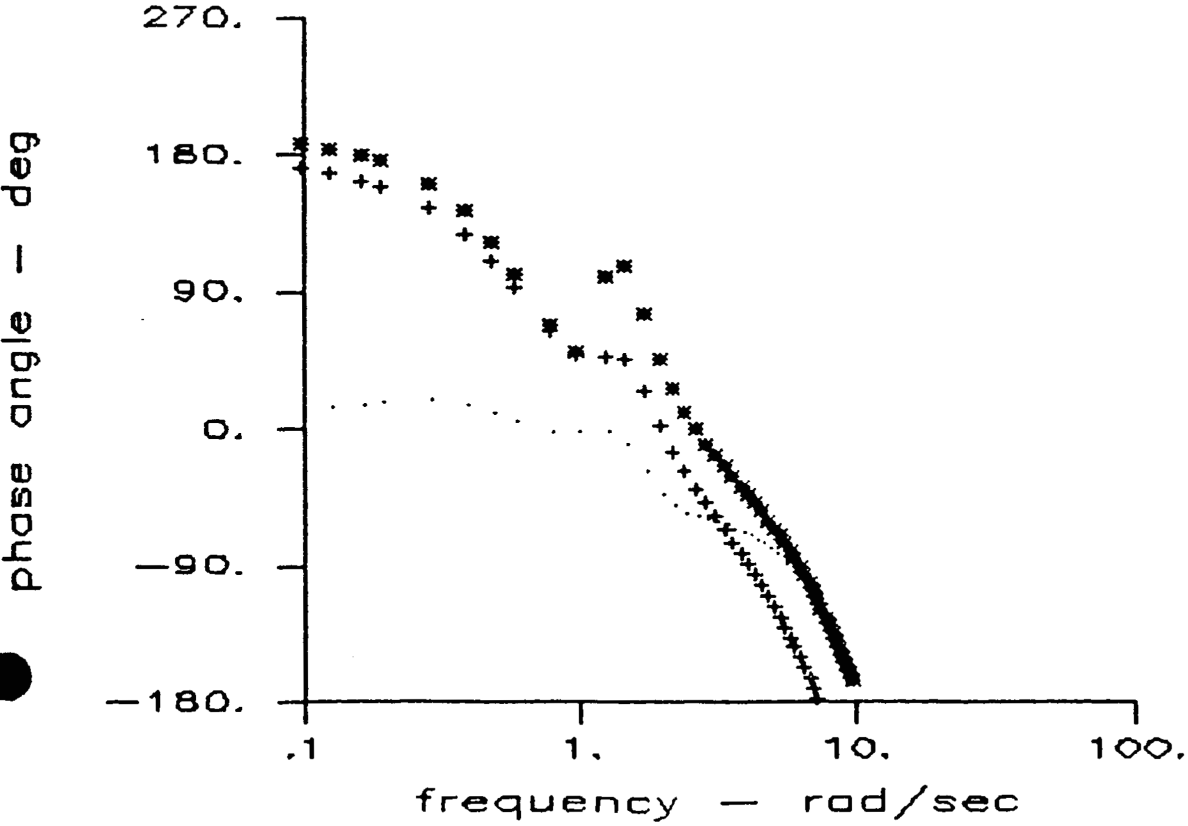


NLR Configuration G-1 : Gamma Tracking
magnitude - dB
60.
40.
20.
0.
-20.
-40.
.1
1.
10.
100.
frequency - rad/sec
LEGEND:
· pilot response to gamma error
+ pilot response to gamma
* pilot response to theta
phase angle - deg
270.
180.
90.
0.
-90.
-180.
.1
1.
10.
100.
frequency - rad/sec

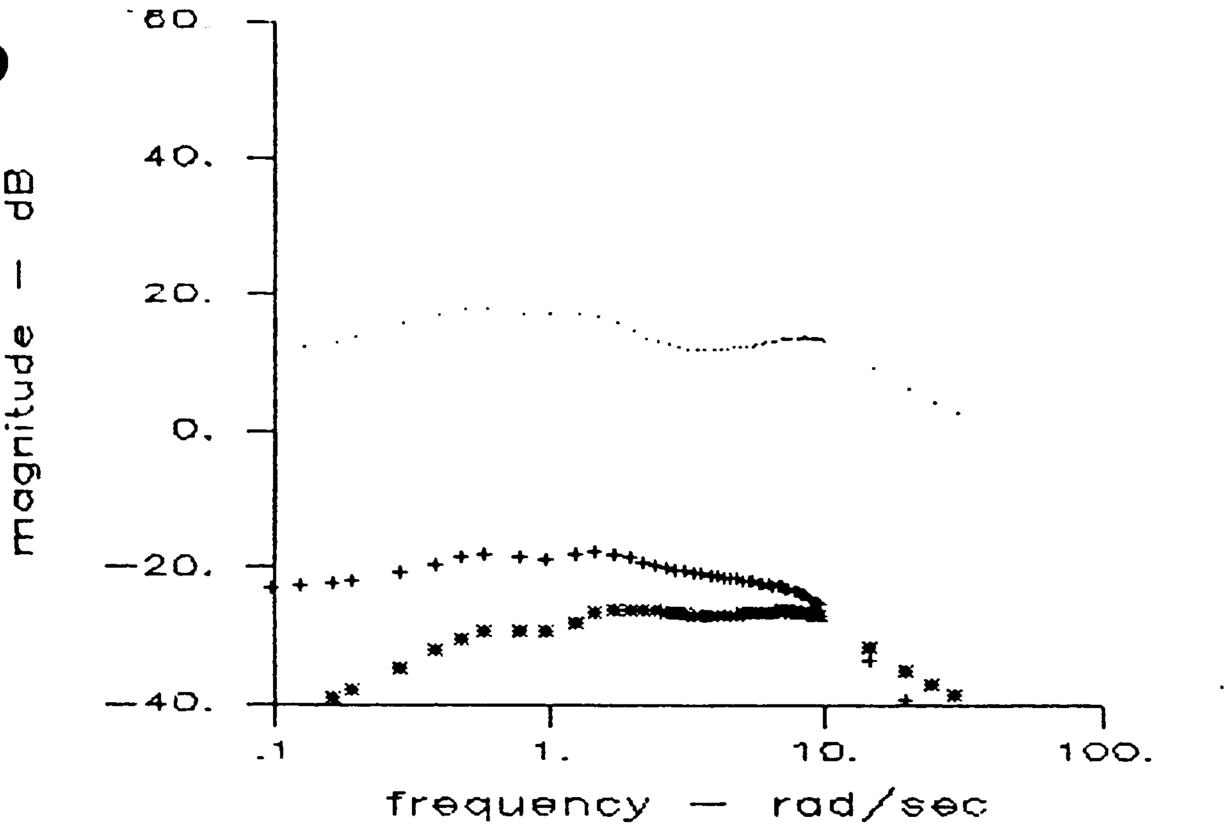
NLR Configuration G-2 : Gamma Tracking



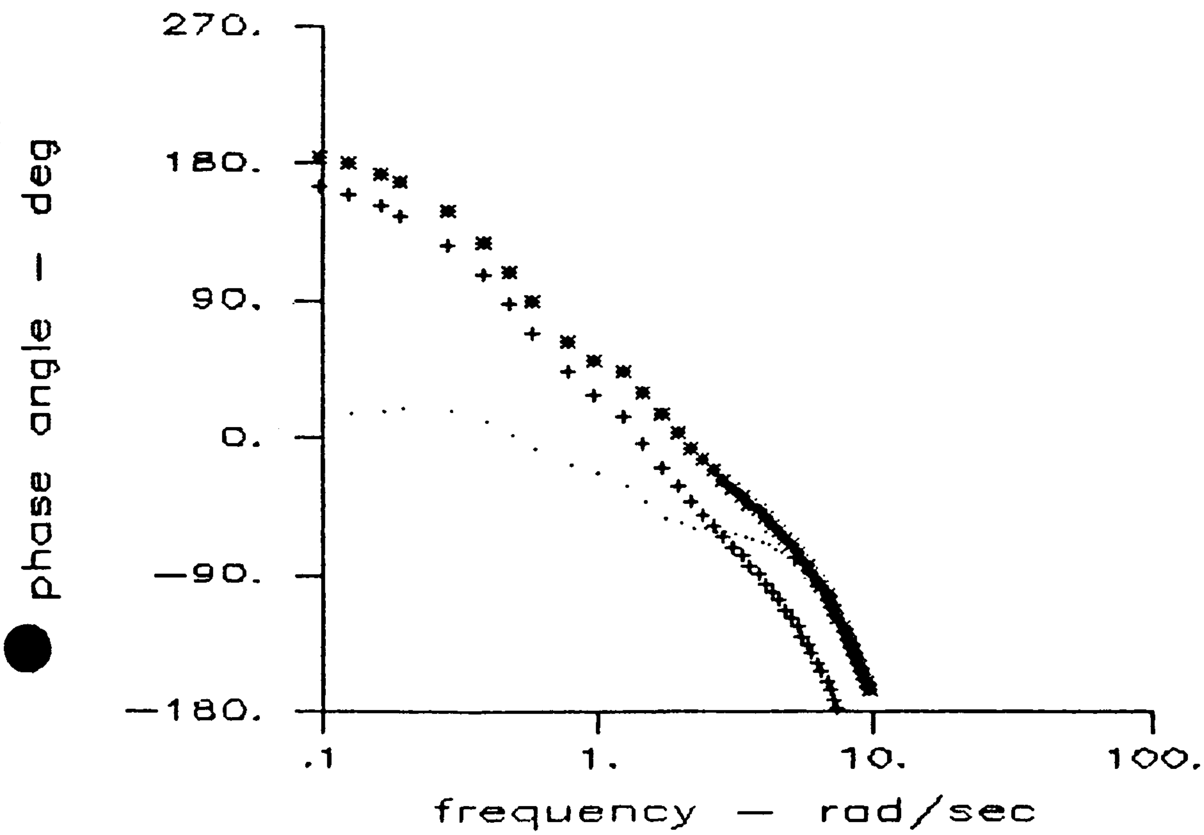
LEGEND:
· pilot response to gamma error
+ pilot response to gamma
* pilot response to theta

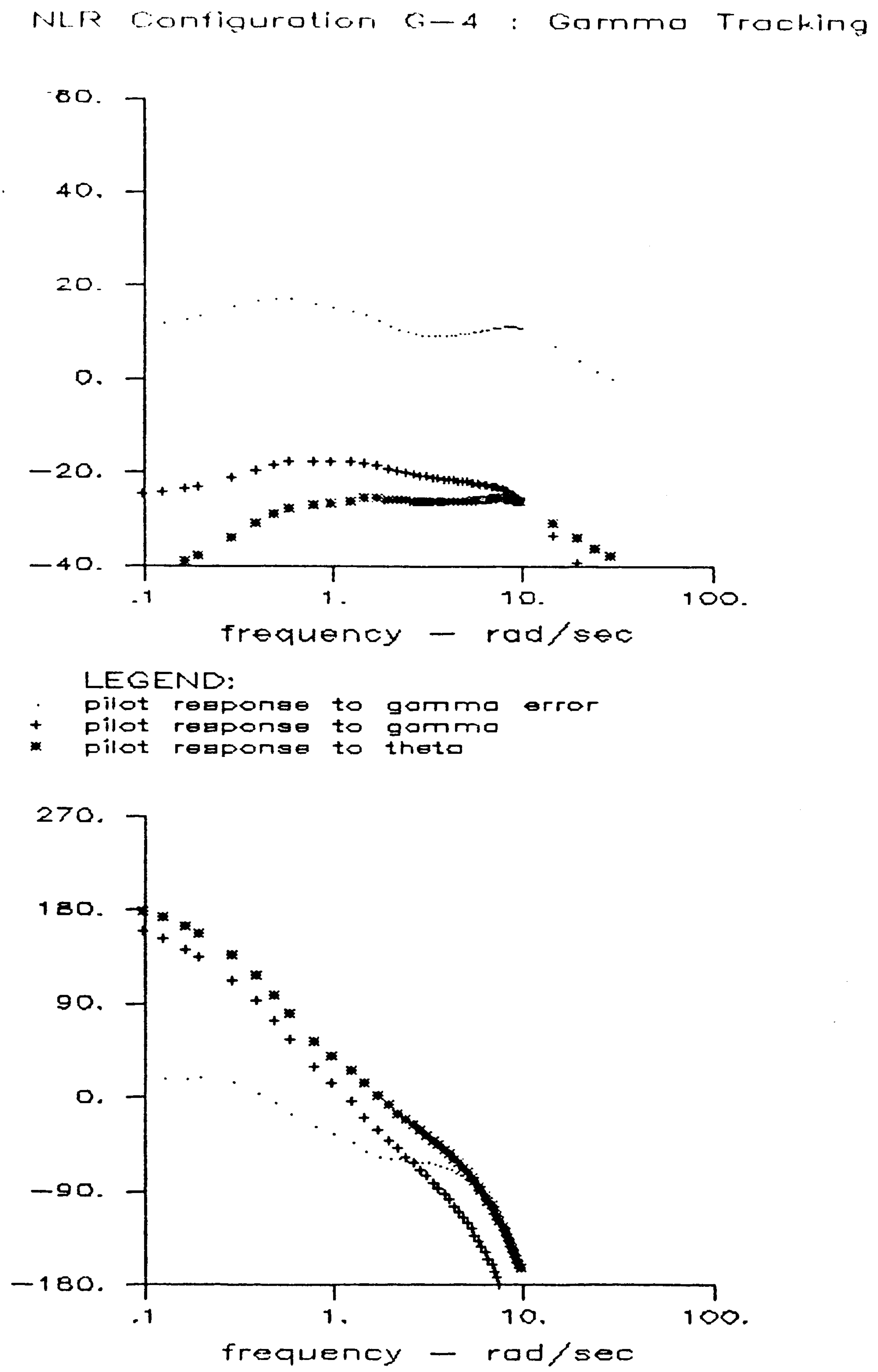


NLR Configuration G-3 : Gamma Tracking

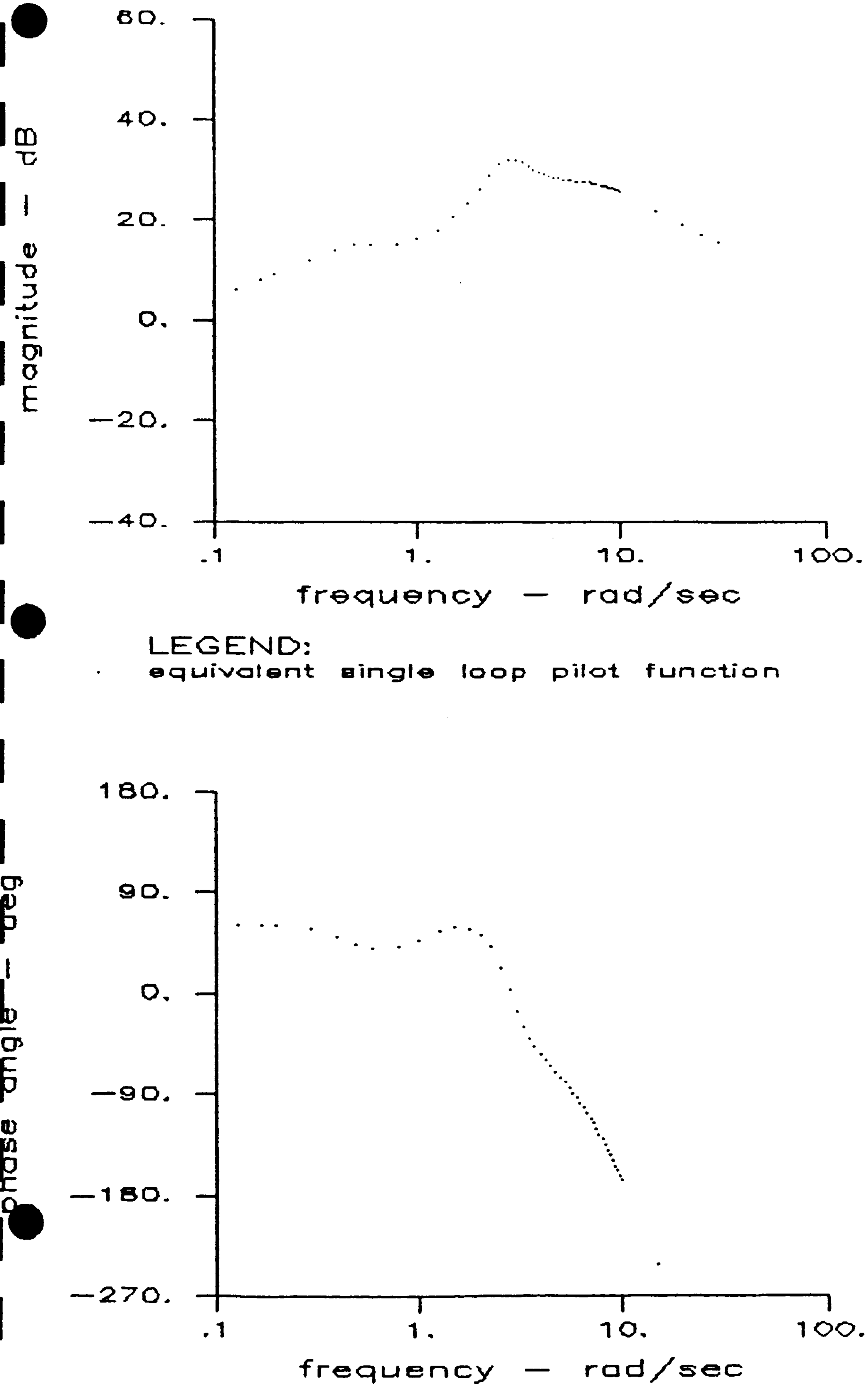


LEGEND:
· pilot response to gamma error
+ pilot response to gamma
* pilot response to theta

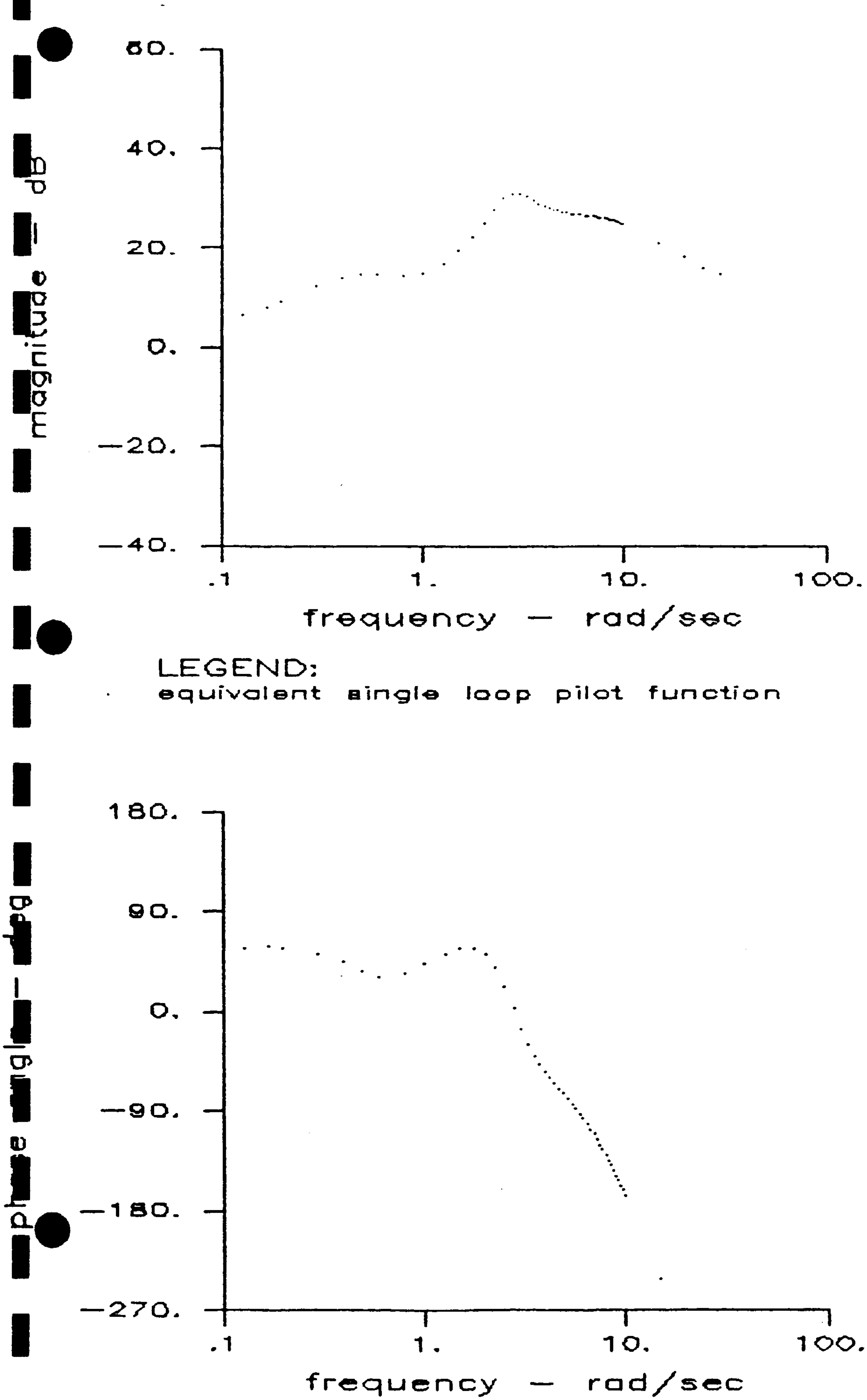



NLR Configuration G-4 : Gamma Tracking
80.
40.
20.
0.
-20.
-40.
magnitude - dB
.1
1.
10.
100.
frequency - rad/sec
LEGEND:
· pilot response to gamma error
+ pilot response to gamma
* pilot response to theta
270.
180.
90.
0.
-90.
-180.
phase angle - deg
.1
1.
10.
100.
frequency - rad/sec

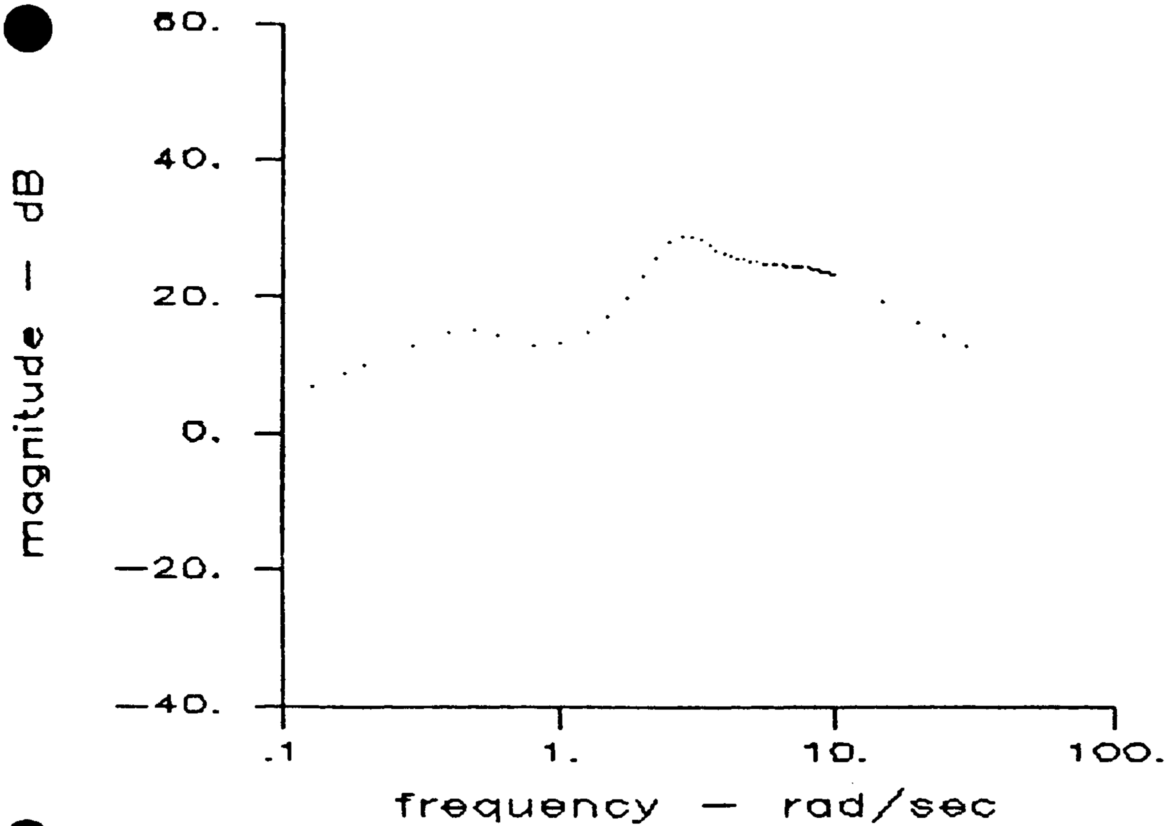
NLR Configuration E-1 : Gamma Tracking



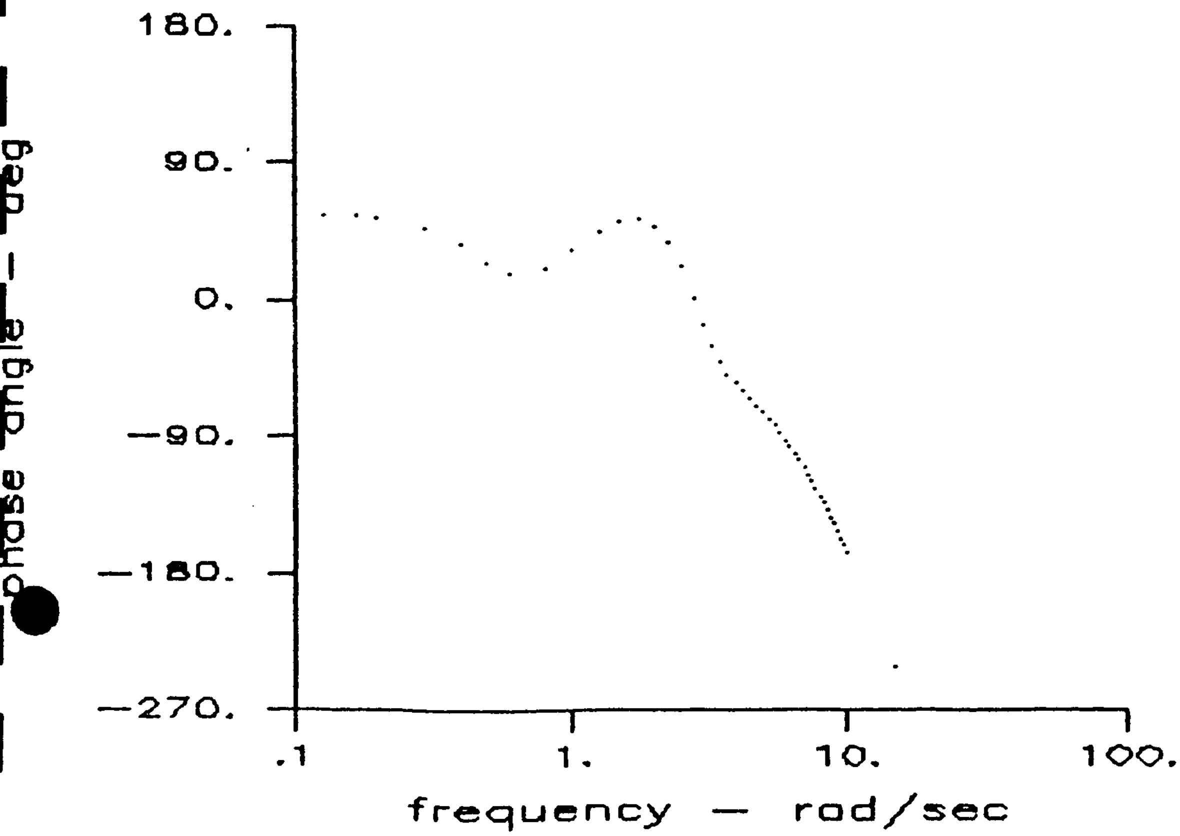
NLR Configuration E-2 : Gamma Tracking



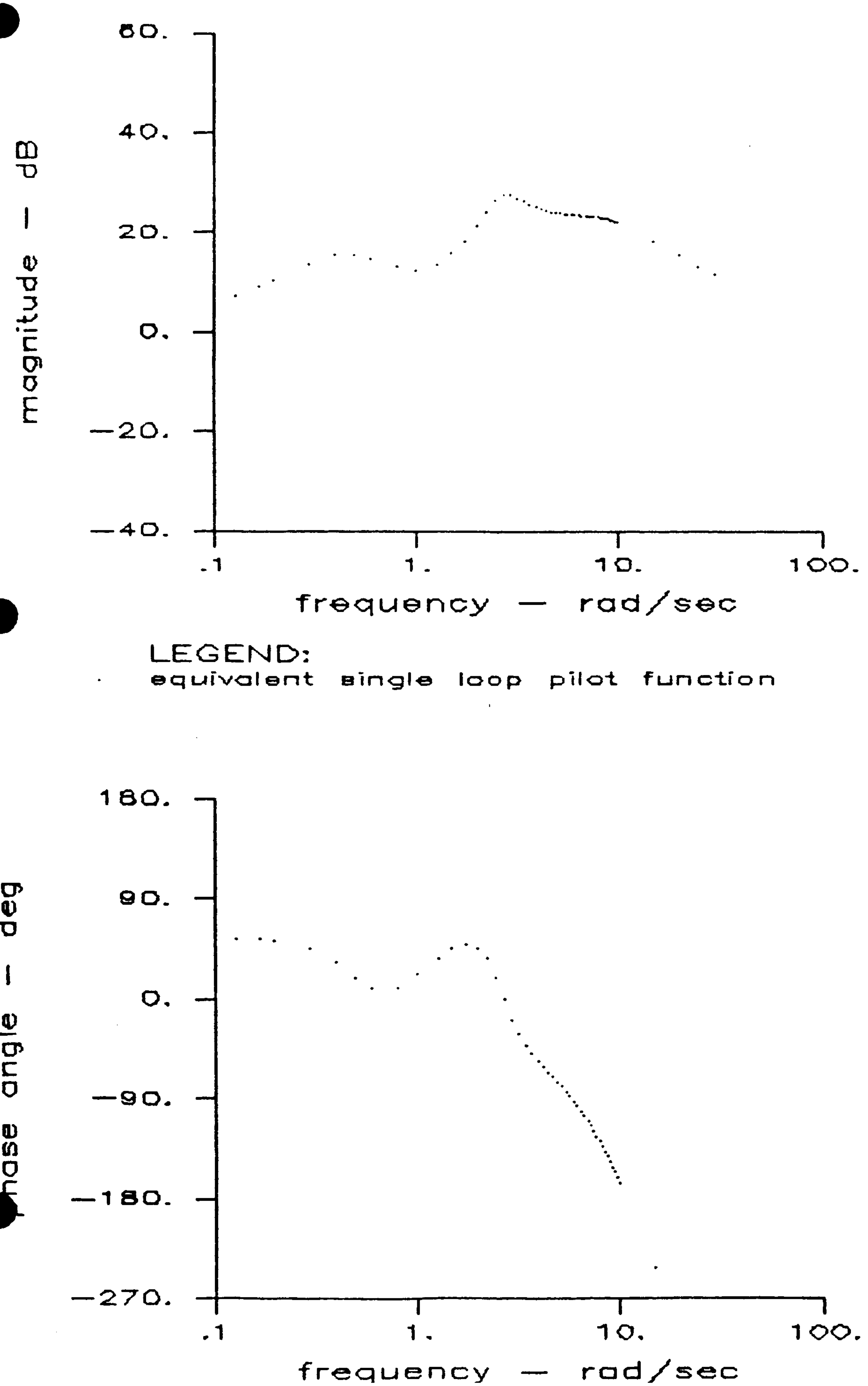
NLR Configuration E-3 : Gamma Tracking



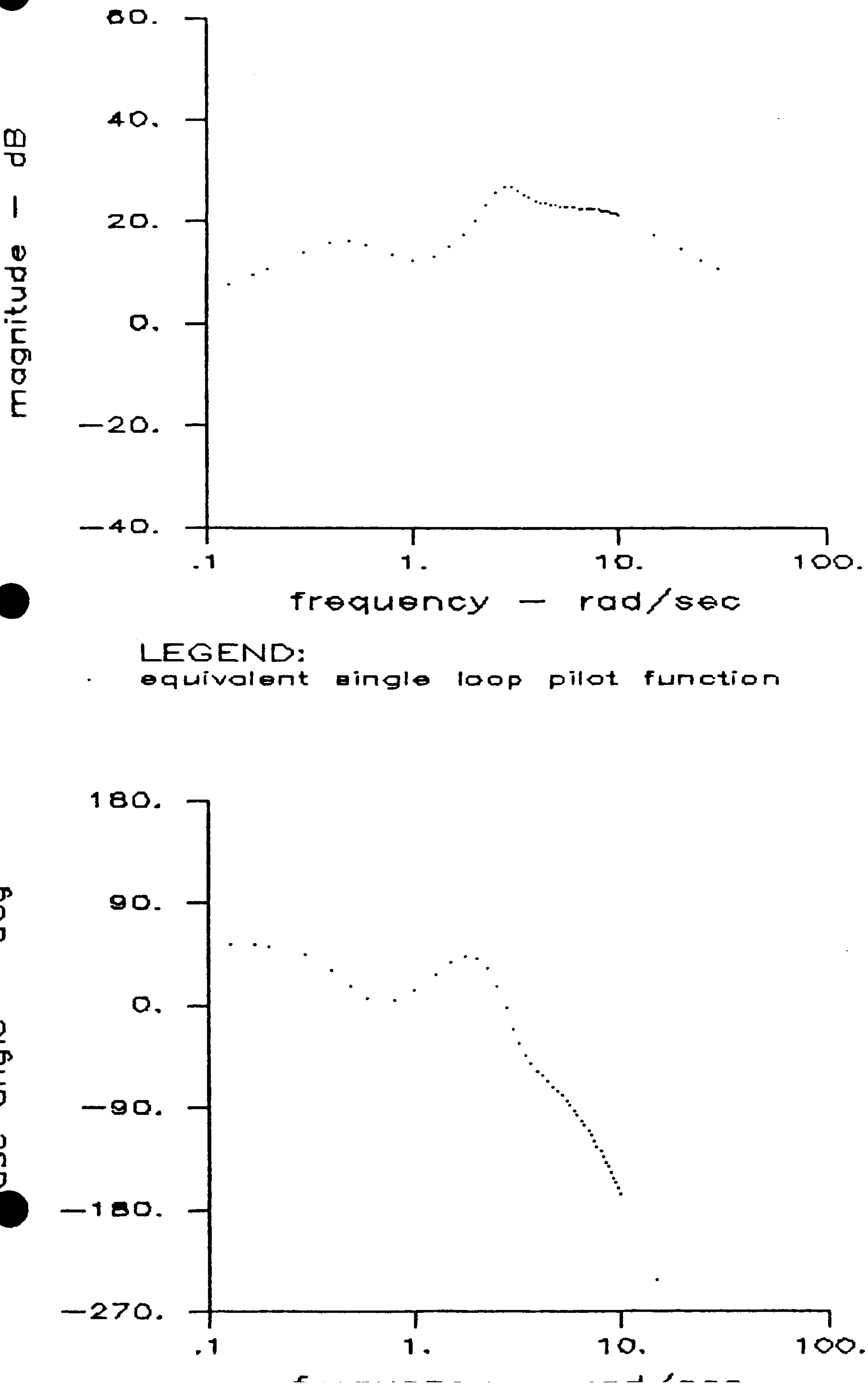
LEGEND:
· equivalent single loop pilot function



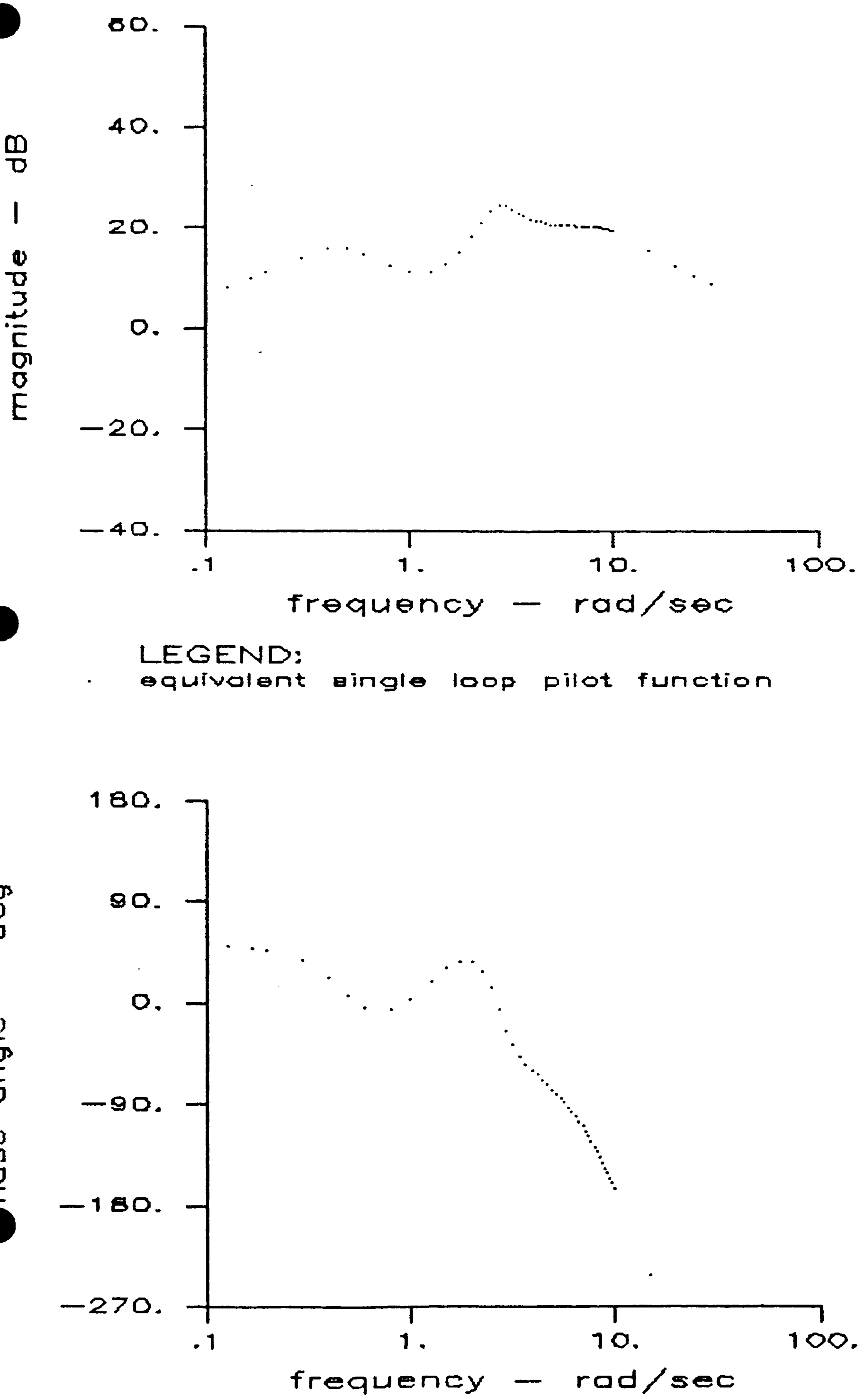
NLR Configuration E-4 : Gamma Tracking



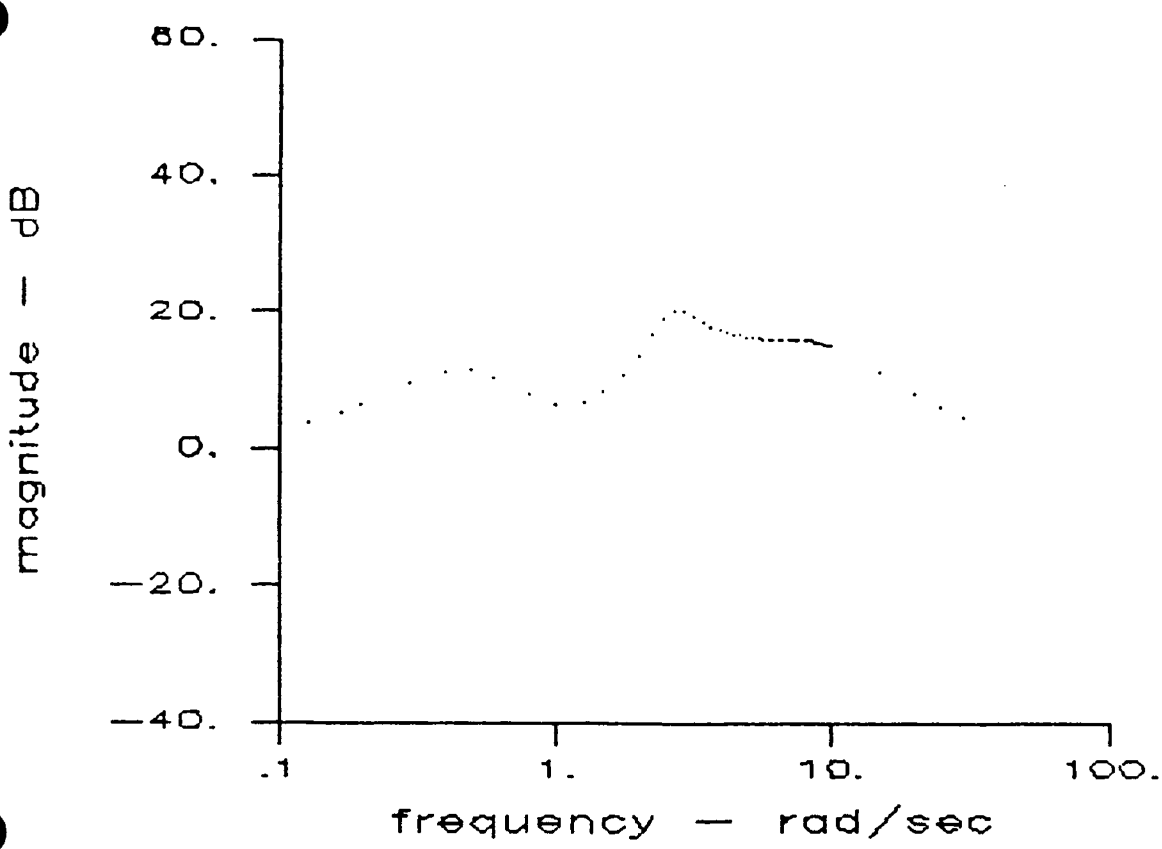
NLR Configuration E-5 : Gamma Tracking



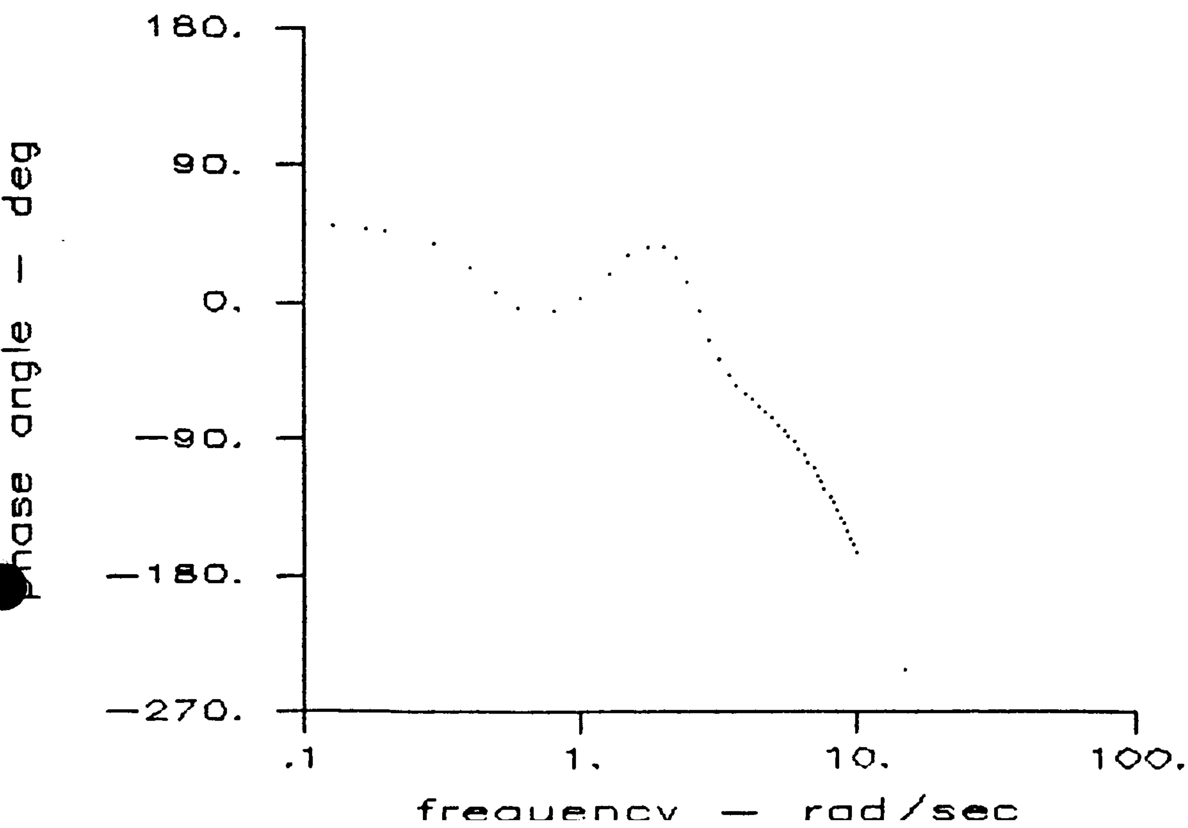
NLR Configuration F-3 : Gamma Tracking



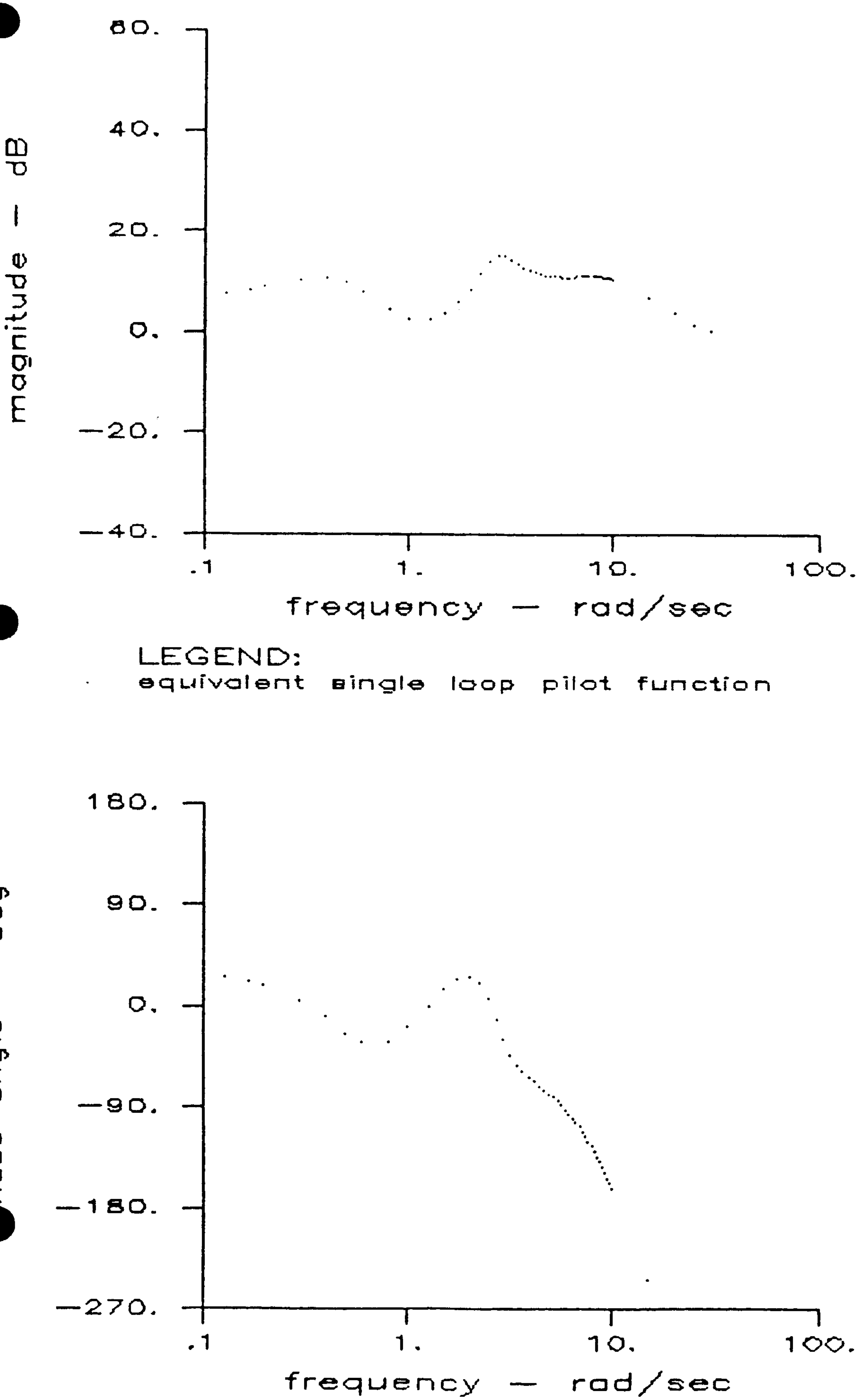
NLR Configuration F-2 : Gamma Tracking



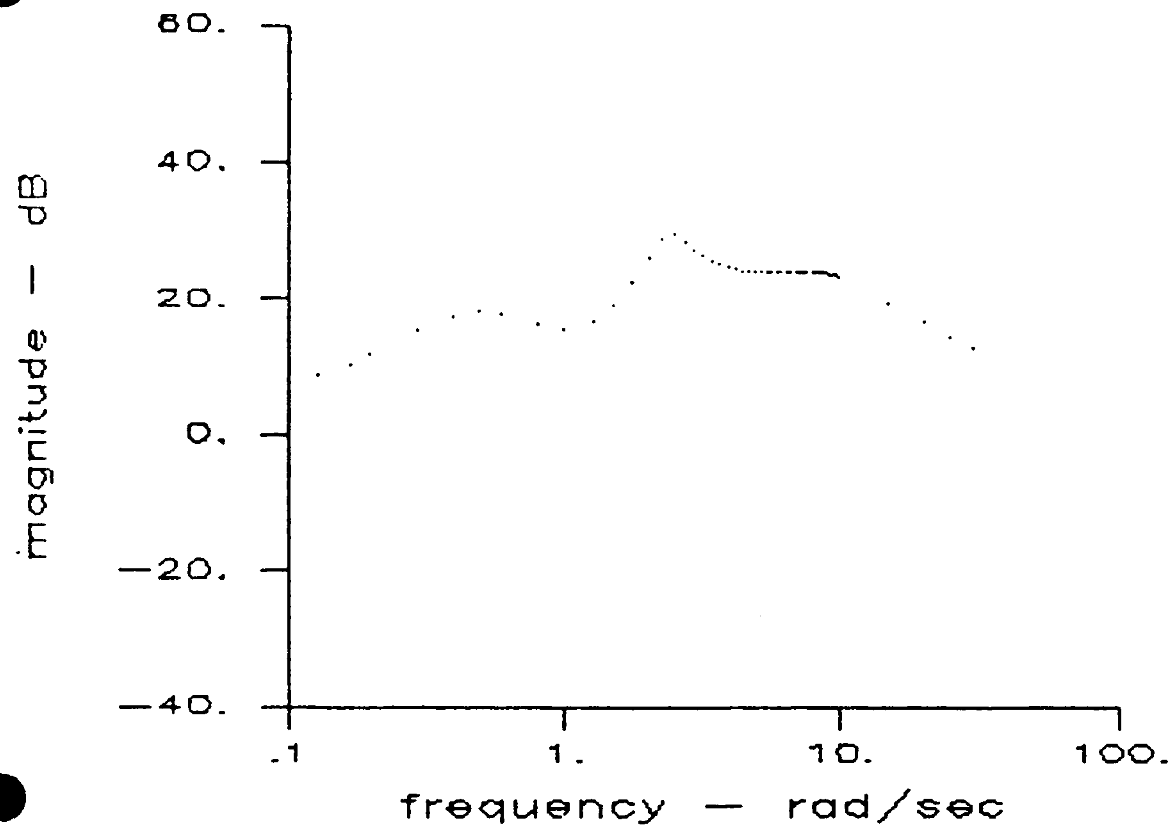
LEGEND:
· equivalent single loop pilot function



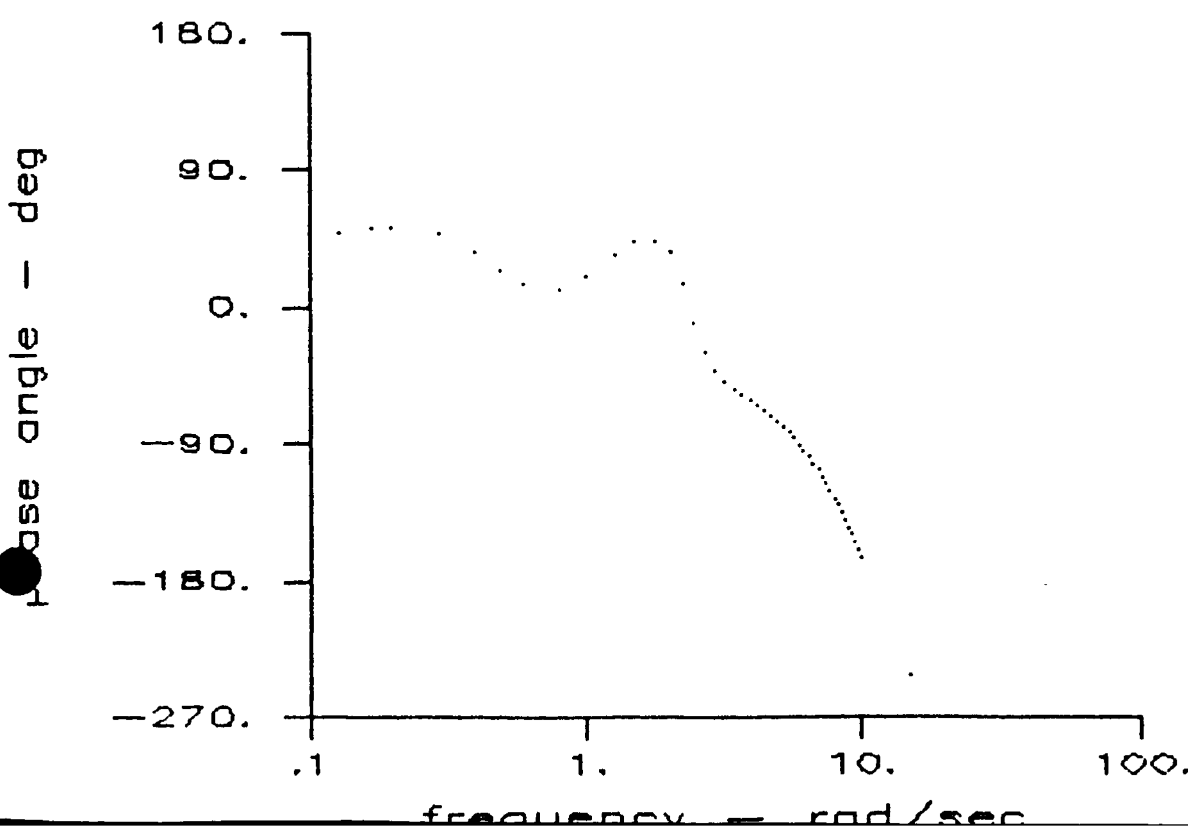
NLR Configuration F-1 : Gamma Tracking



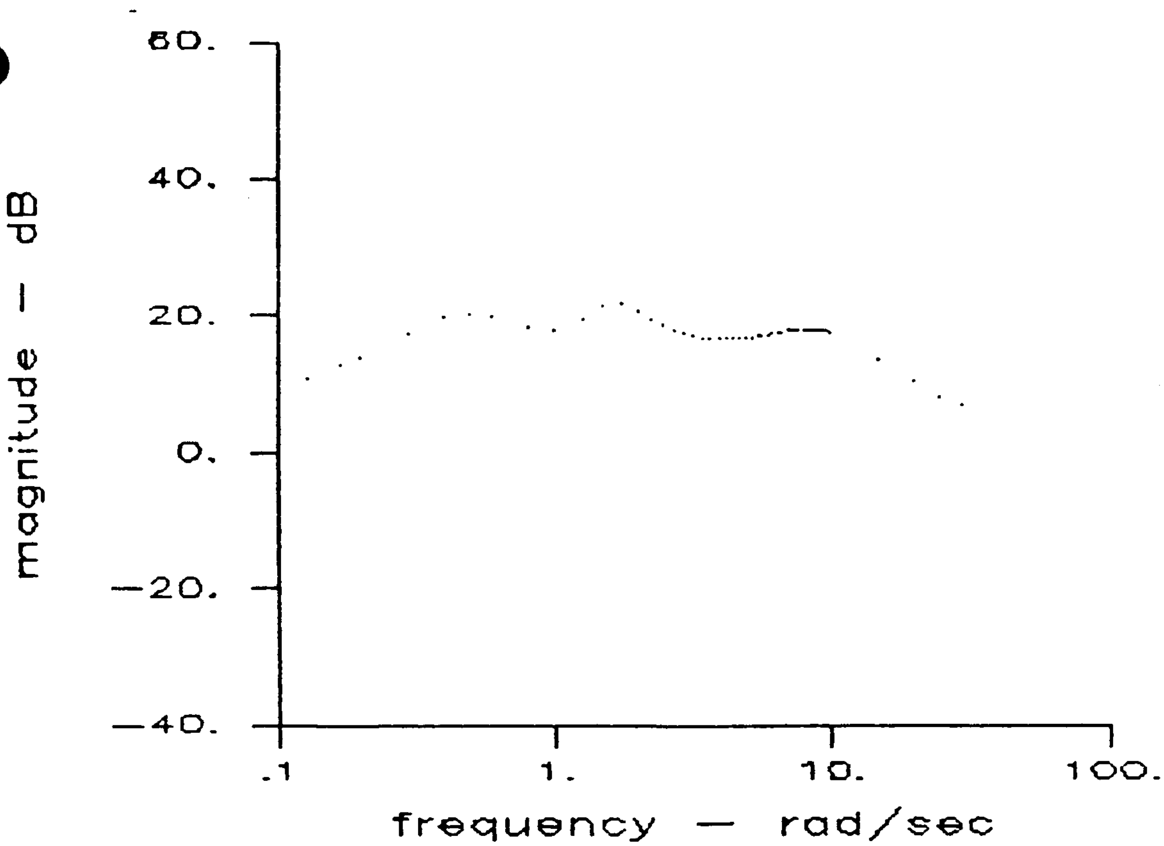
NLR Configuration G-1 : Gamma Tracking



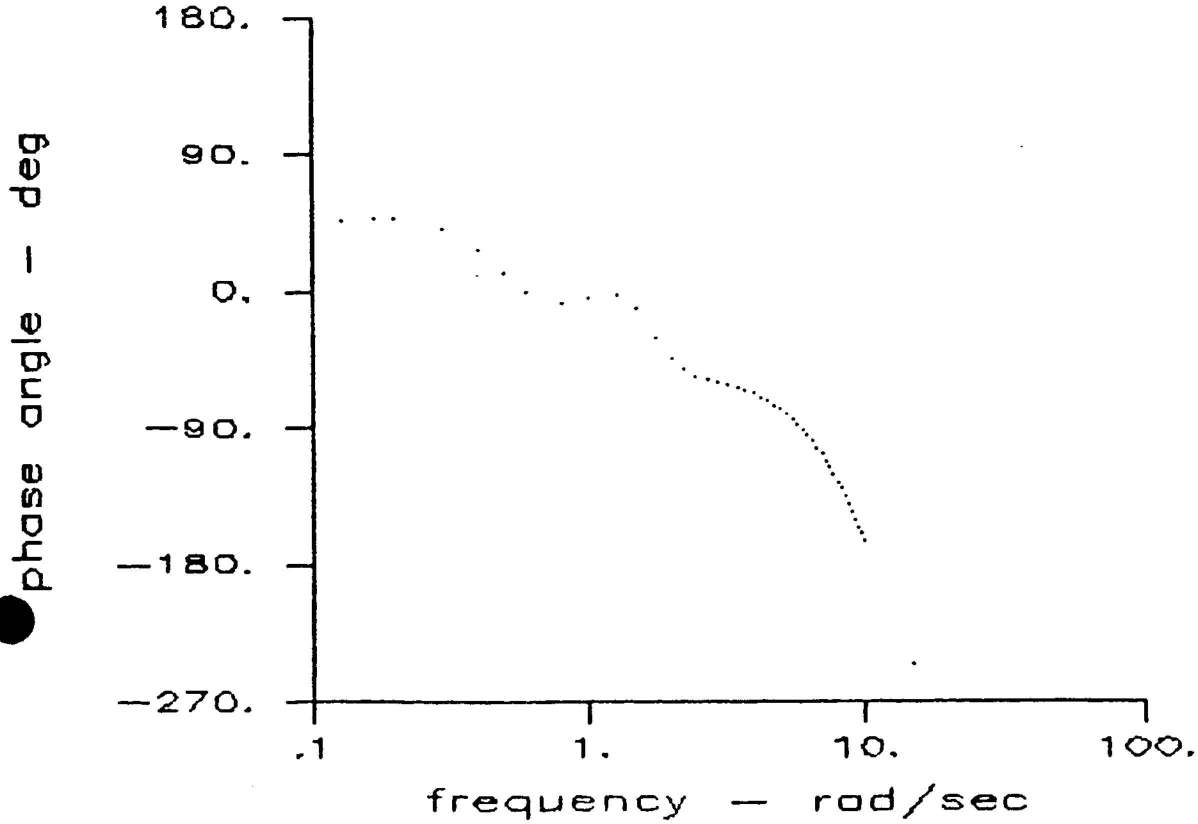
LEGEND:
· equivalent single loop pilot function



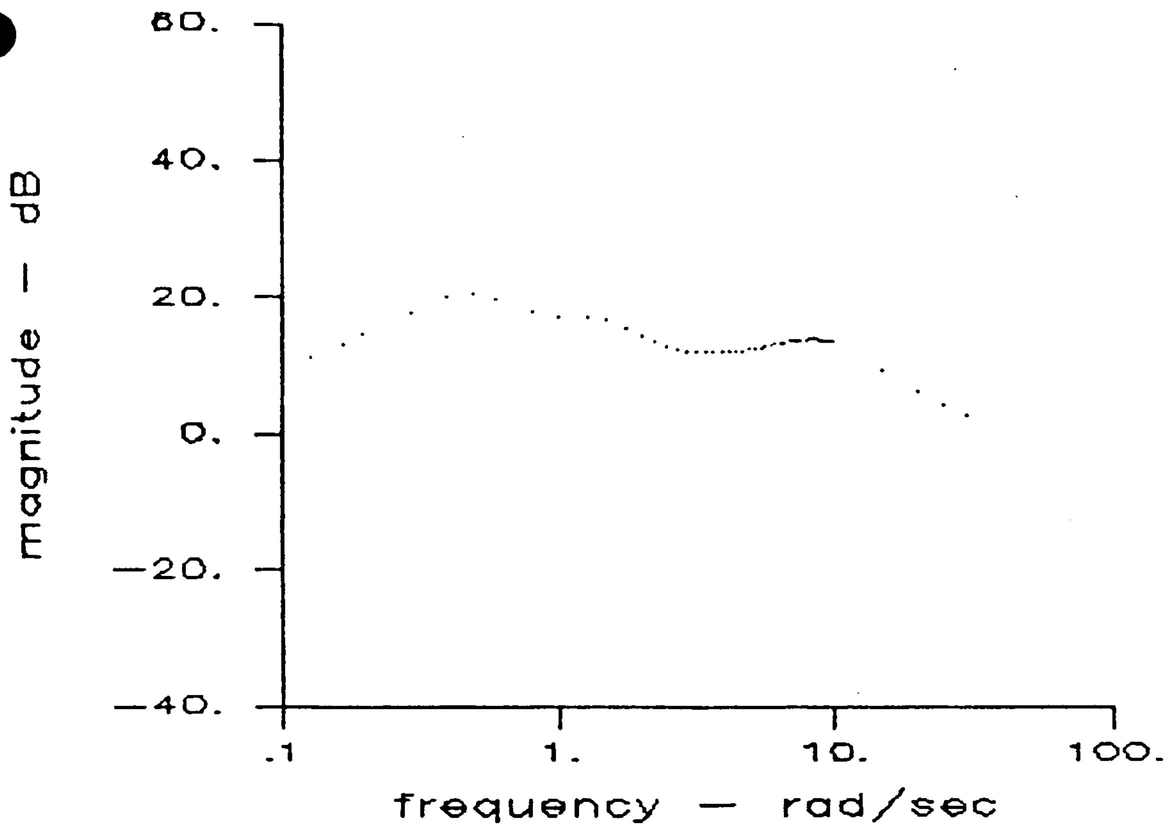
NLR Configuration G-2 : Gamma Tracking



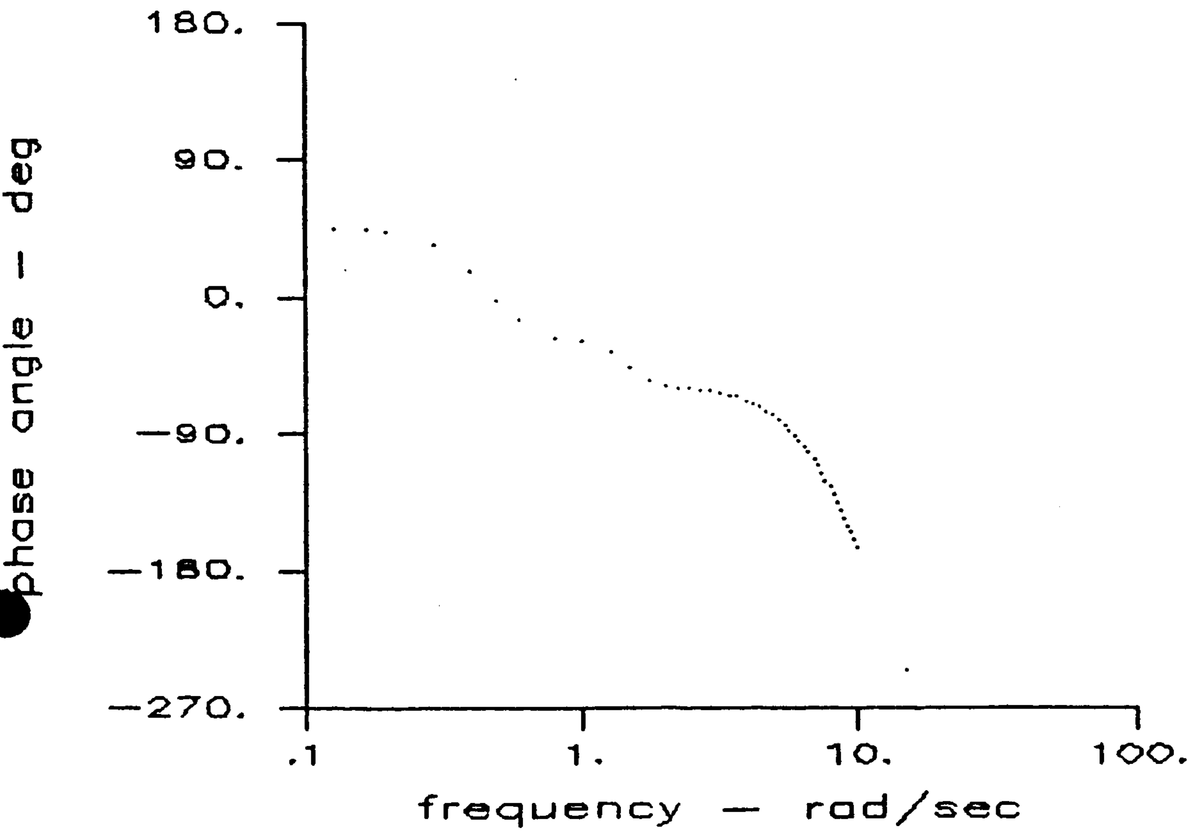
LEGEND:
· equivalent single loop pilot function



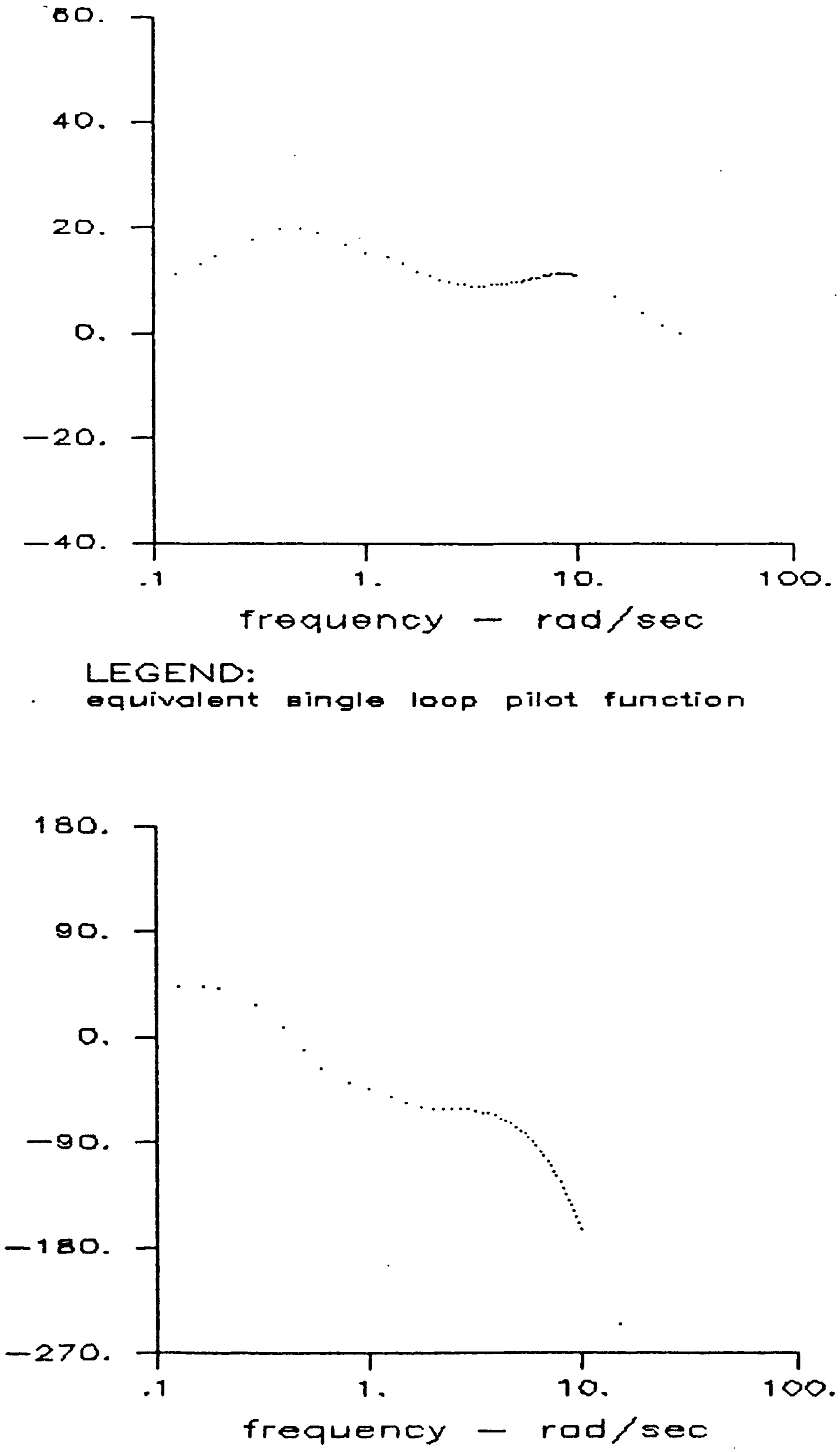
NLR Configuration G-3 : Gamma Tracking



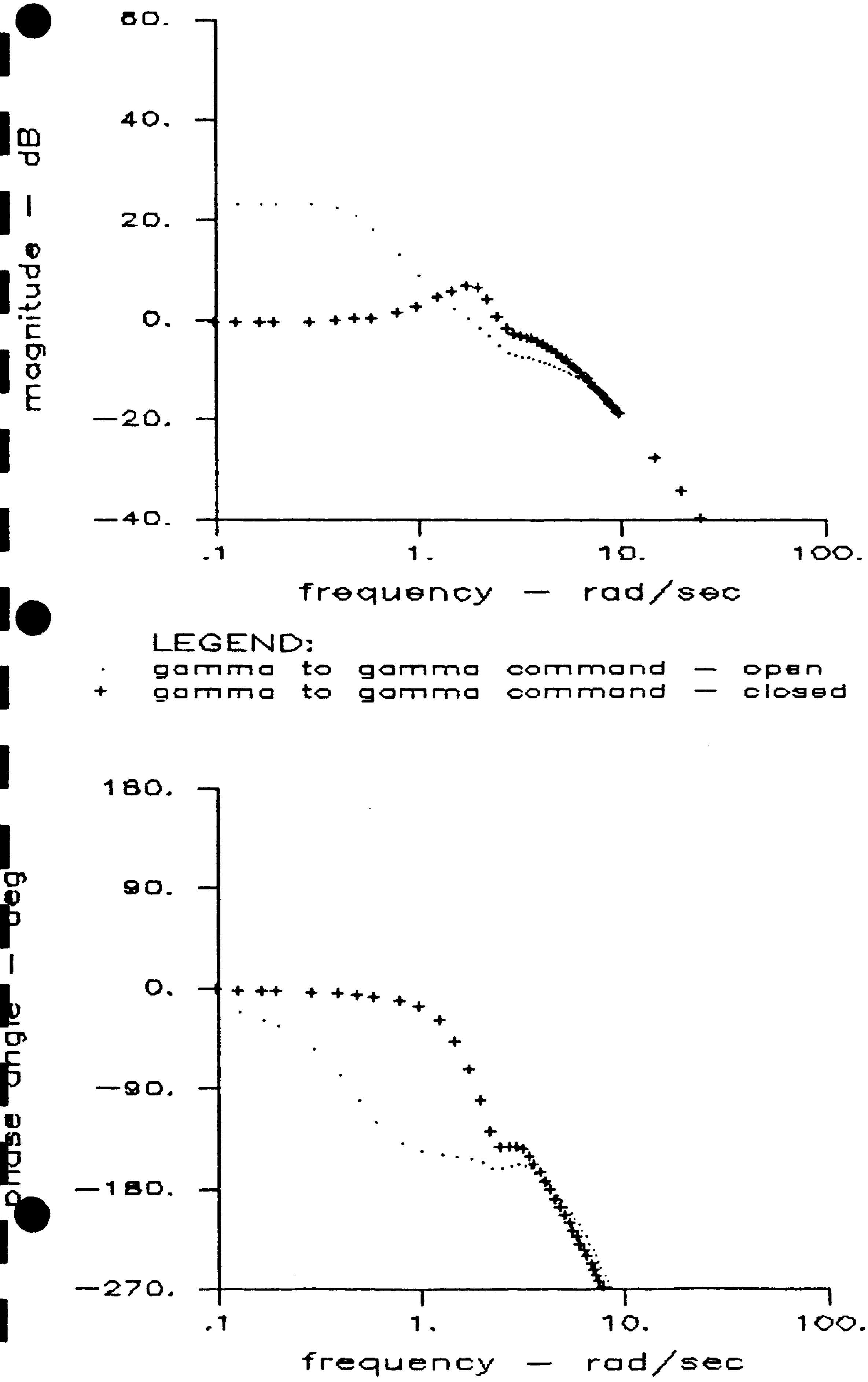
LEGEND:
· equivalent single loop pilot function



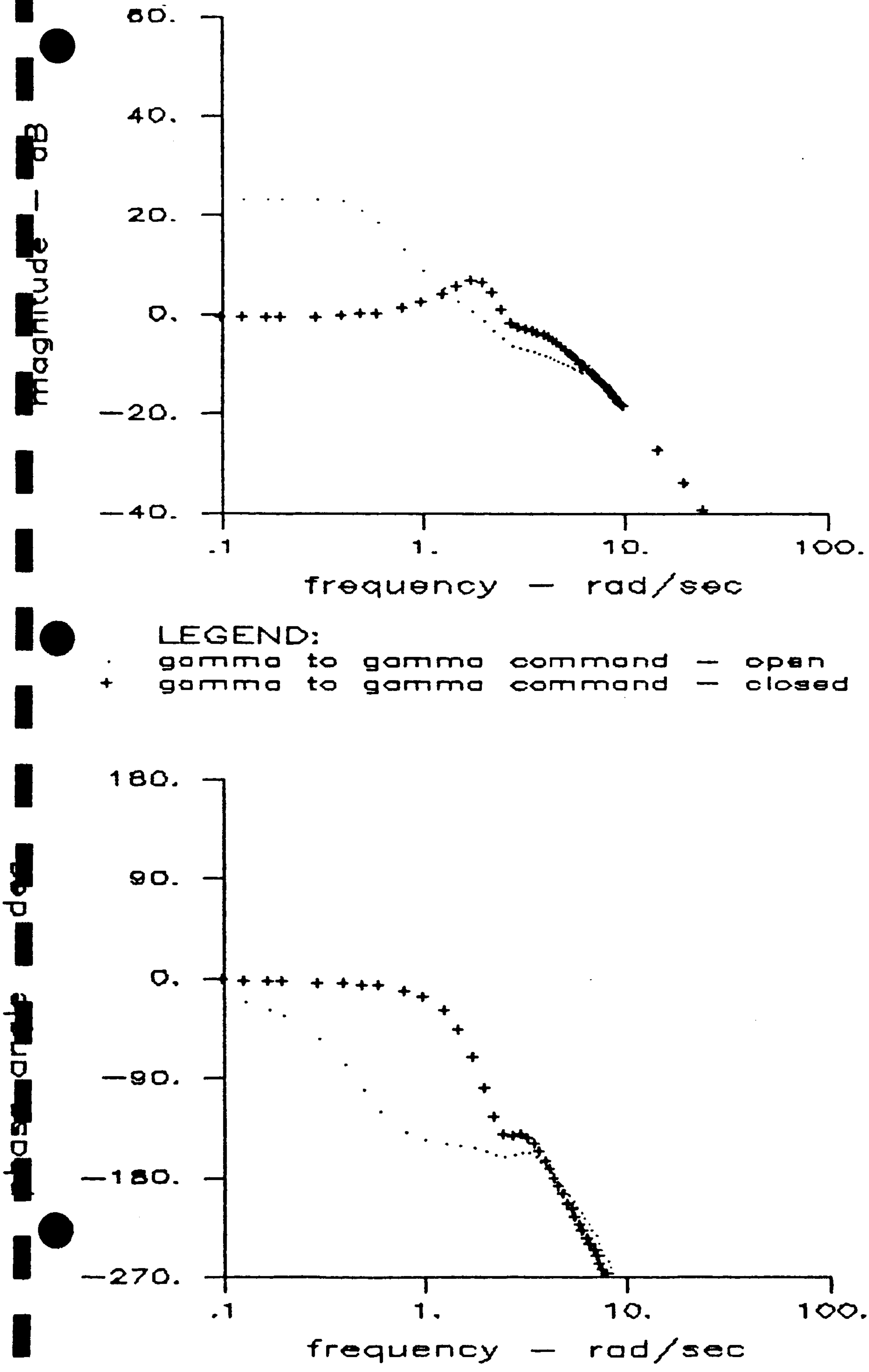
NLR Configuration G-4 : Gamma Tracking



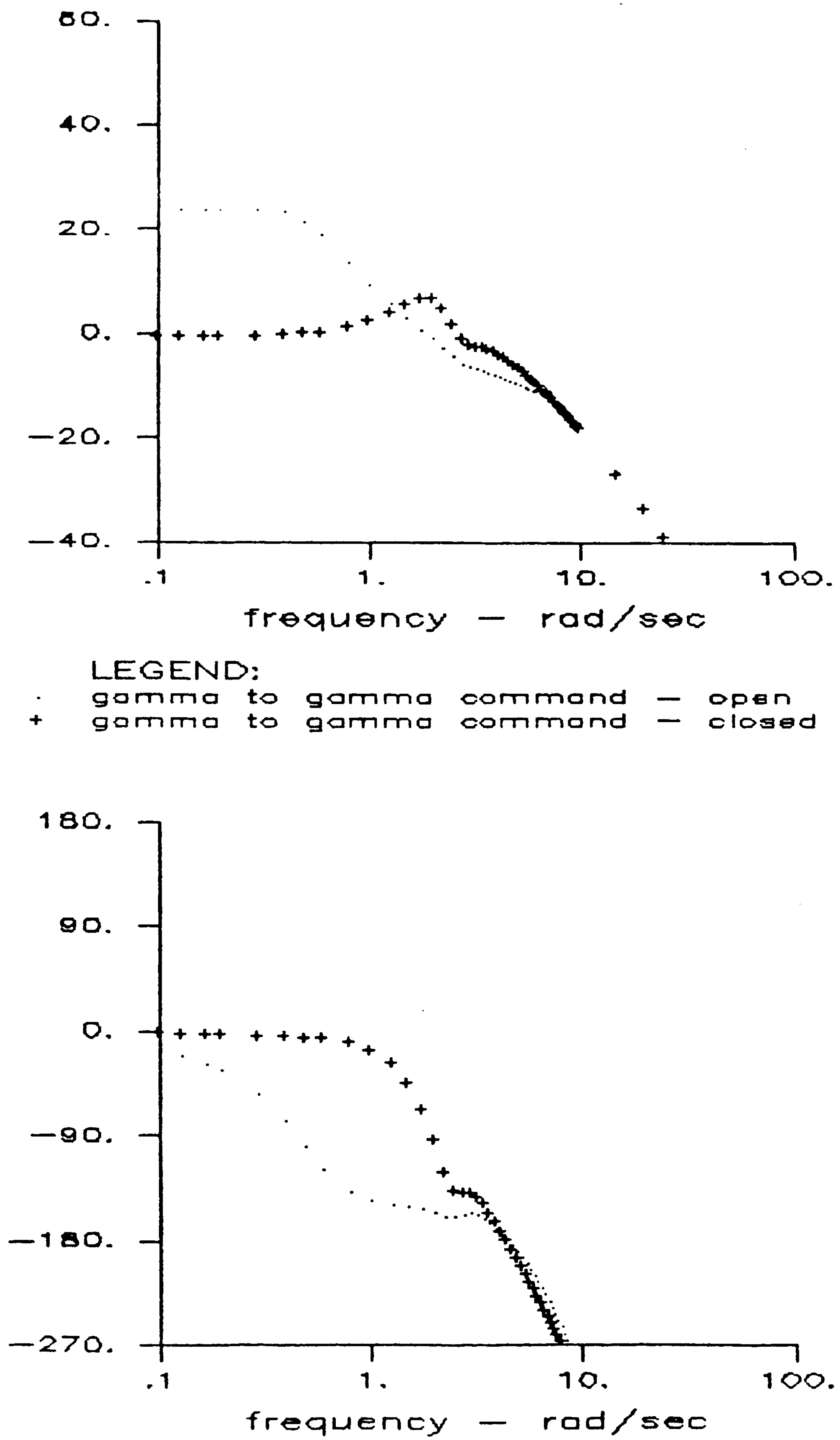
NLR Configuration E-1 : Gamma Tracking



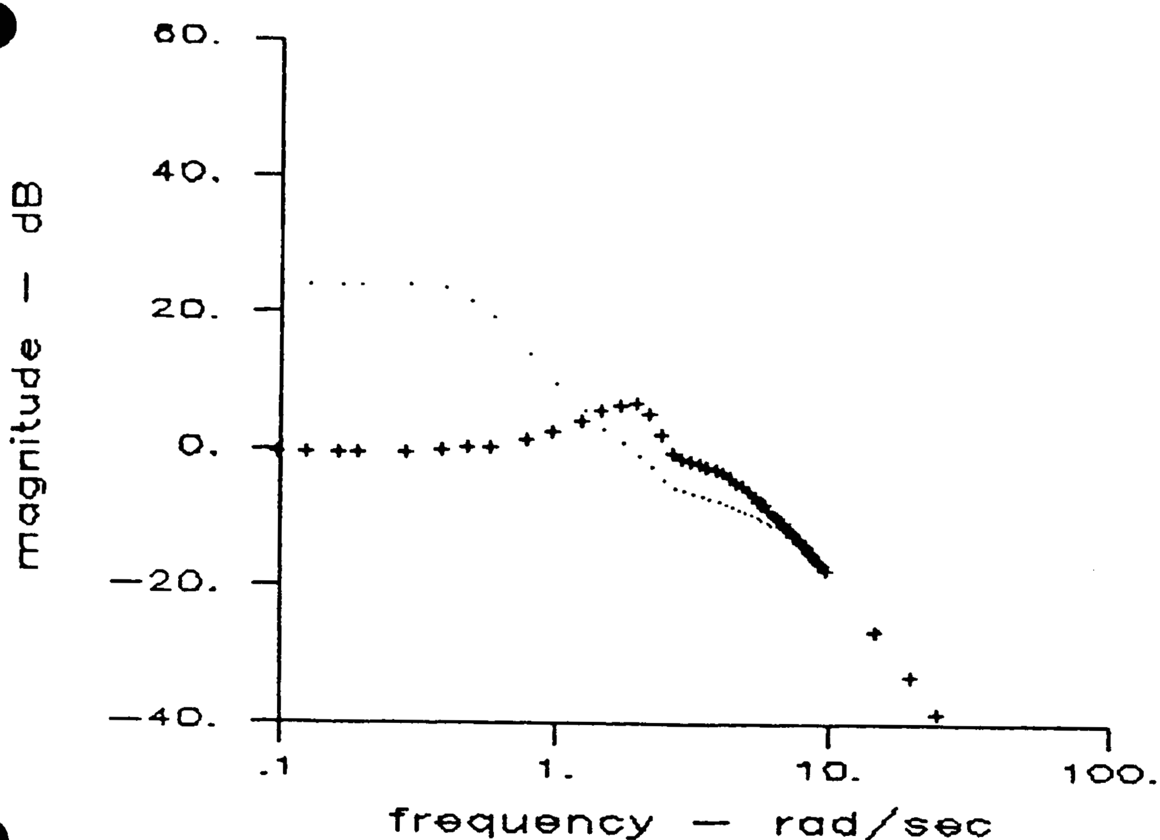
NLR Configuration E-2 : Gamma Tracking



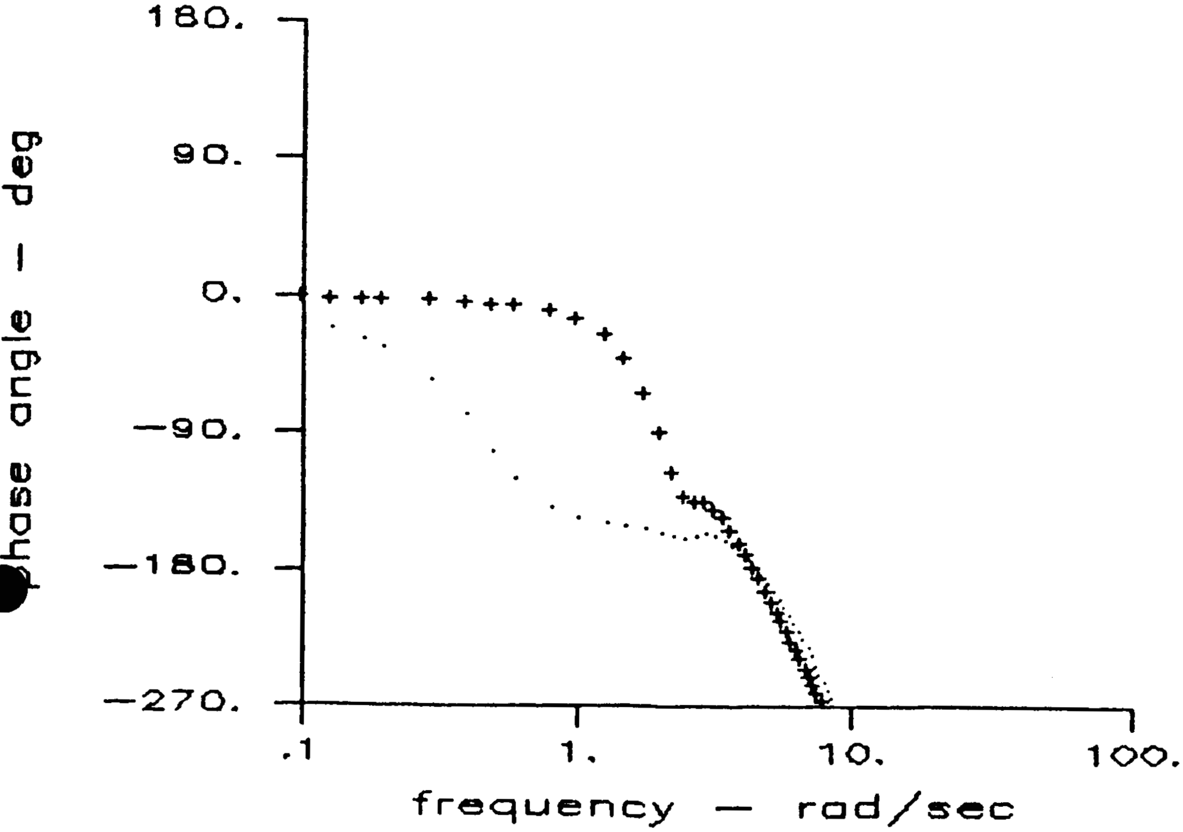
NLR Configuration E-3 : Gamma Tracking



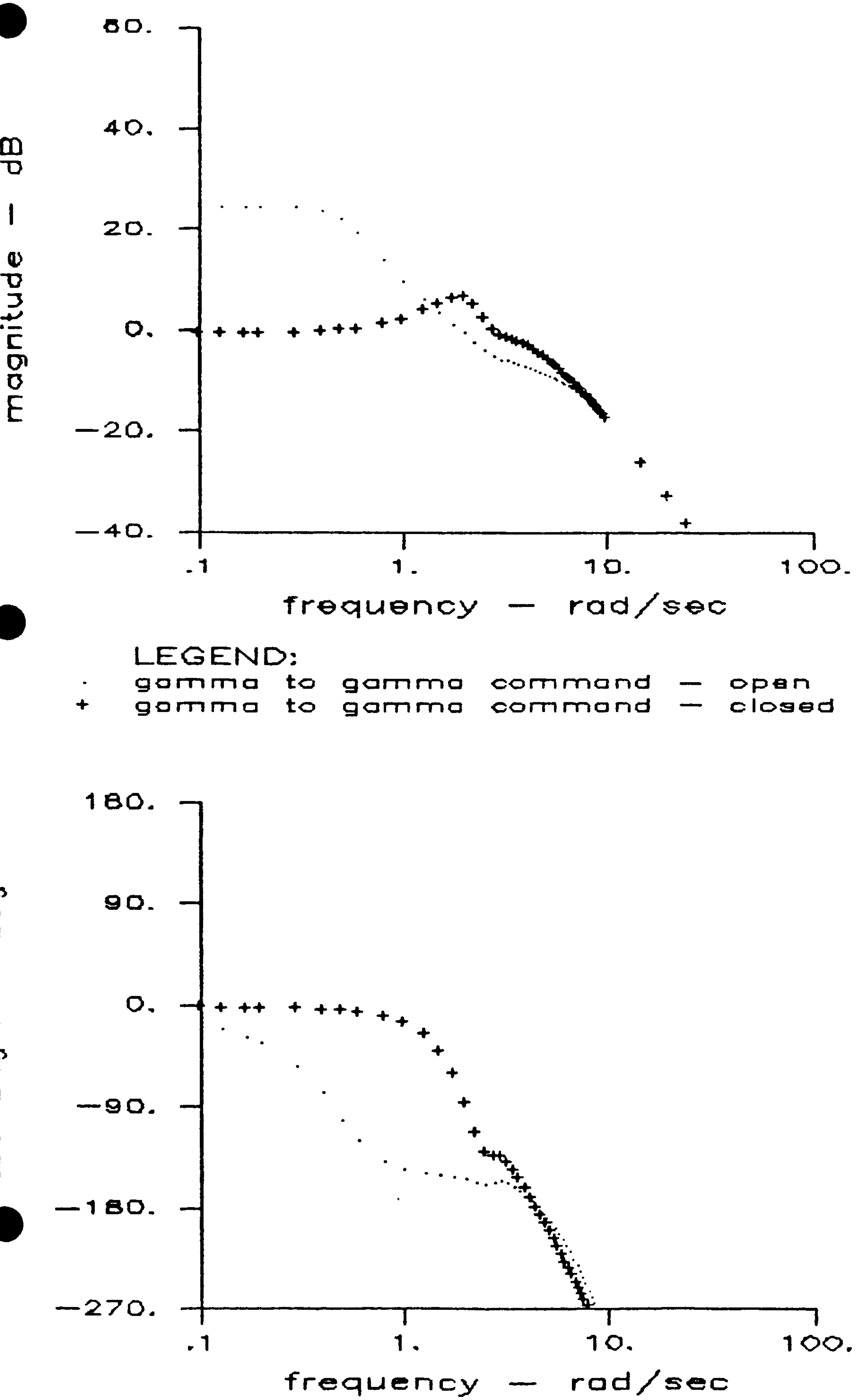
NLR Configuration E-4 : Gamma Tracking



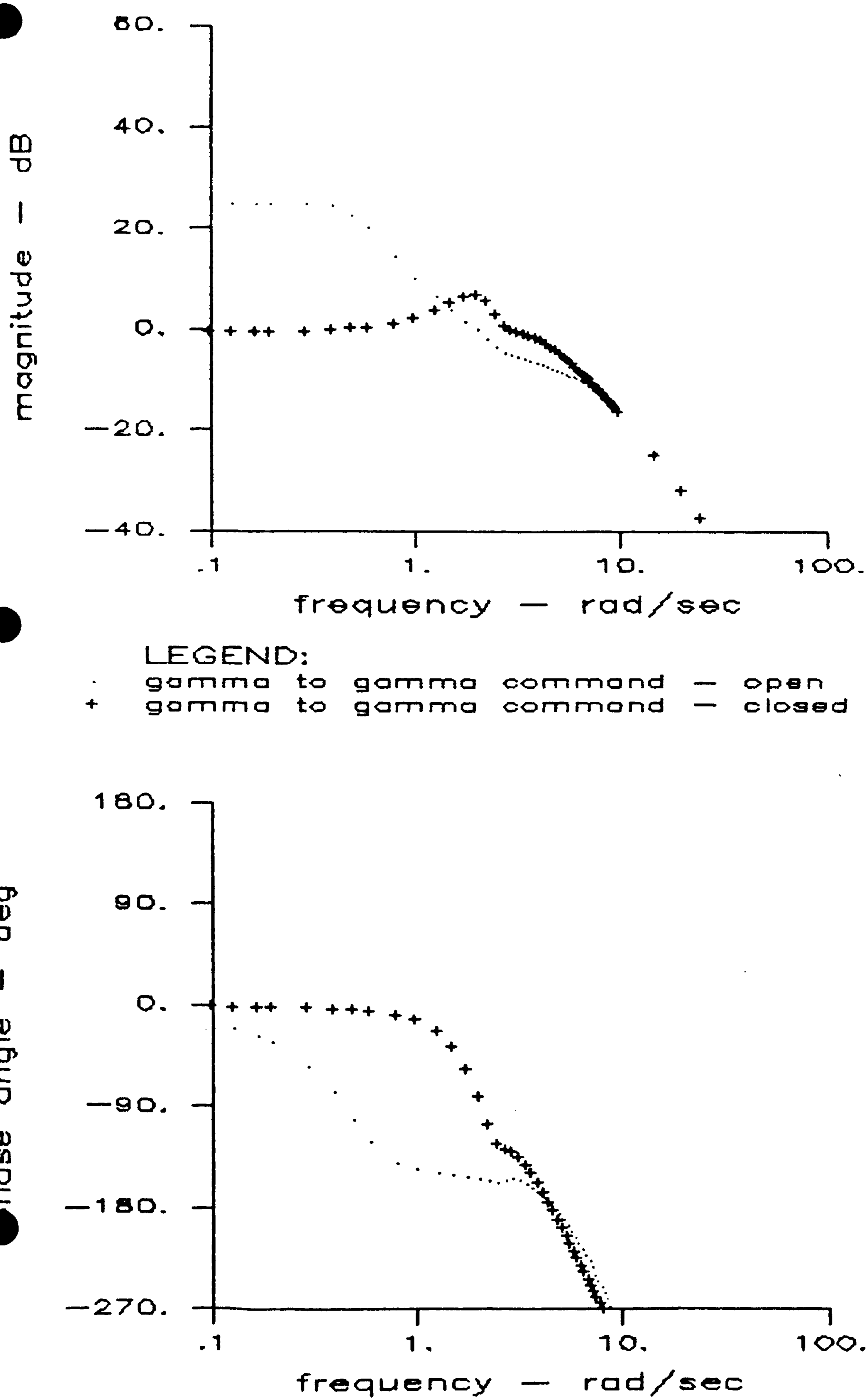
LEGEND:
· gamma to gamma command - open
+ gamma to gamma command - closed



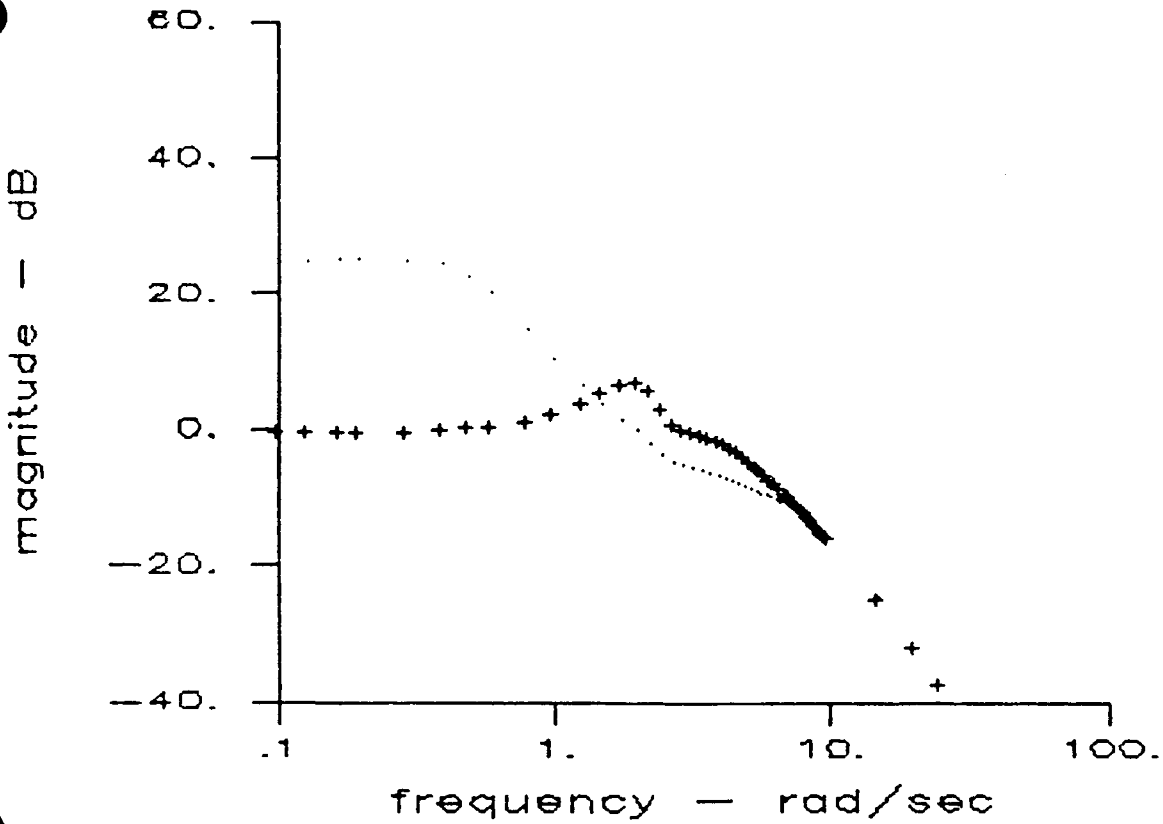
NLR Configuration E-5 : Gamma Tracking



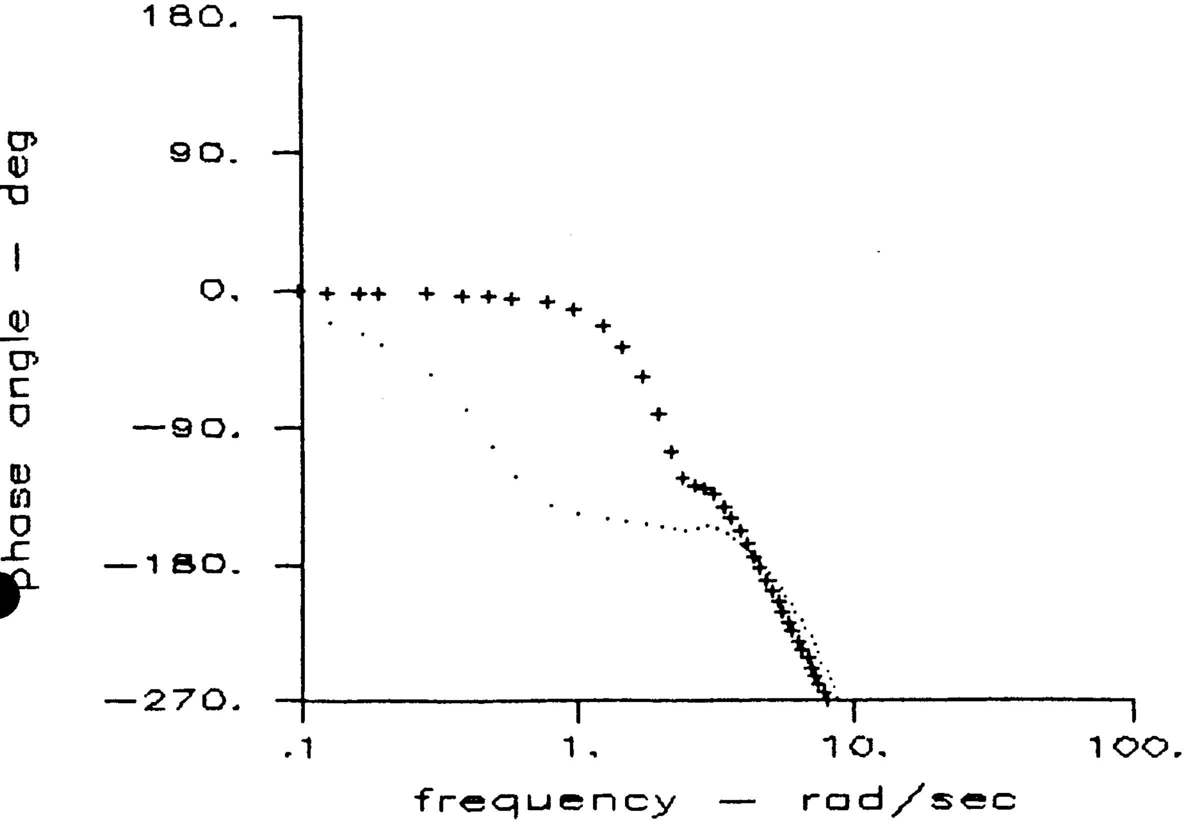
NLR Configuration F-3 : Gamma Tracking



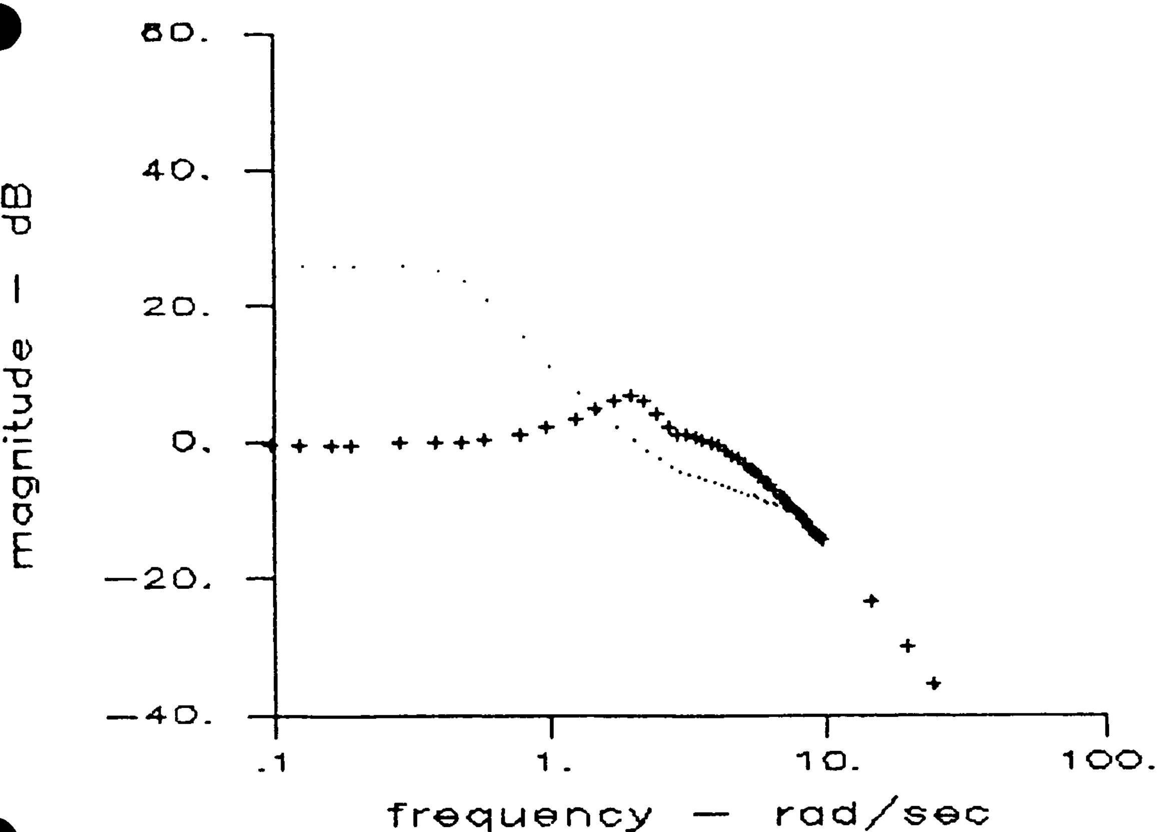
NLR Configuration F-2 : Gamma Tracking



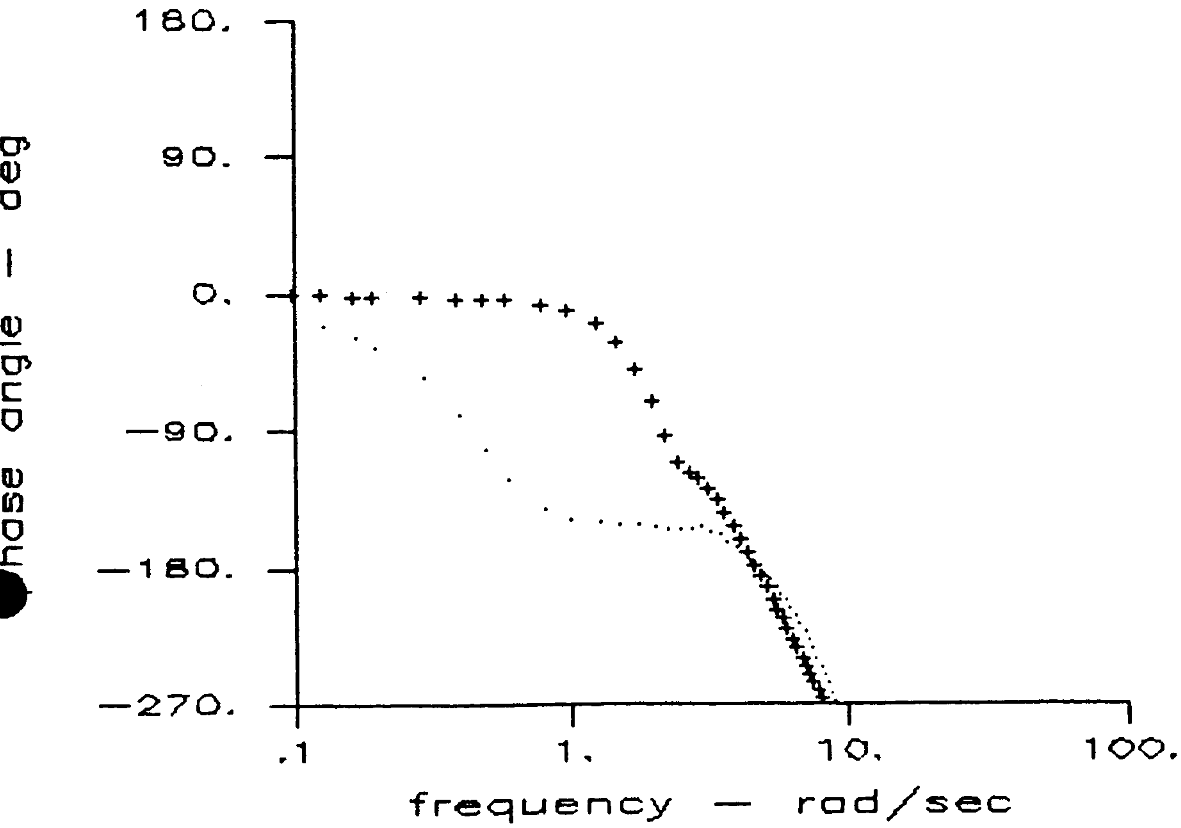
LEGEND:
. gamma to gamma command - open
+ gamma to gamma command - closed



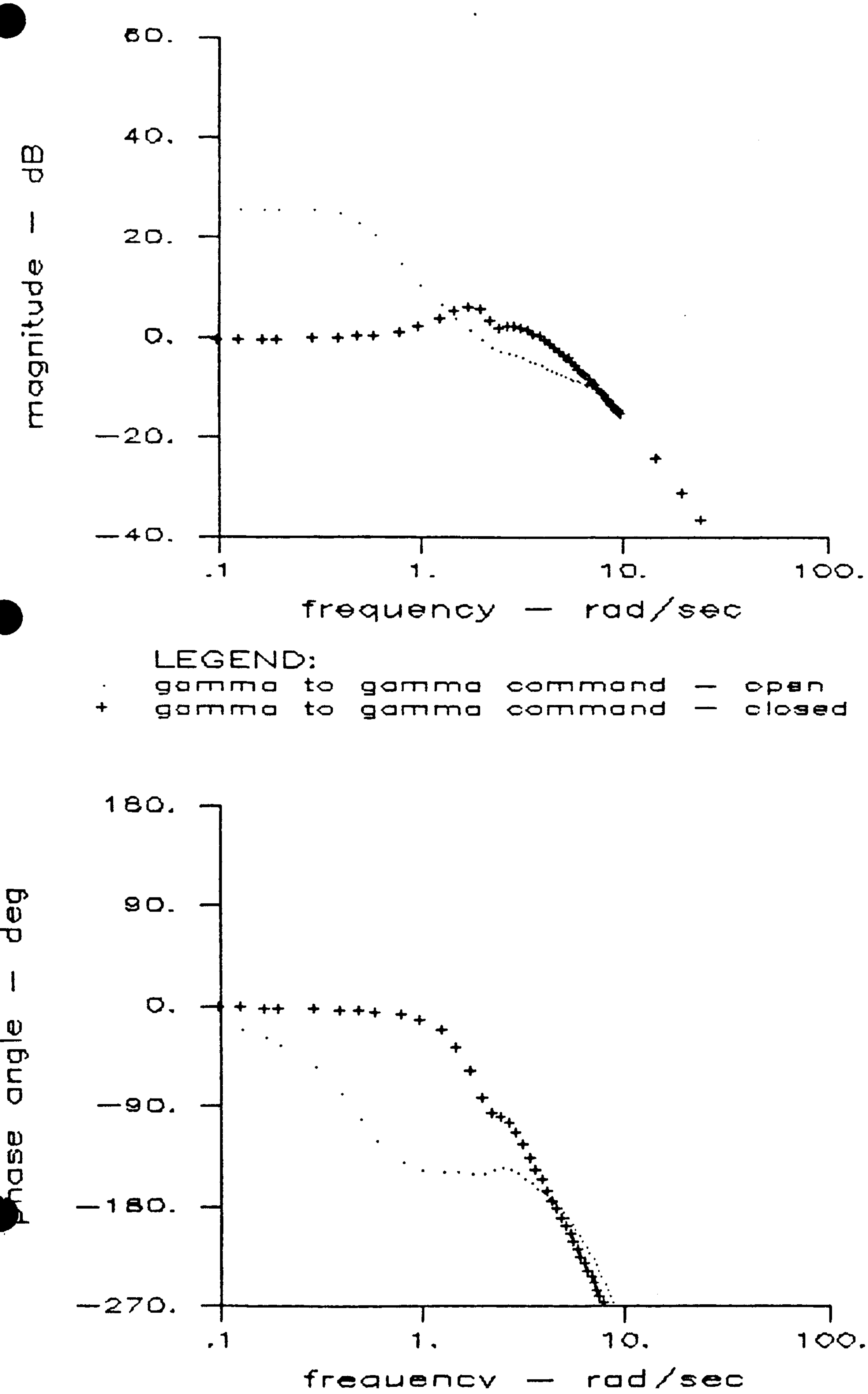
NLR Configuration F-1 : Gamma Tracking



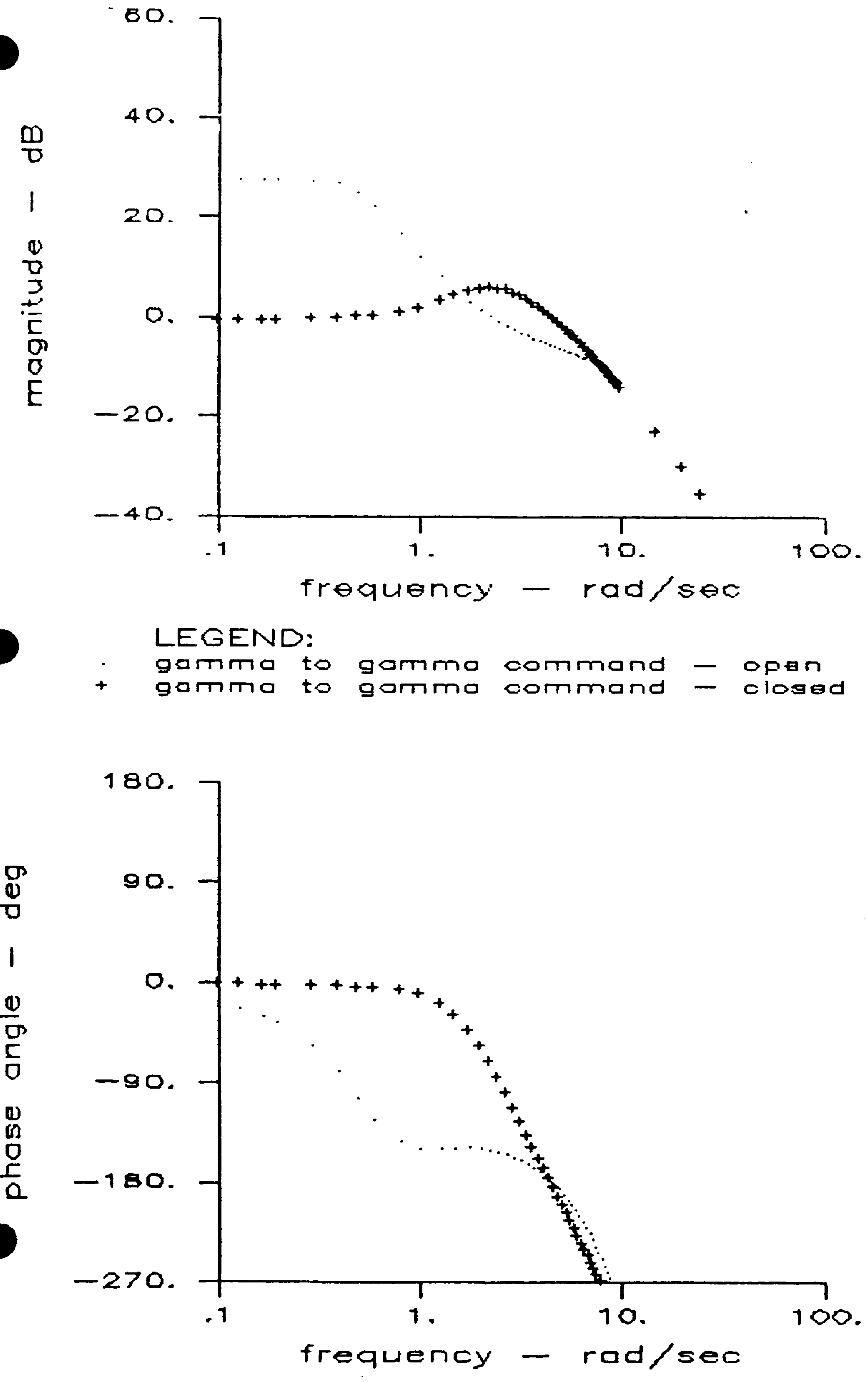
LEGEND:
· gamma to gamma command - open
+ gamma to gamma command - closed

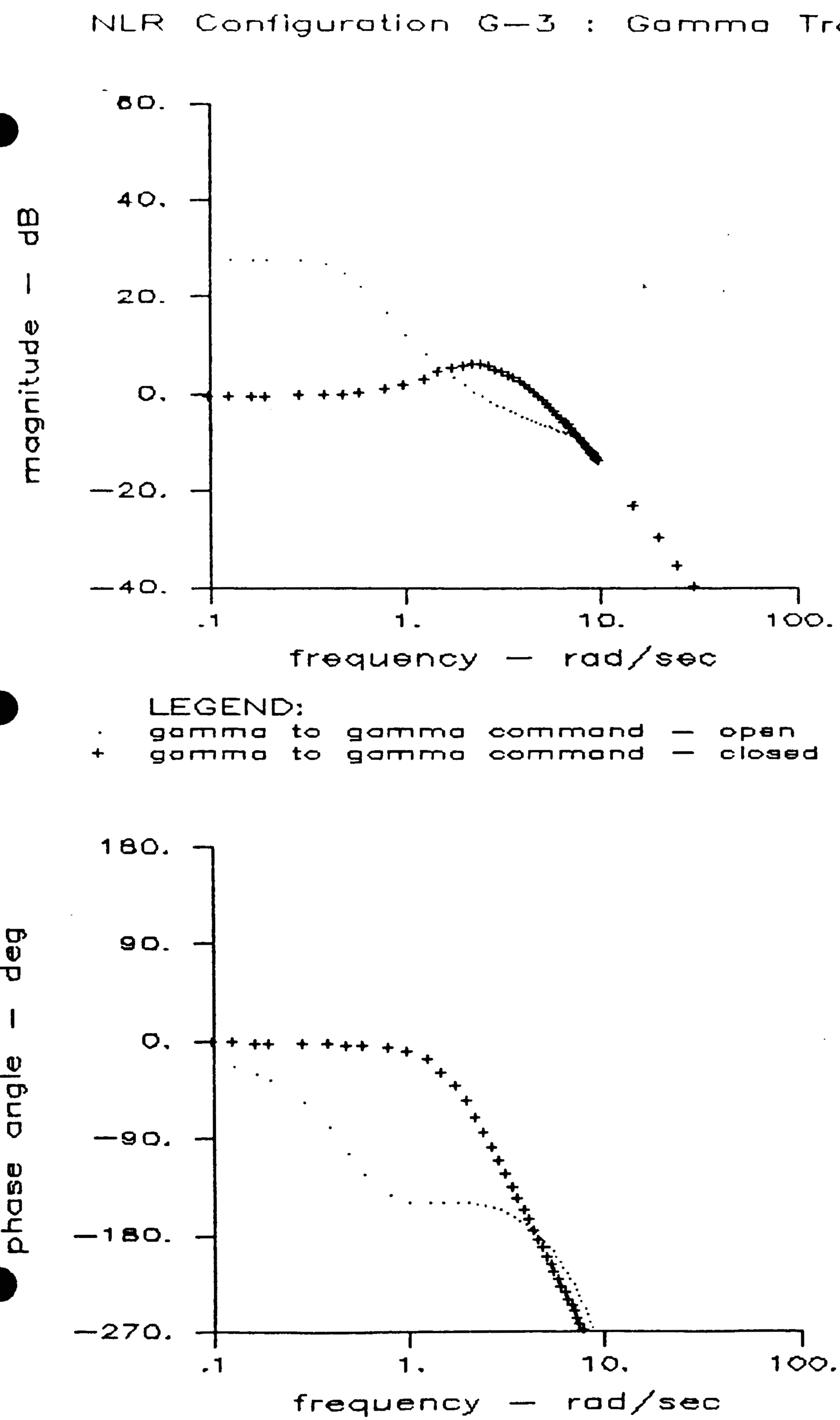


NLR Configuration G—1 : Gamma Tracking



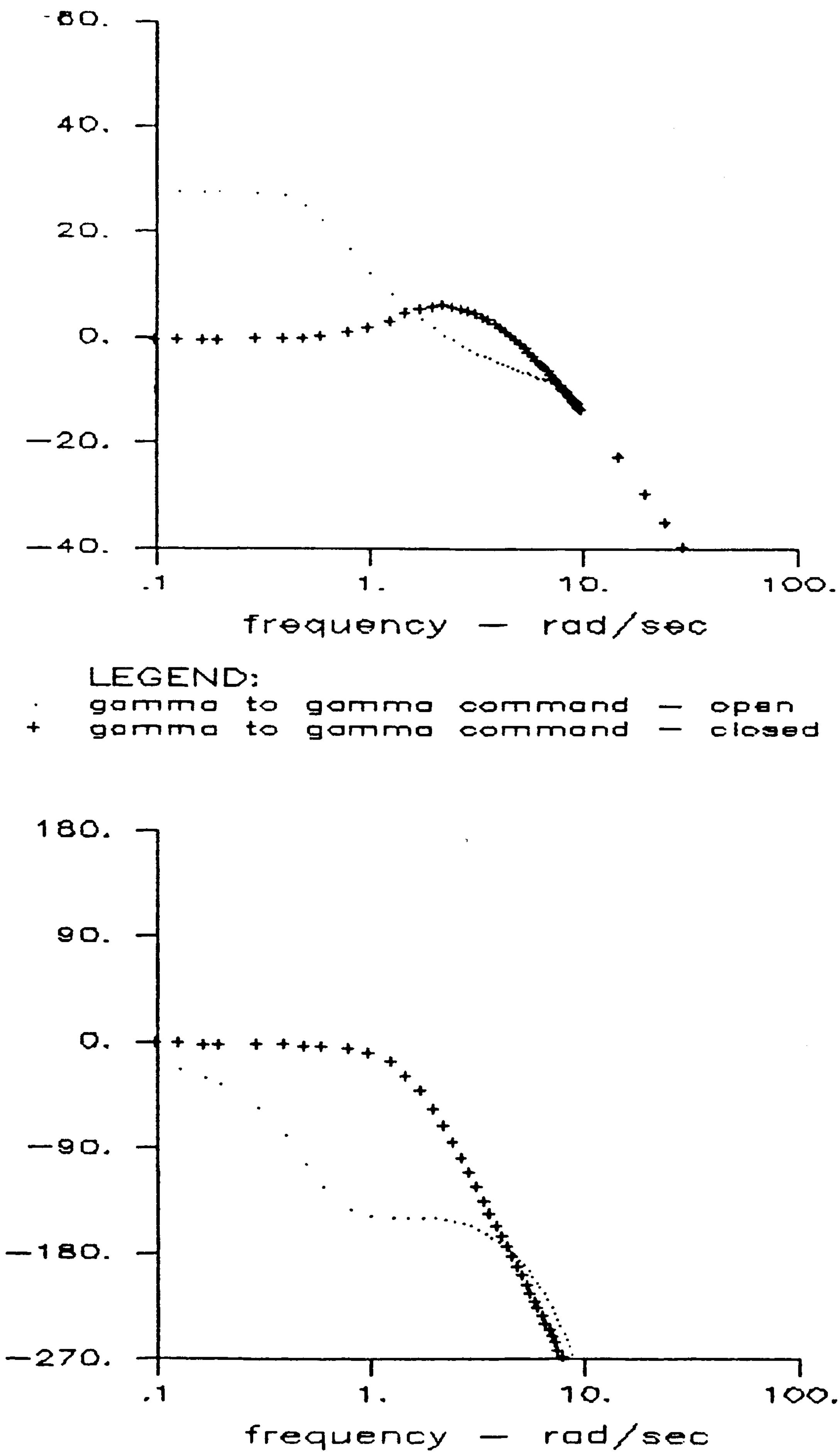
NLR Configuration G-2 : Gamma Tracking



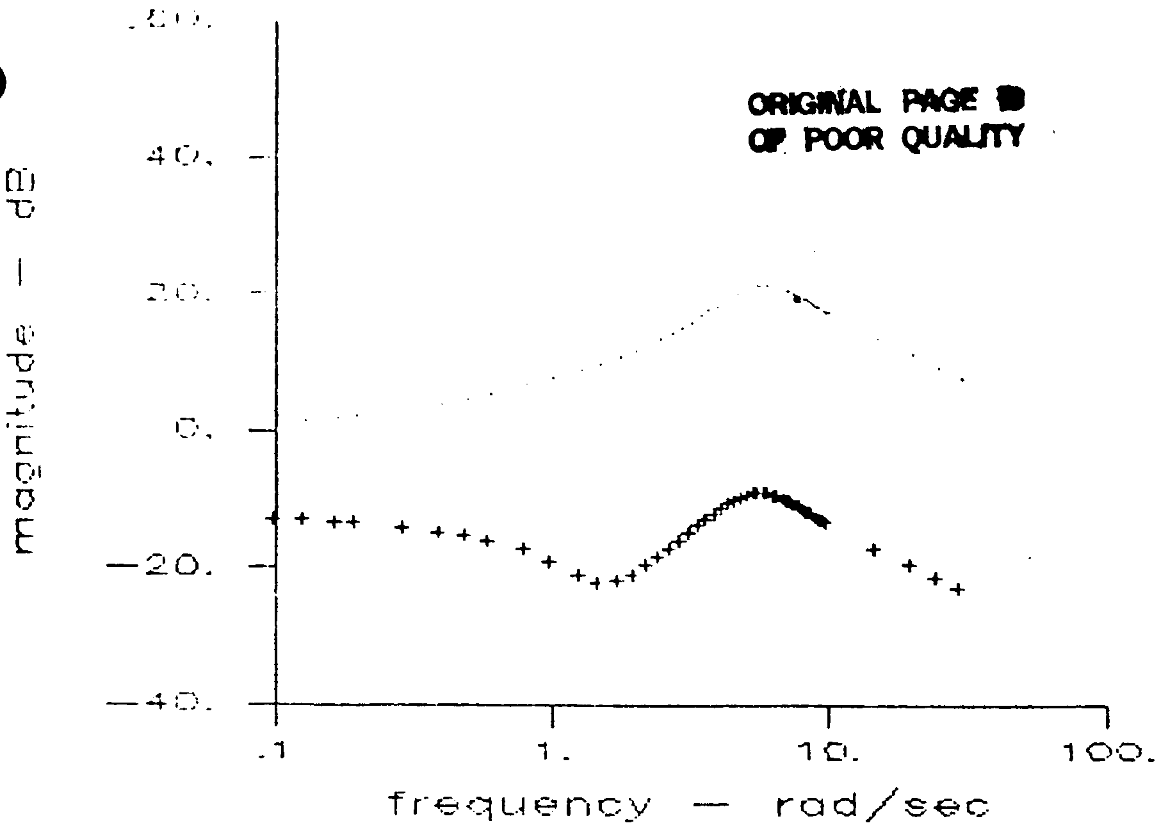


NLR Configuration G-3 : Gamma Tracking
60.
40.
20.
0.
-20.
-40.
magnitude - dB
.1
1.
10.
100.
frequency - rad/sec
LEGEND:
· gamma to gamma command - open
+ gamma to gamma command - closed
180.
90.
0.
-90.
-180.
-270.
phase angle - deg
.1
1.
10.
100.
frequency - rad/sec

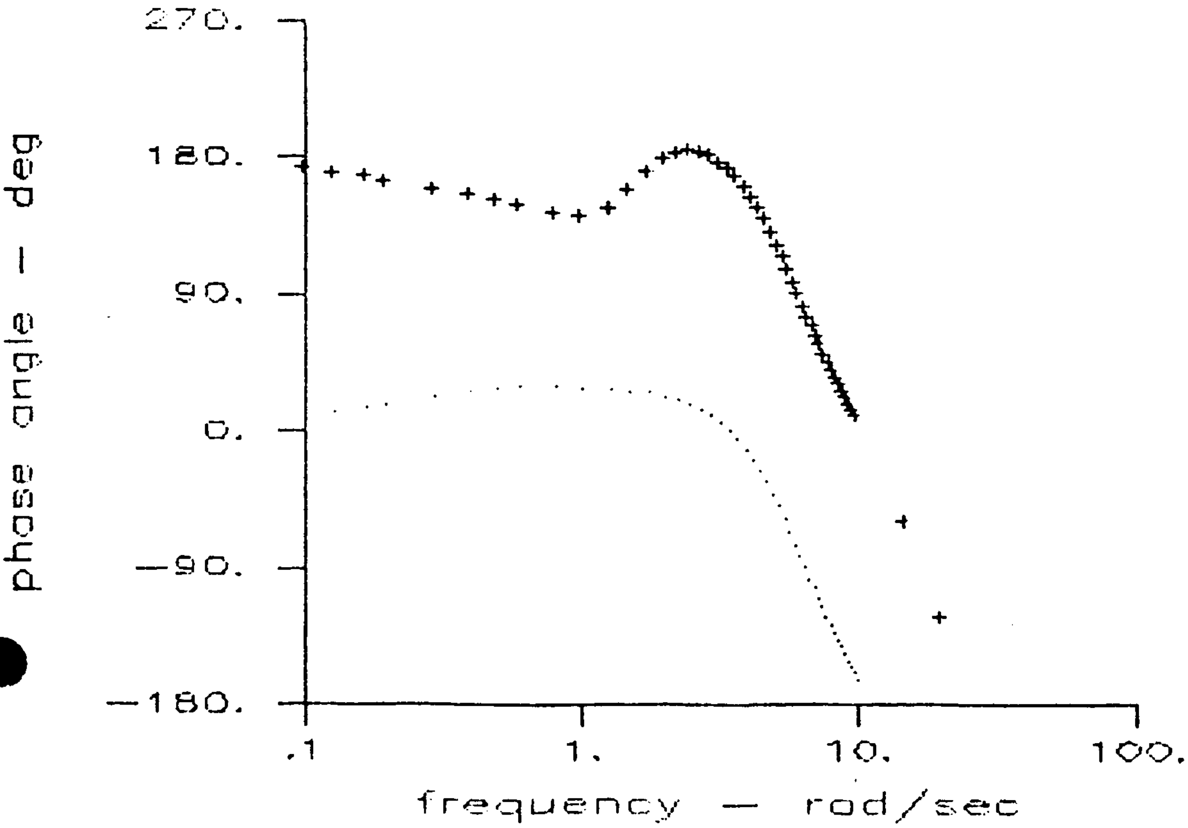
NLR Configuration G-4 : Gamma Tracking

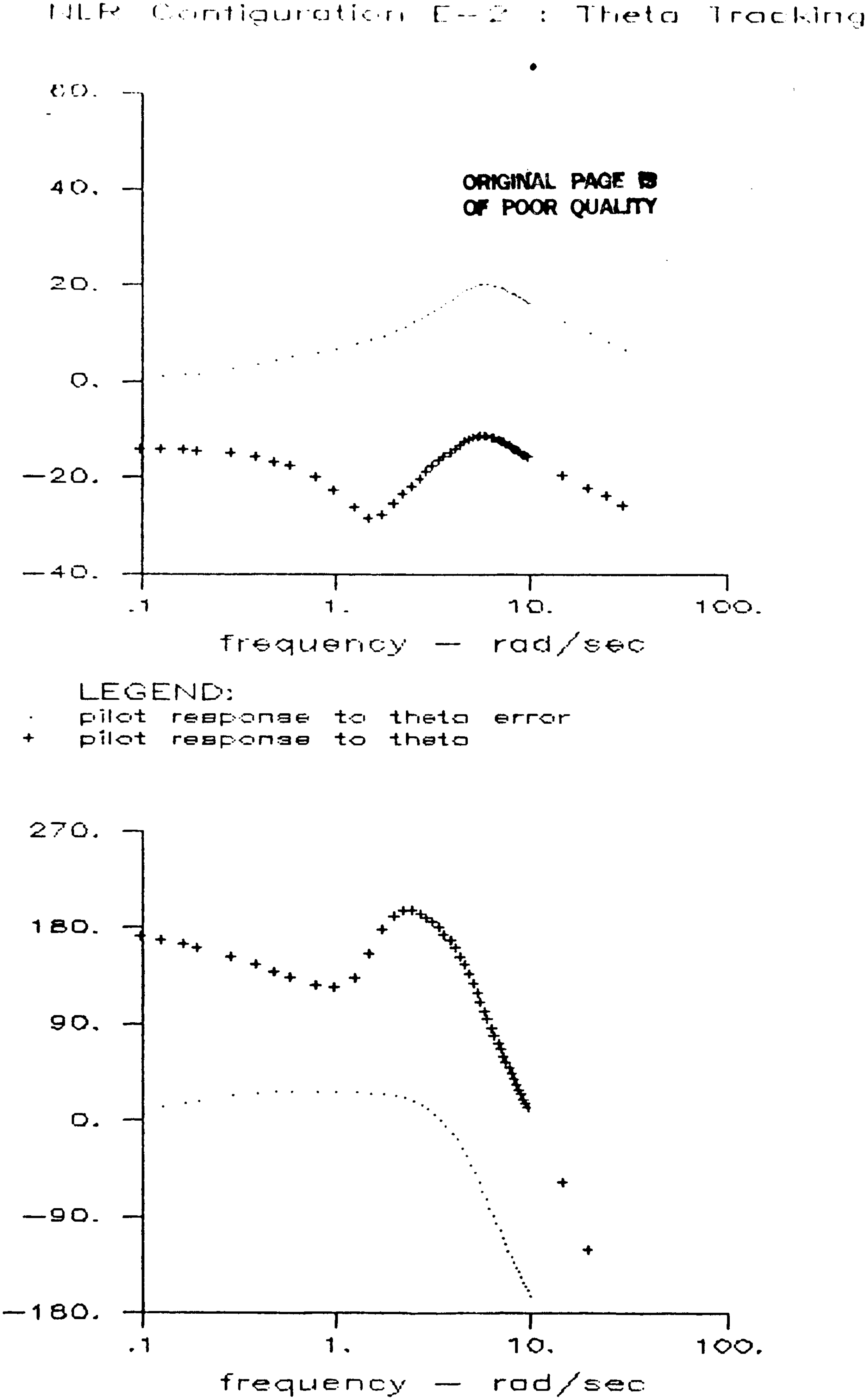


[illegible] Configuration [illegible] : Theta Tracking



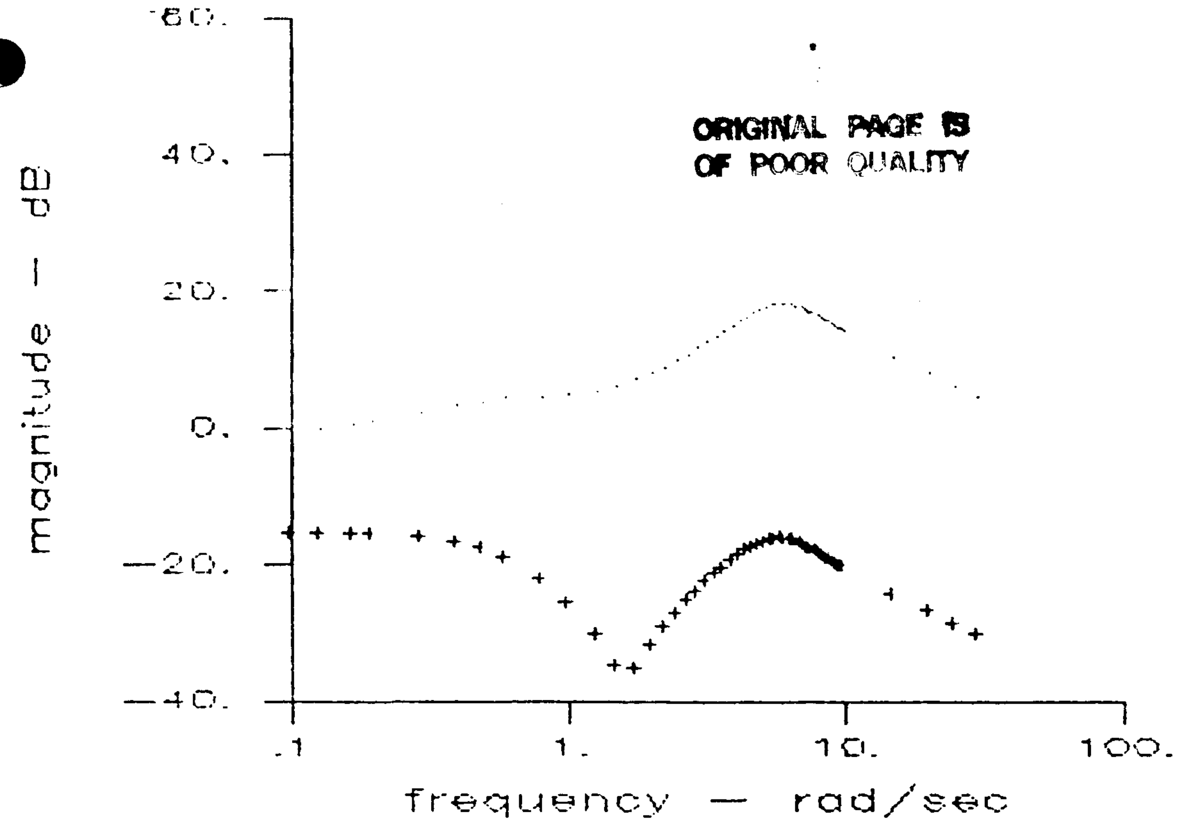
LEGEND:
· pilot response to theta error
+ pilot response to theta



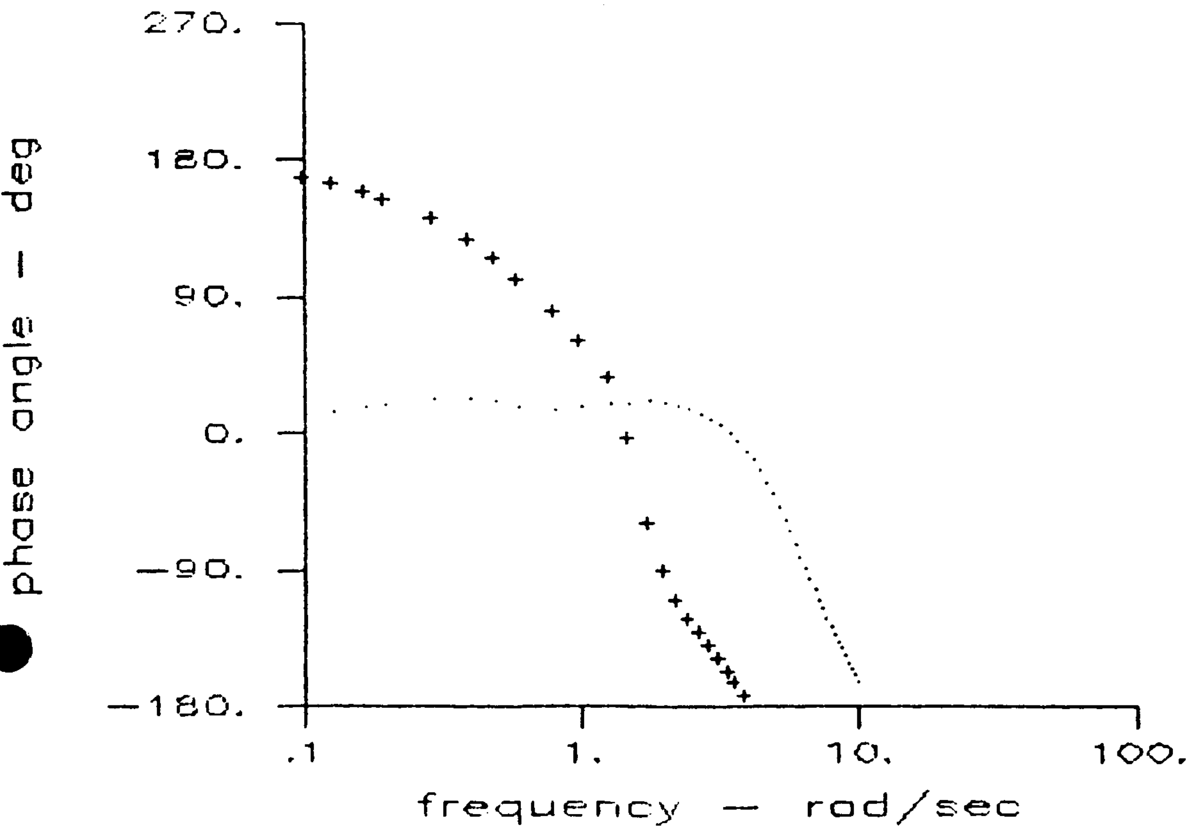


NLR Configuration E-2 : Theta Tracking
ORIGINAL PAGE IS
OF POOR QUALITY
magnitude — dB
60.
40.
20.
0.
-20.
-40.
.1
1.
10.
100.
frequency — rad/sec
LEGEND:
· pilot response to theta error
+ pilot response to theta
phase angle — deg
270.
180.
90.
0.
-90.
-180.
.1
1.
10.
100.
frequency — rad/sec

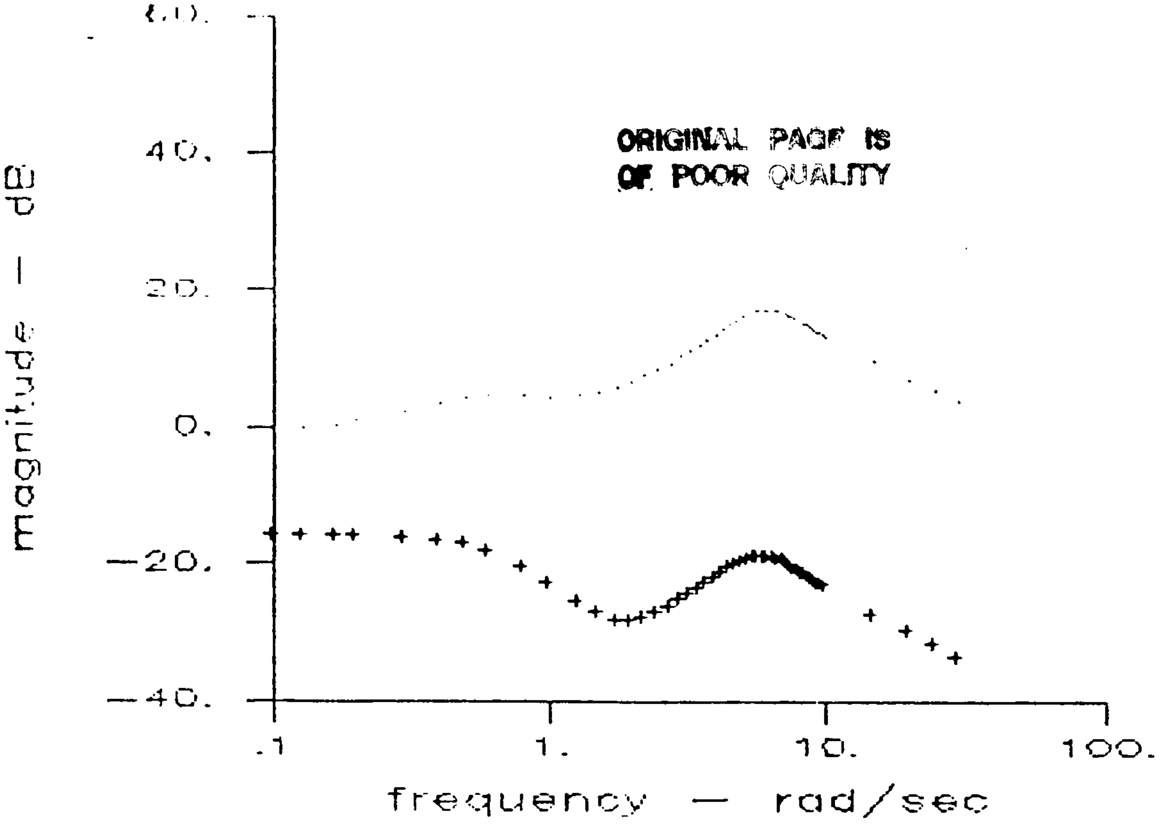
HUD Configuration L-3 : Theta Tracking



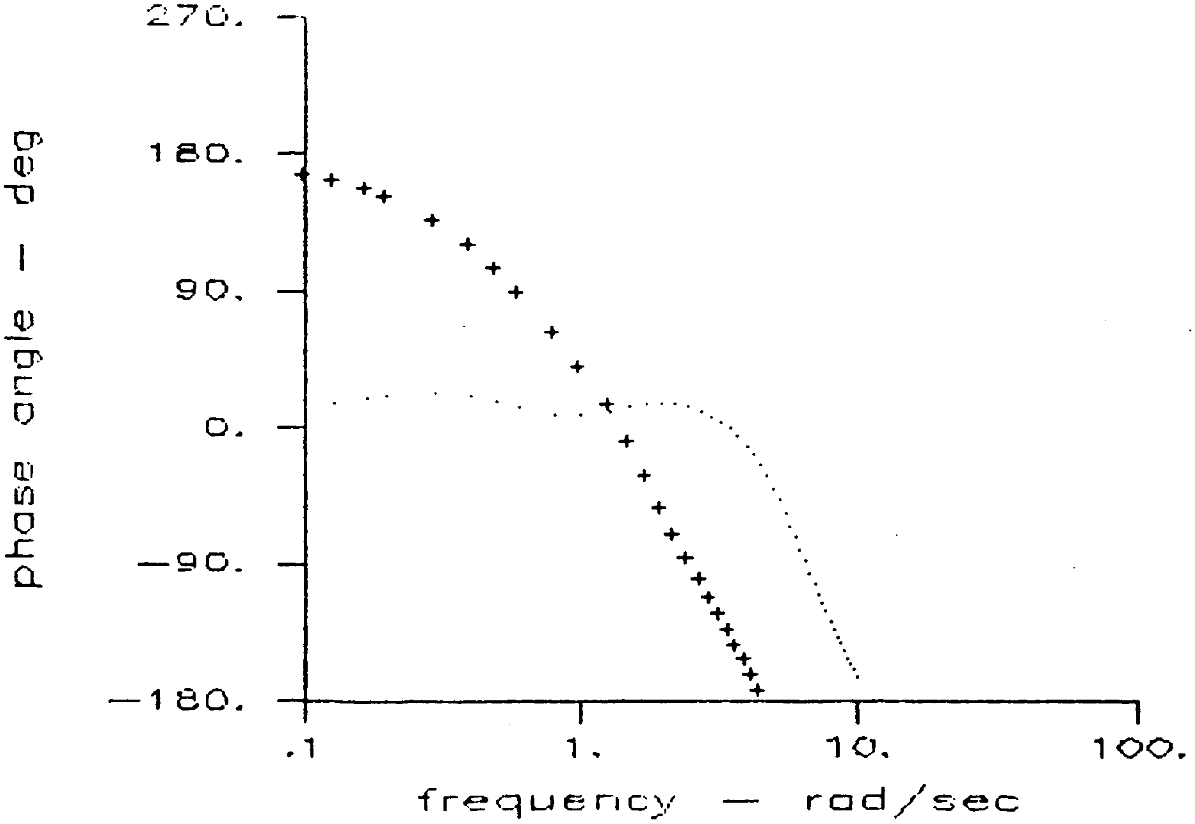
LEGEND:
· pilot response to theta error
\+ pilot response to theta



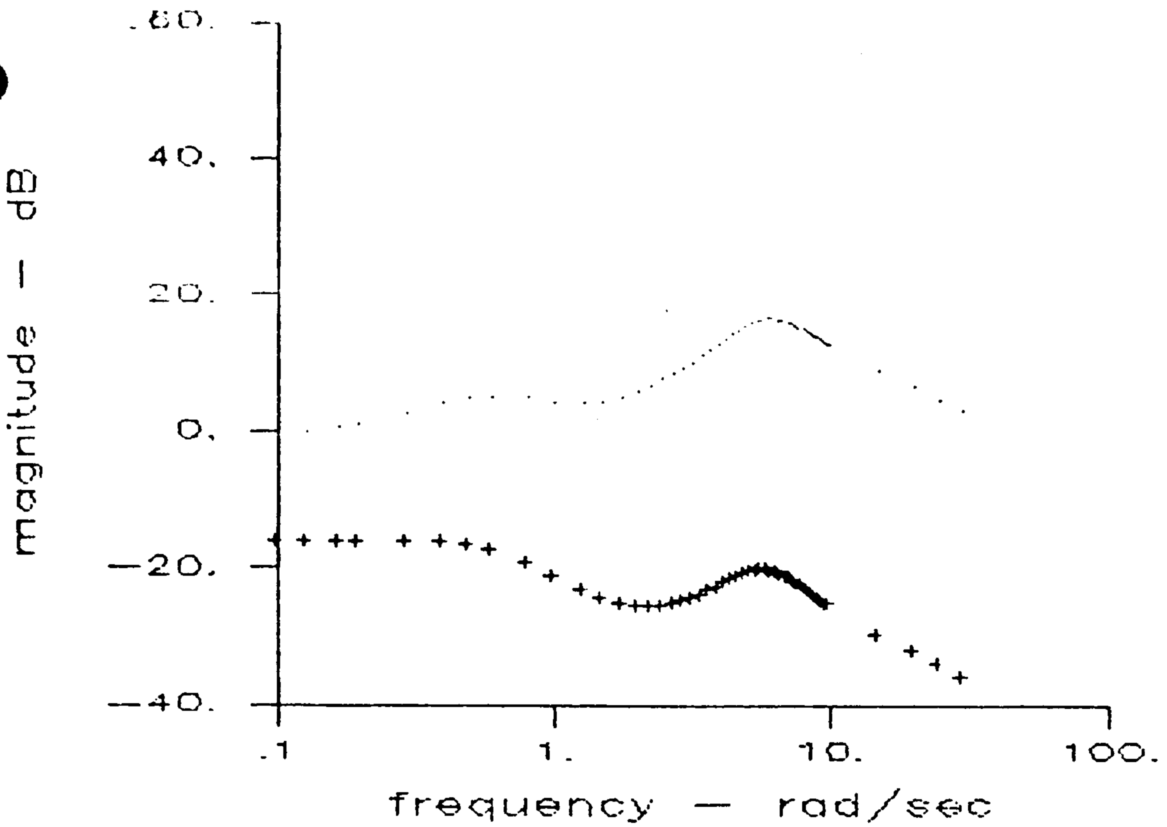
[illegible] Configuration E-4 : Theta Tracking



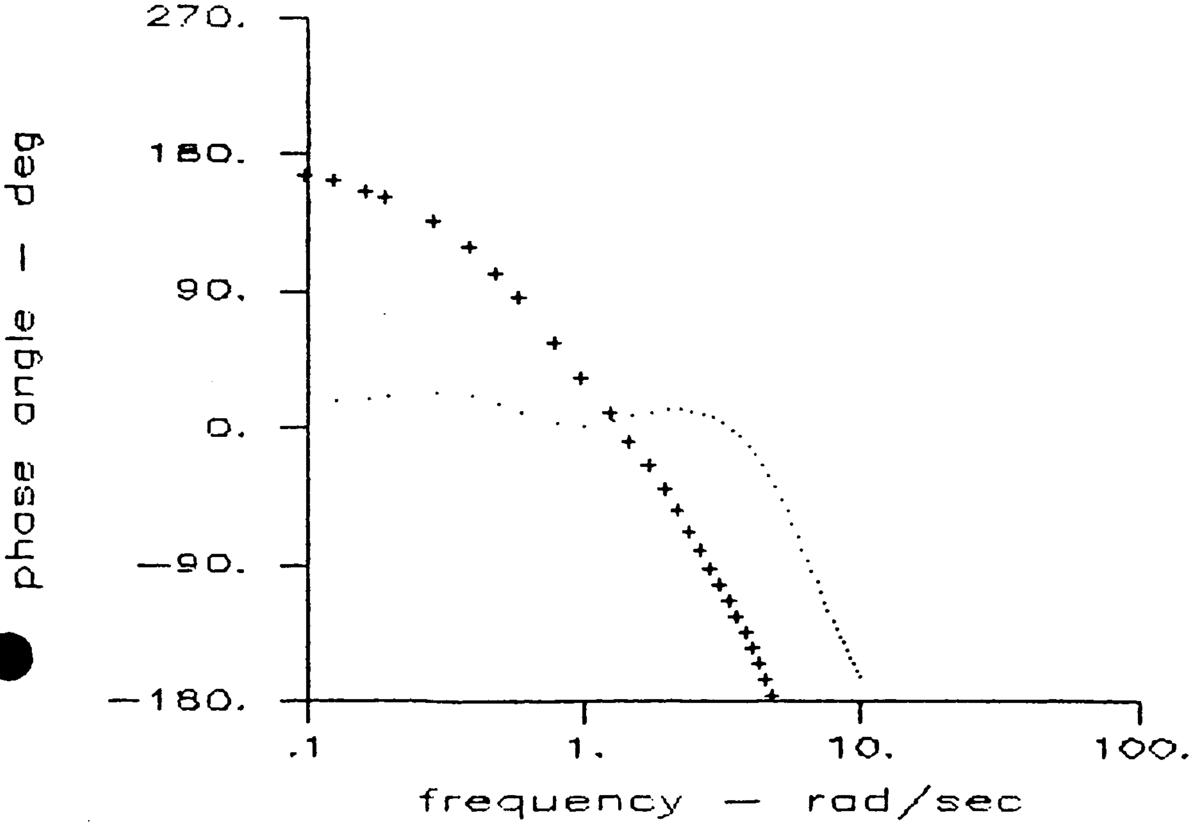
LEGEND:
· pilot response to theta error
\+ pilot response to theta



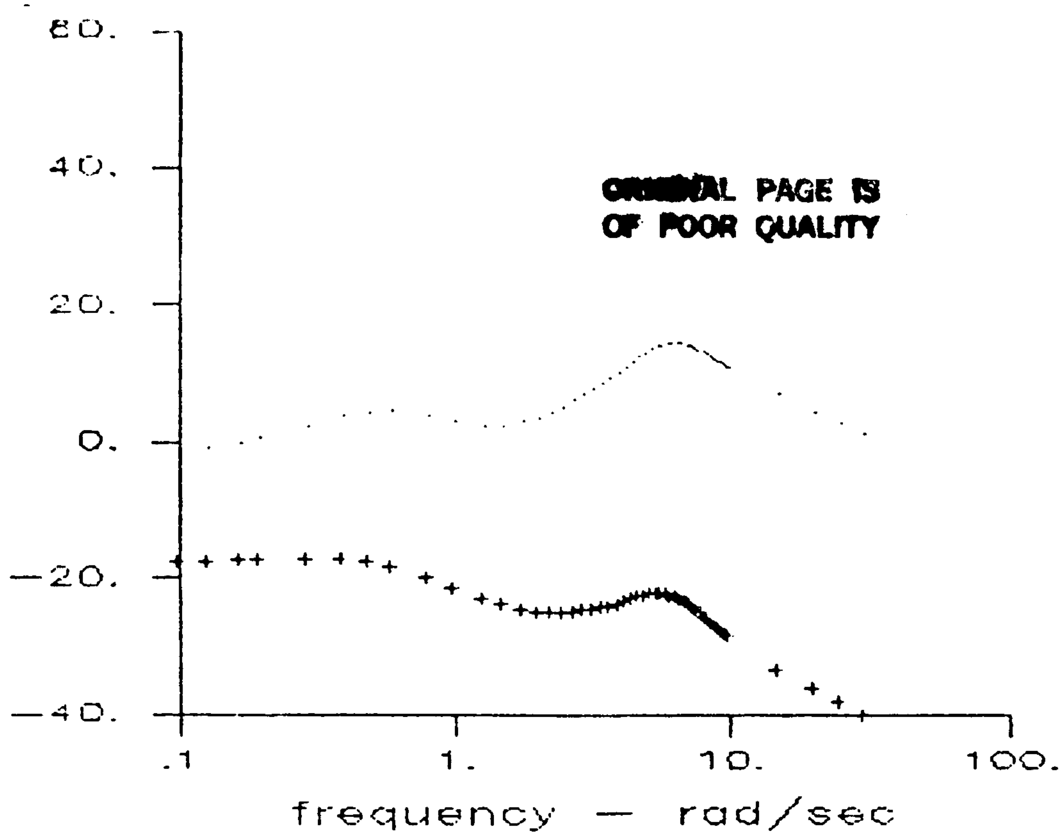
HLK Configuration F-5 : Theta Tracking



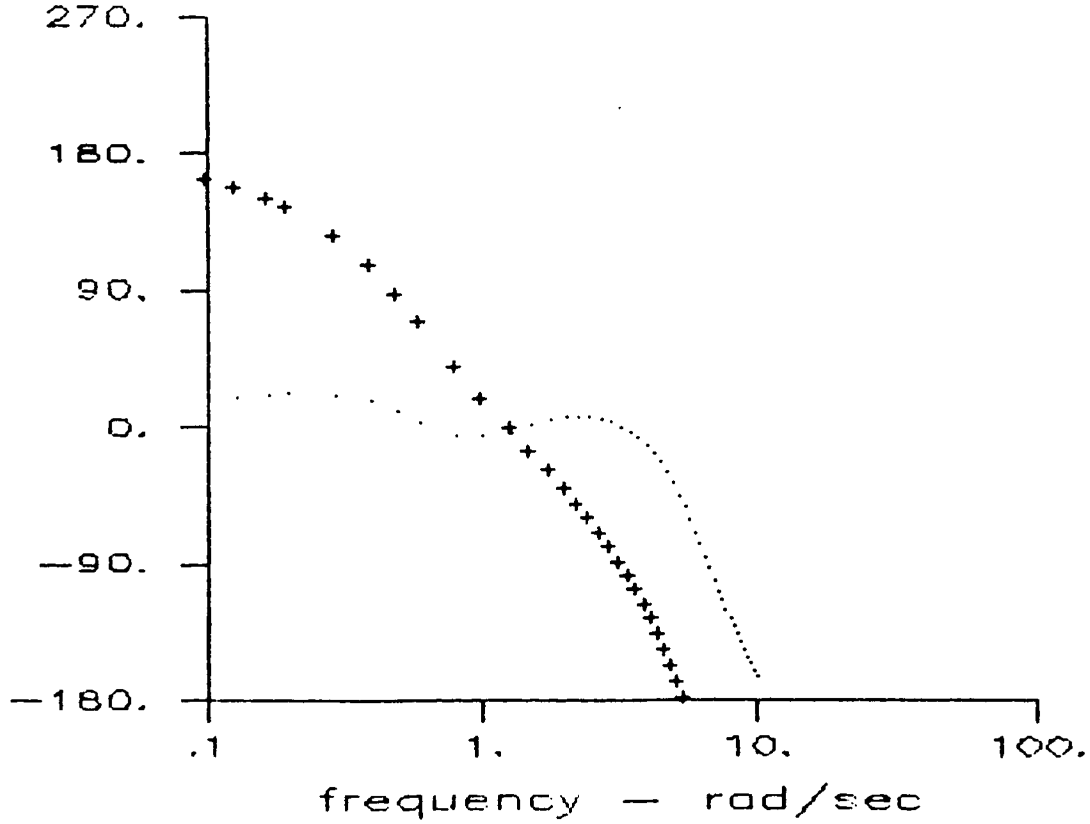
LEGEND:
· pilot response to theta error
+ pilot response to theta



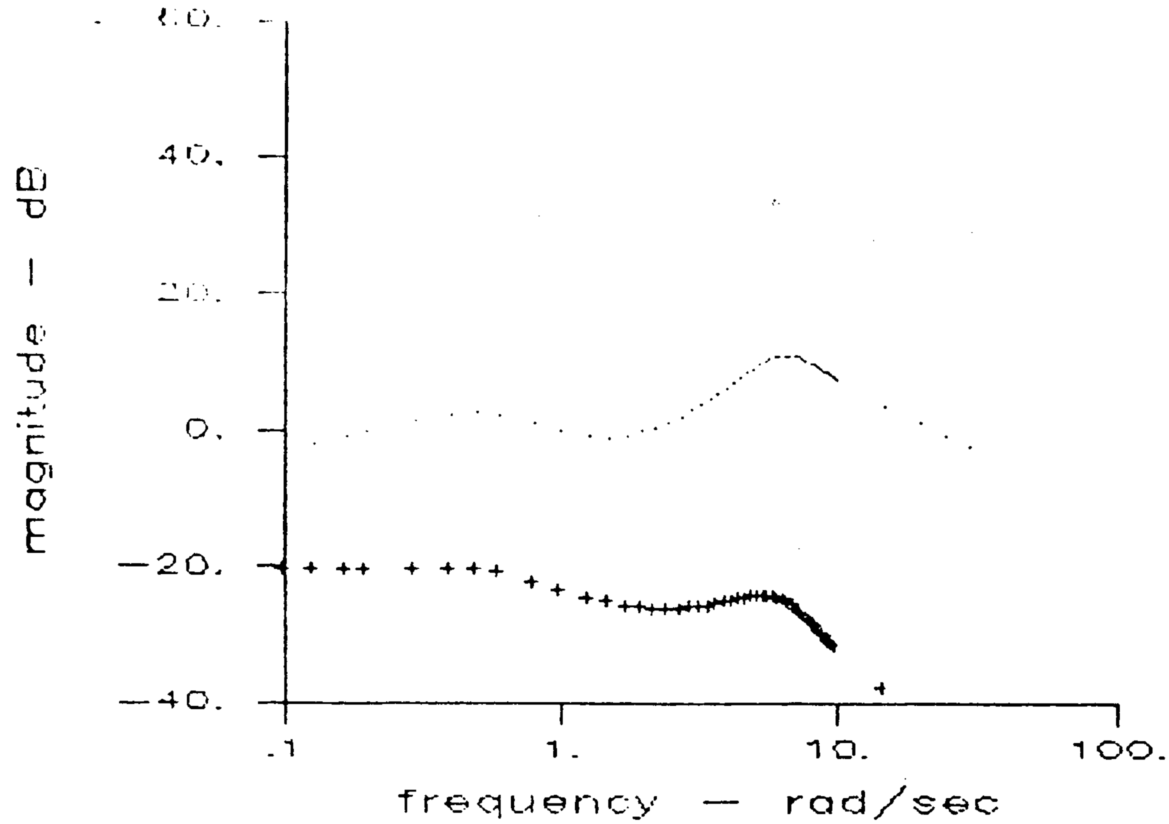
ULR Configuration F-3 : Theta Tracking



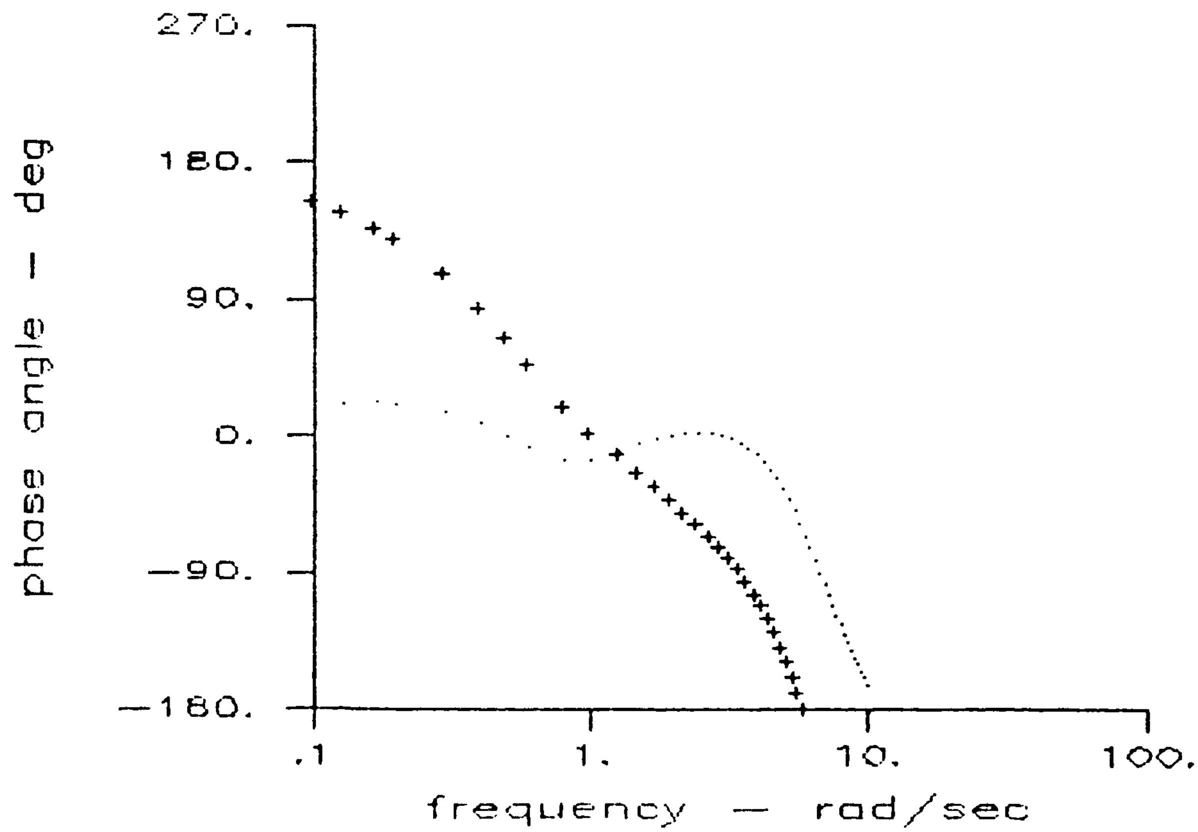
LEGEND:
· pilot response to theta error
+ pilot response to theta



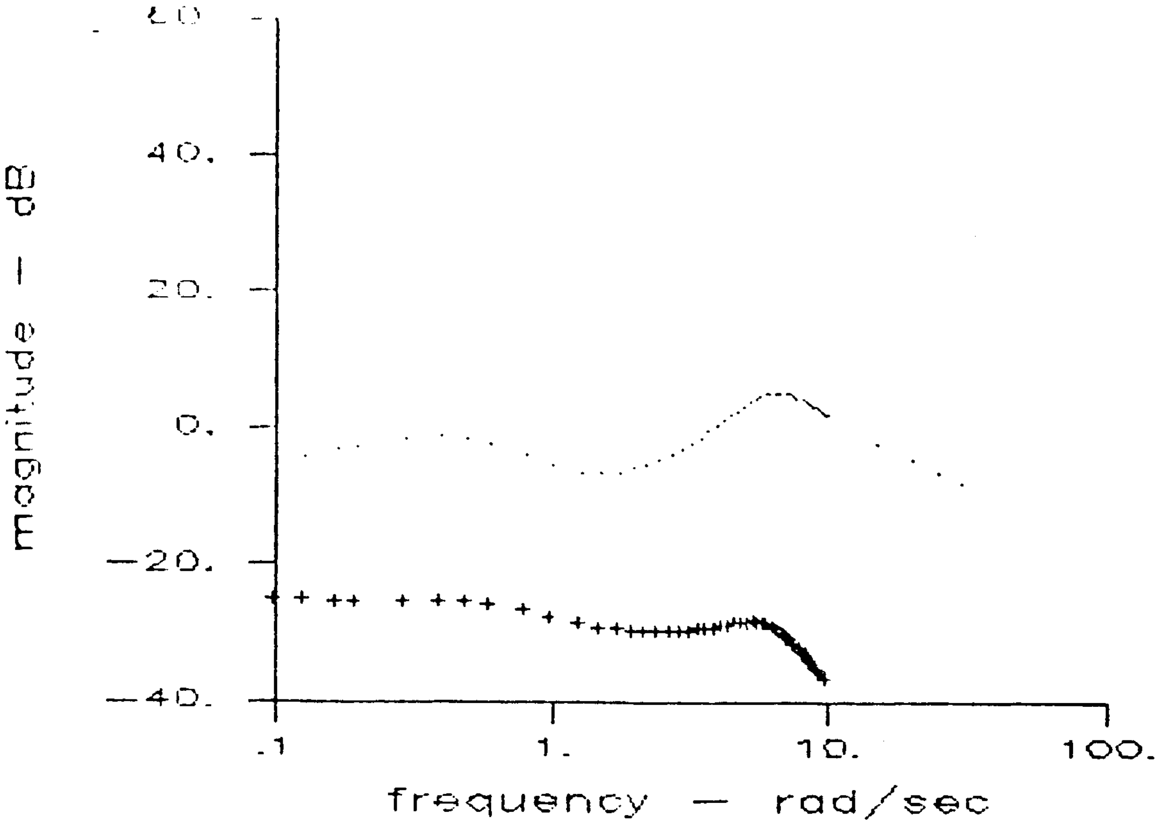
HUD Configuration I-2 : Theta Tracking



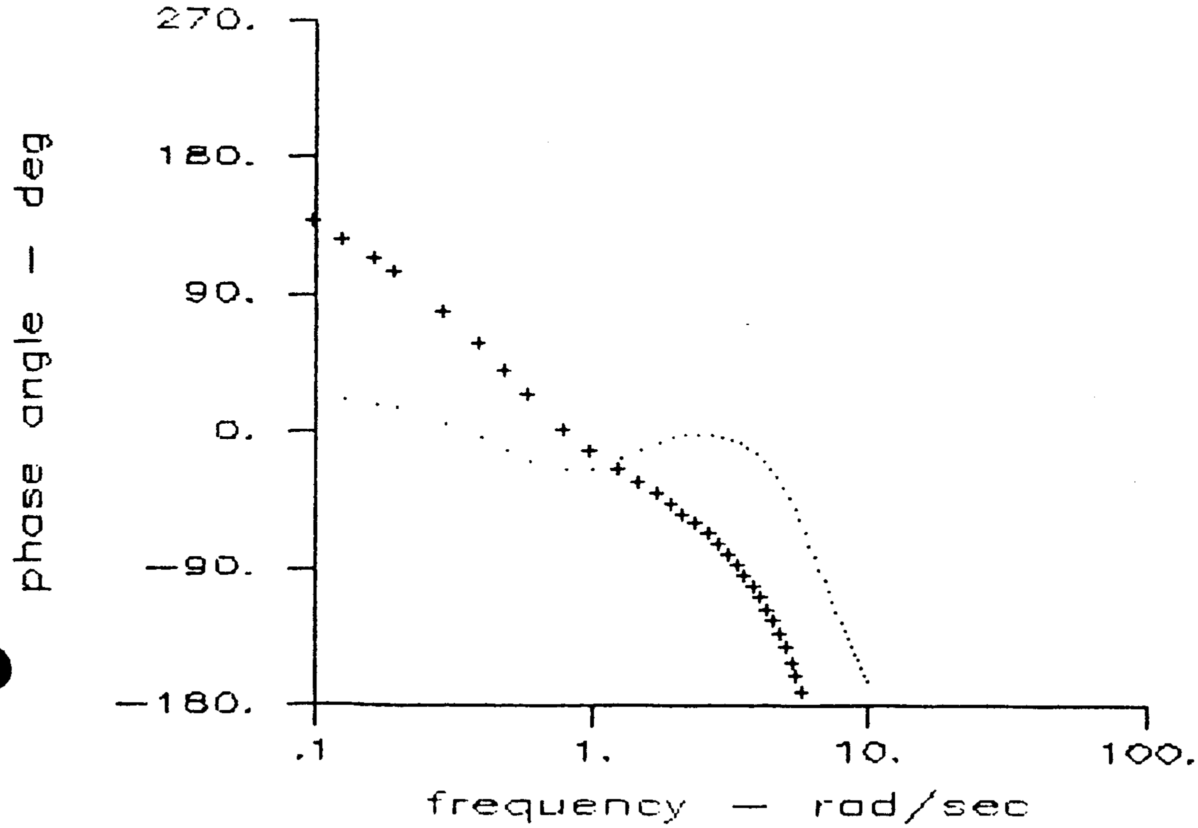
LEGEND:
· pilot response to theta error
+ pilot response to theta



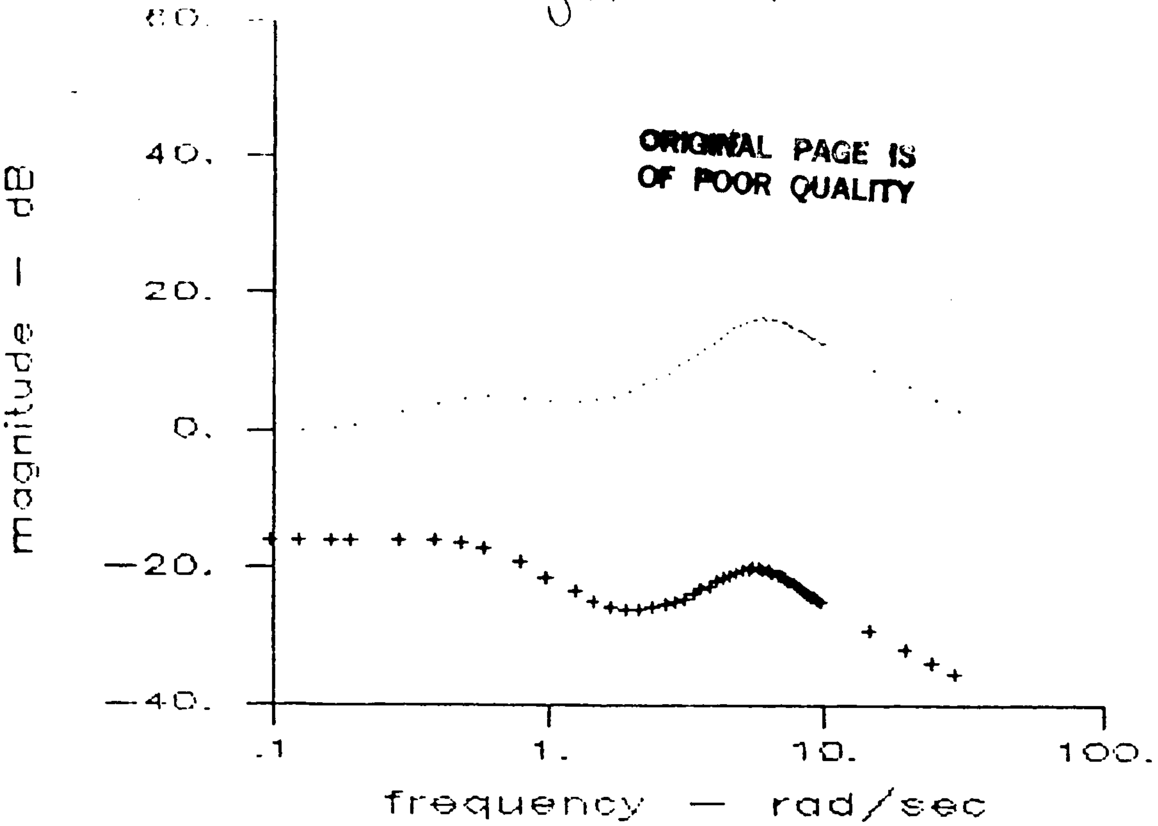
UHF Configuration F-1 : Theta Tracking



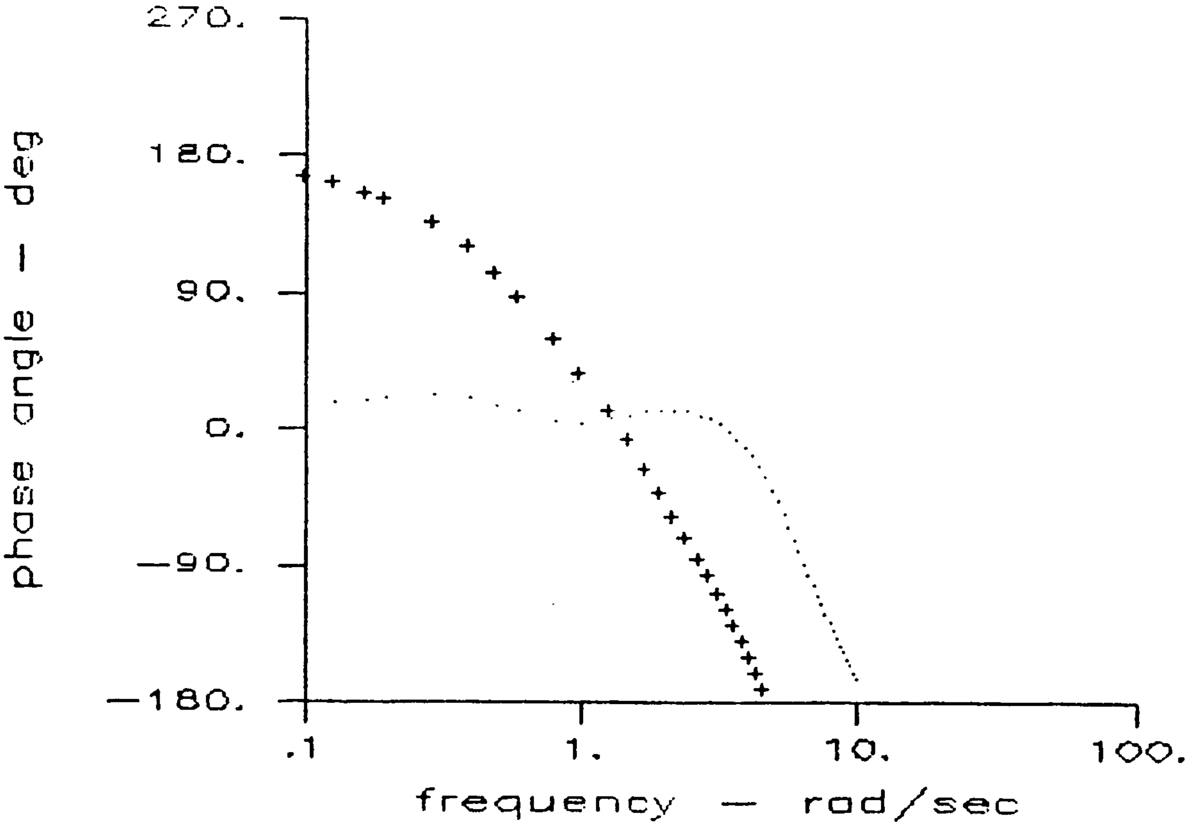
LEGEND:
· pilot response to theta error
+ pilot response to theta



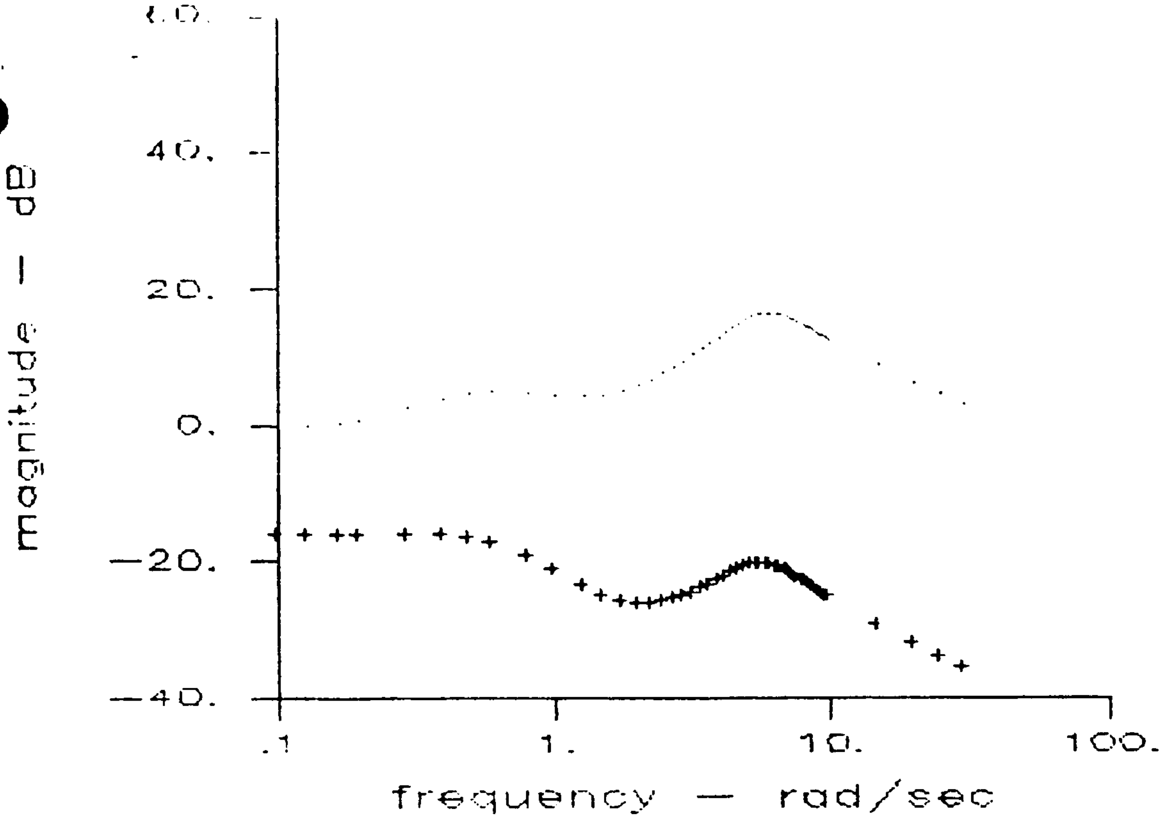
DLR Configuration G-1 : Theta Tracking



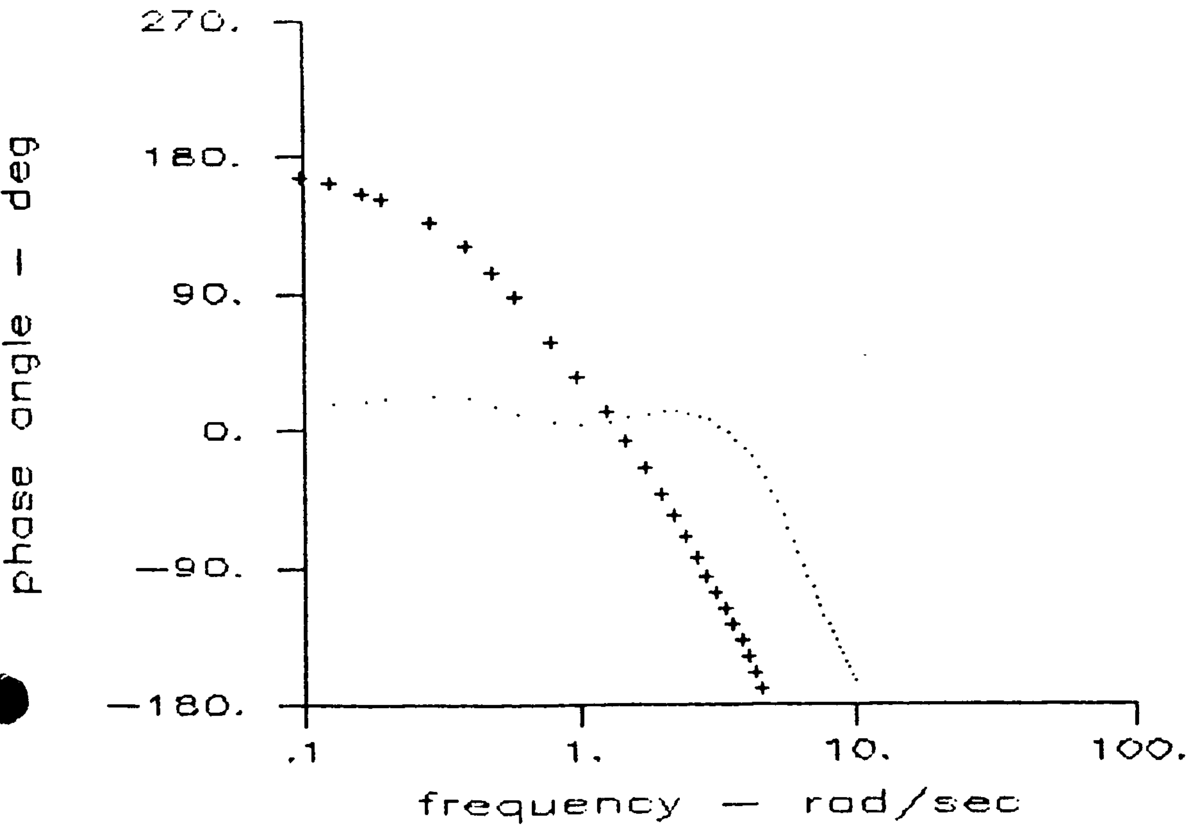
LEGEND:
· pilot response to theta error
+ pilot response to theta



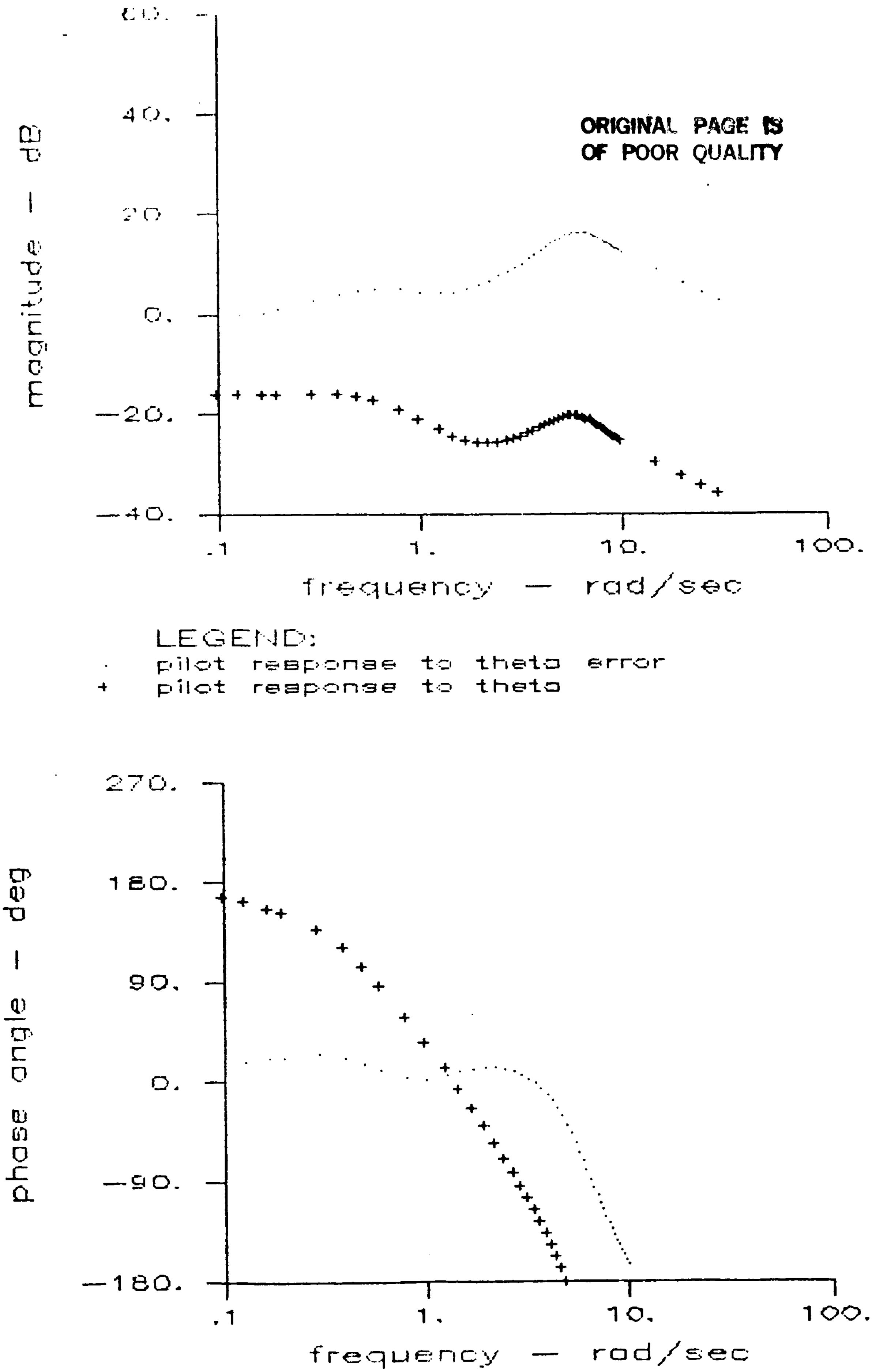
[illegible] Configuration 6-2 : Theta tracking



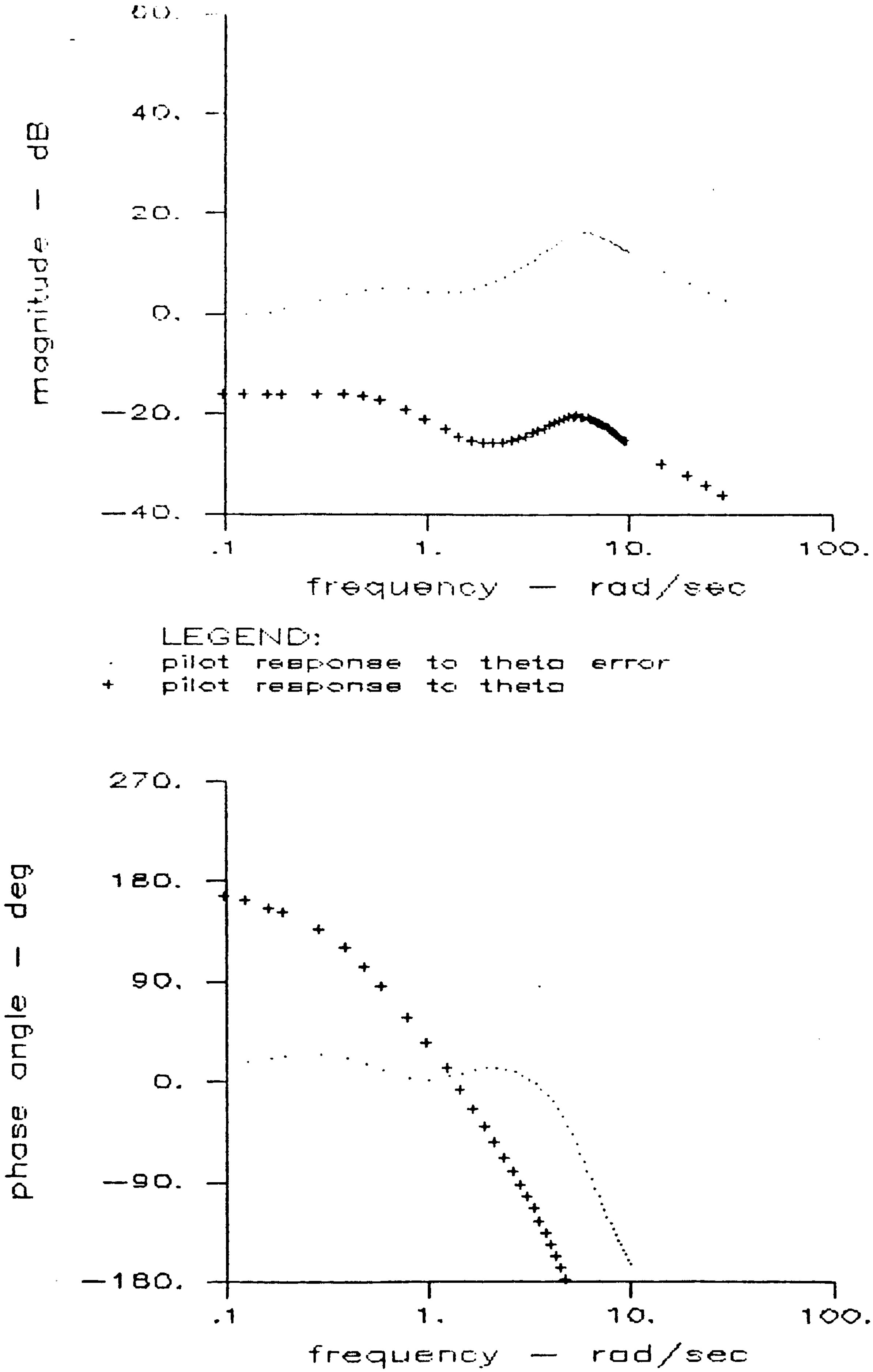
LEGEND:
· · pilot response to theta error
\+ pilot response to theta



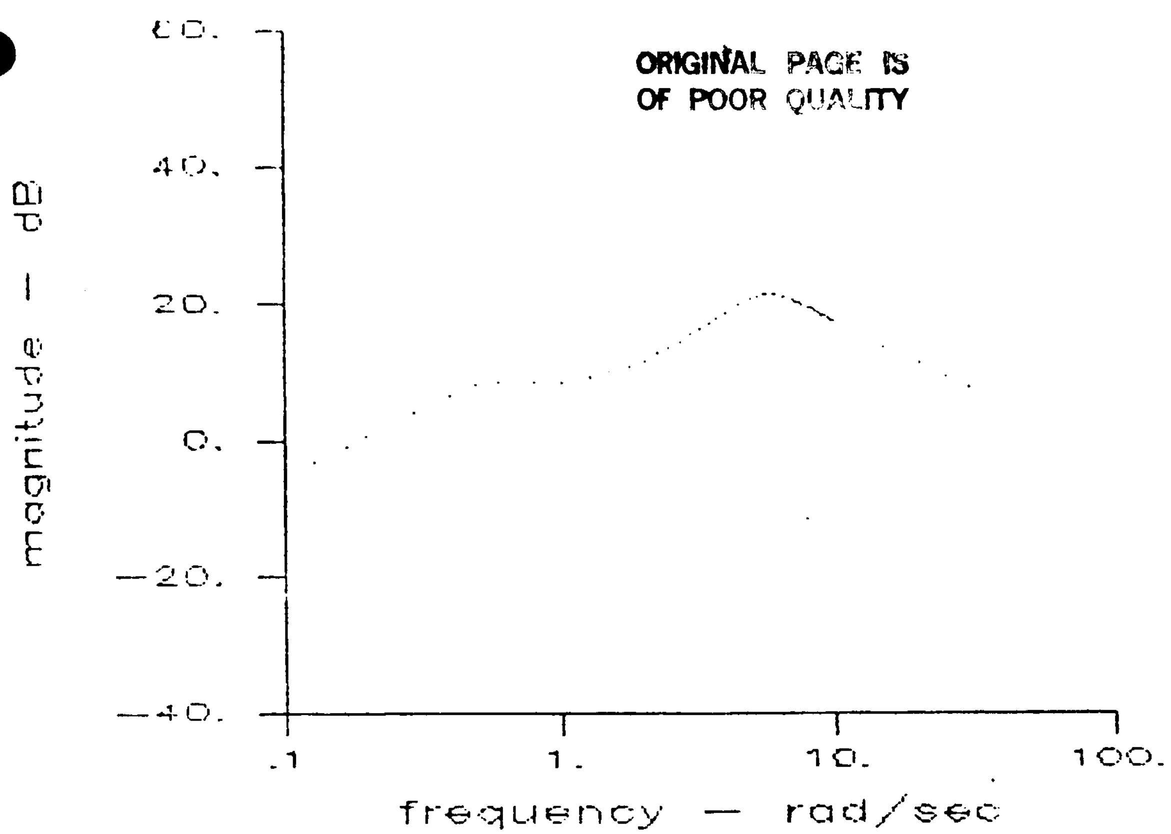
NLF Configuration G-3 : Theta Tracking



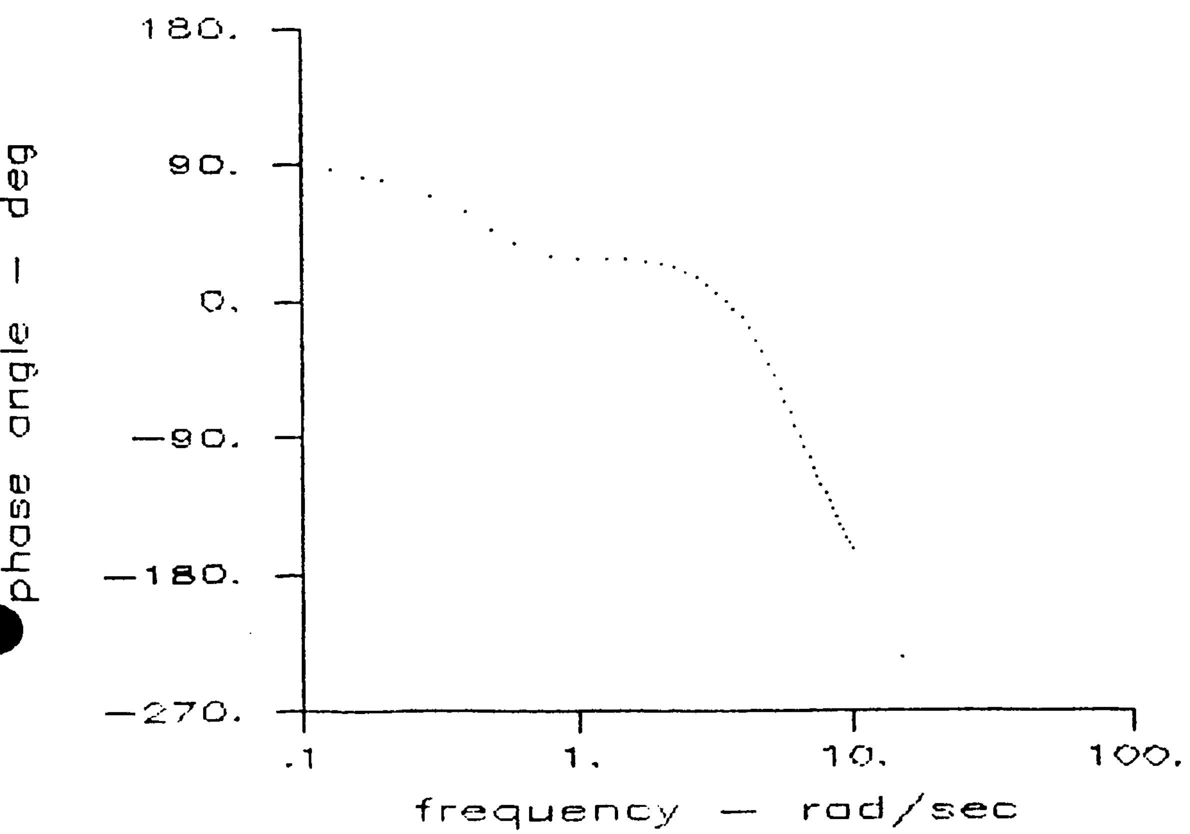
NLR Configuration G-4 : Theta Tracking



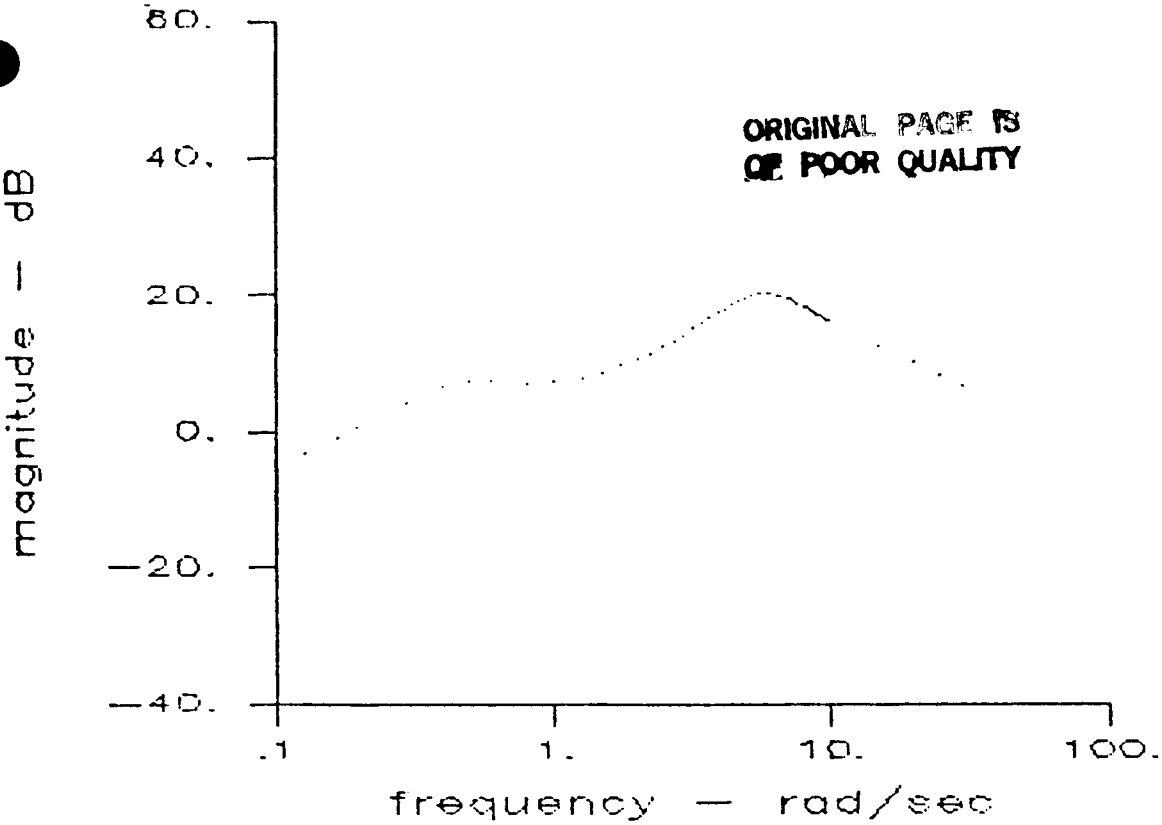
NHP Configuration E-1 : Theta Tracking



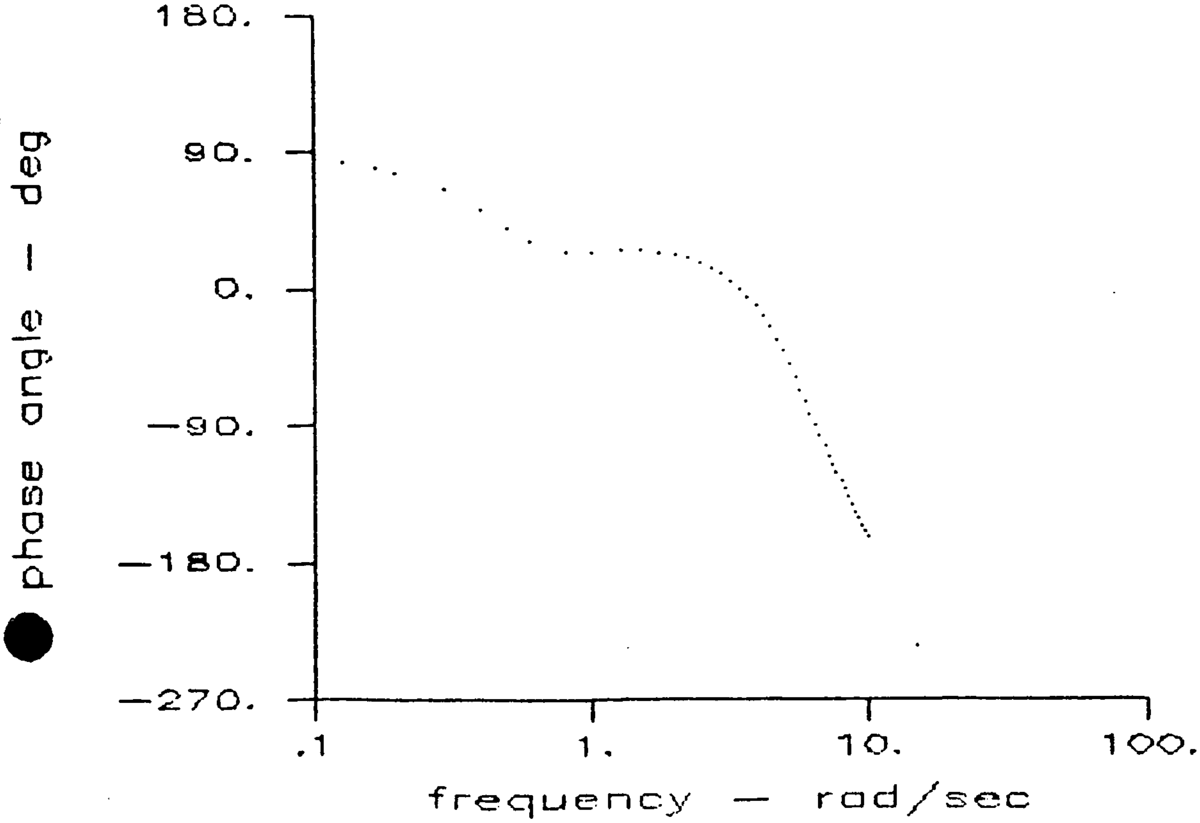
LEGEND:
· equivalent single loop pilot function



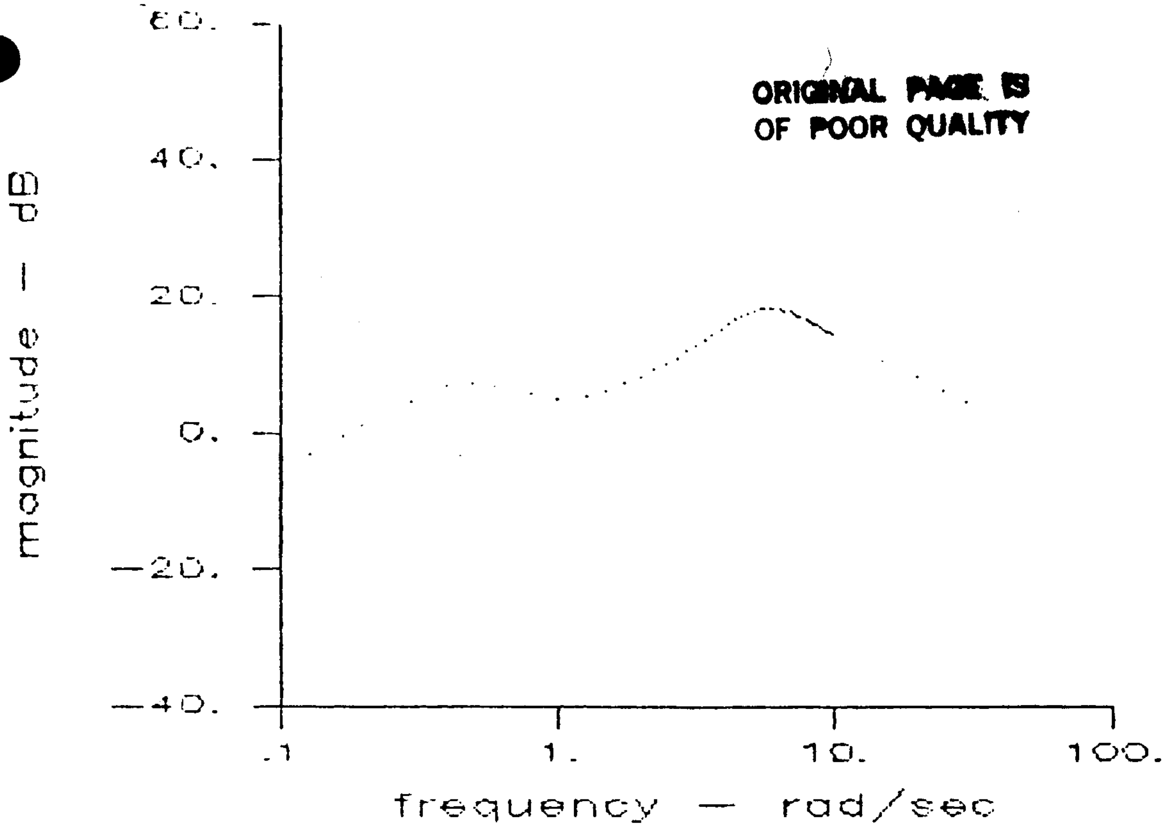
NLR Configuration L-2 : Theta Tracking



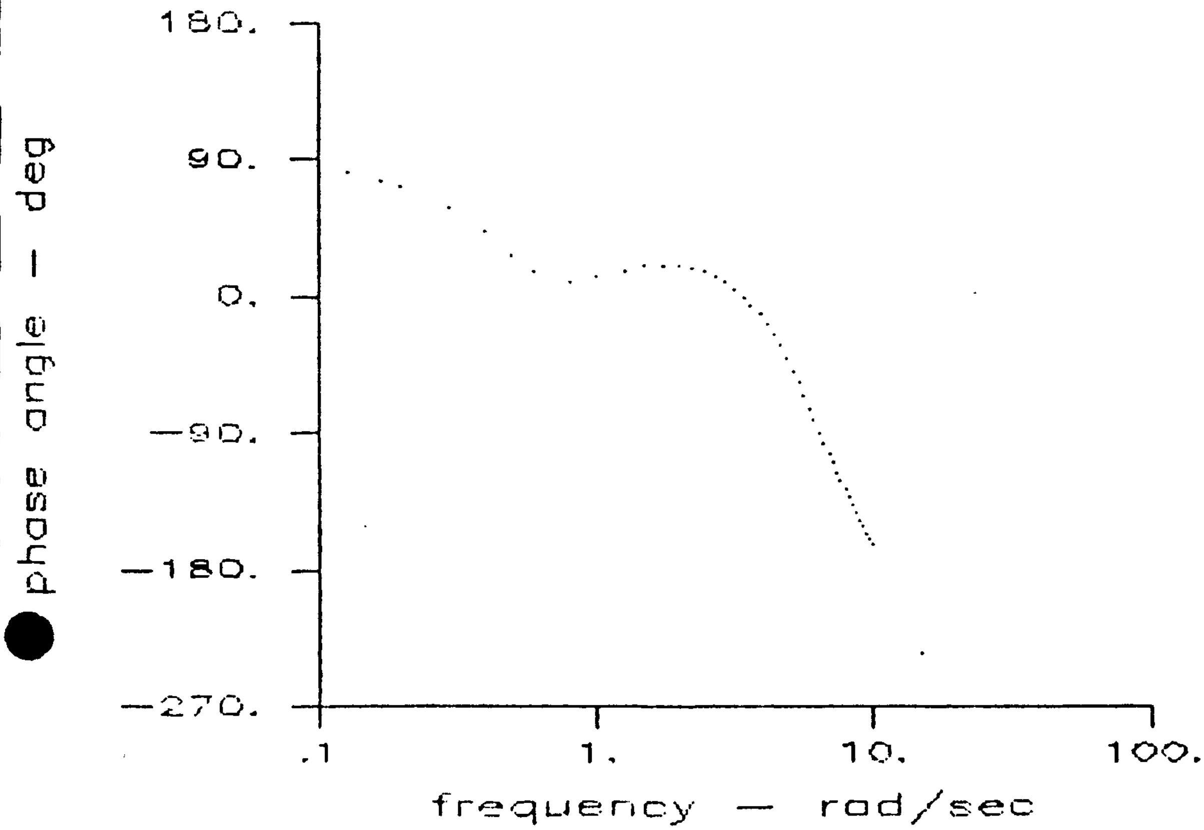
LEGEND:
· equivalent single loop pilot function



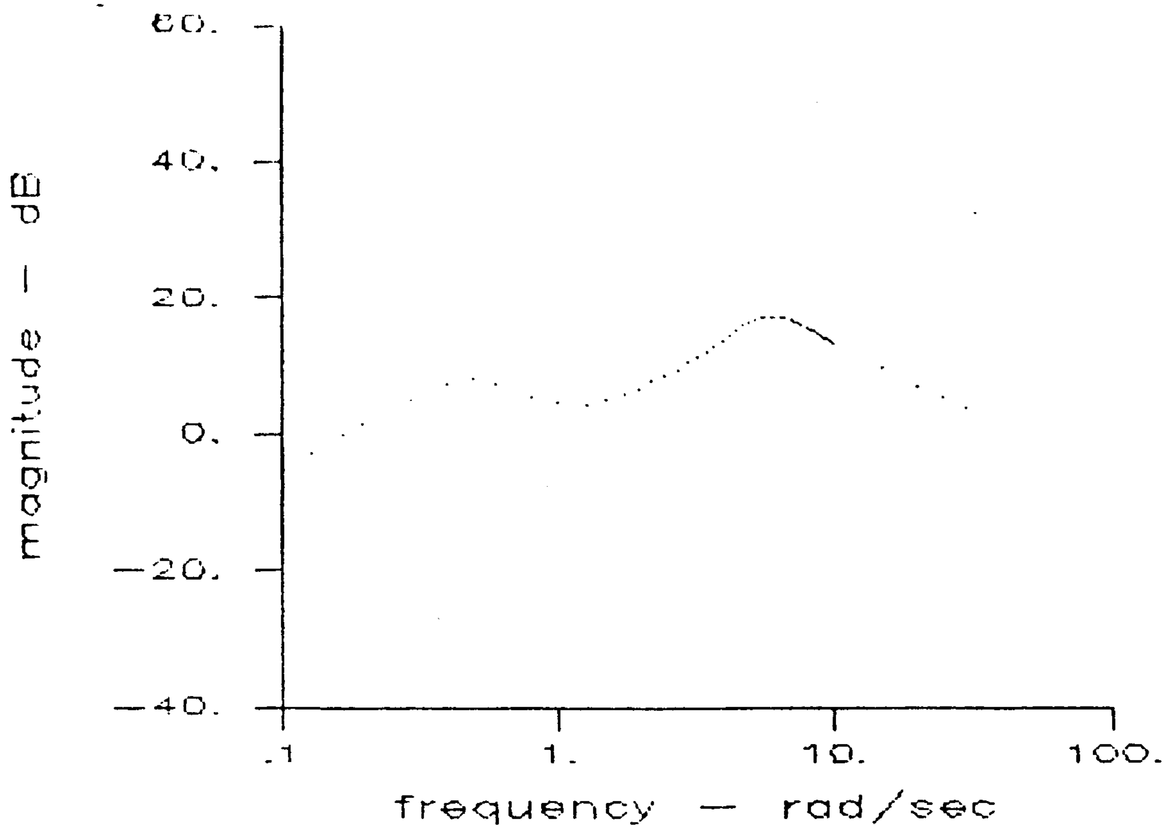
NLP Configuration E-3 : Theta Tracking



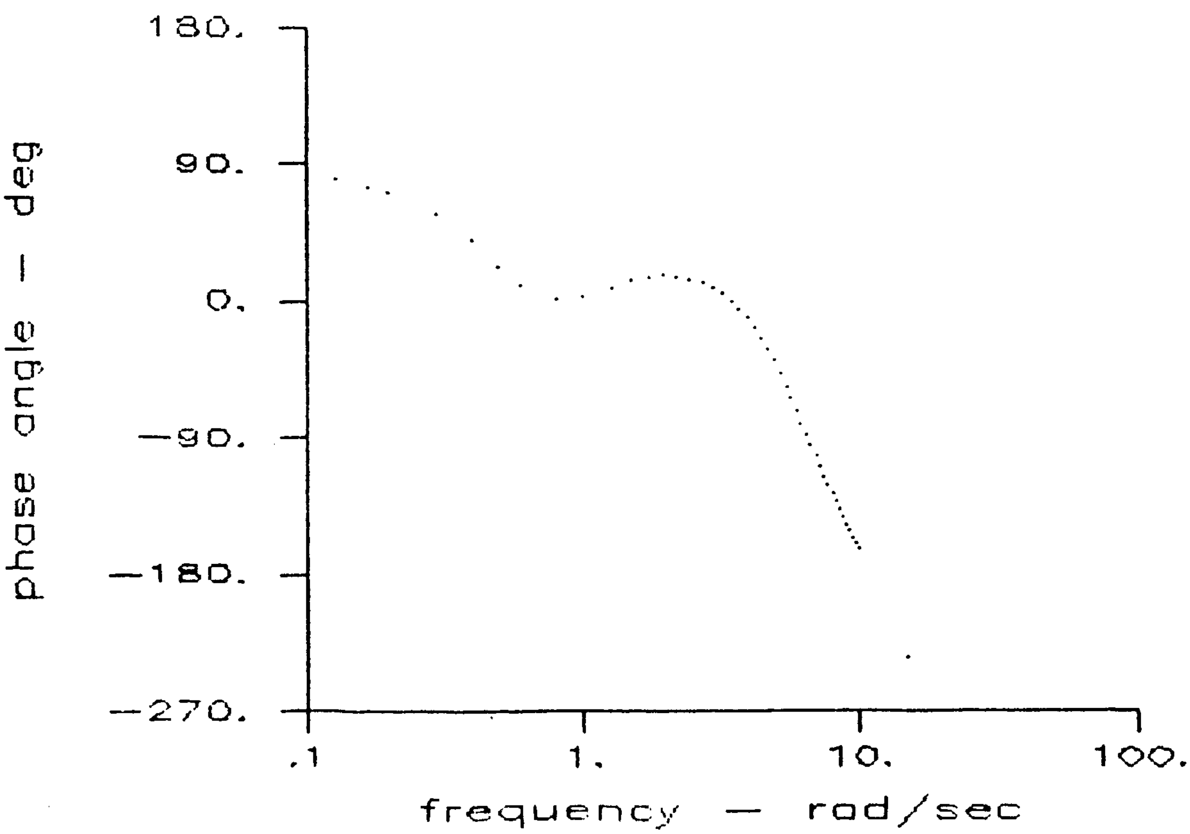
LEGEND:
equivalent single loop pilot function



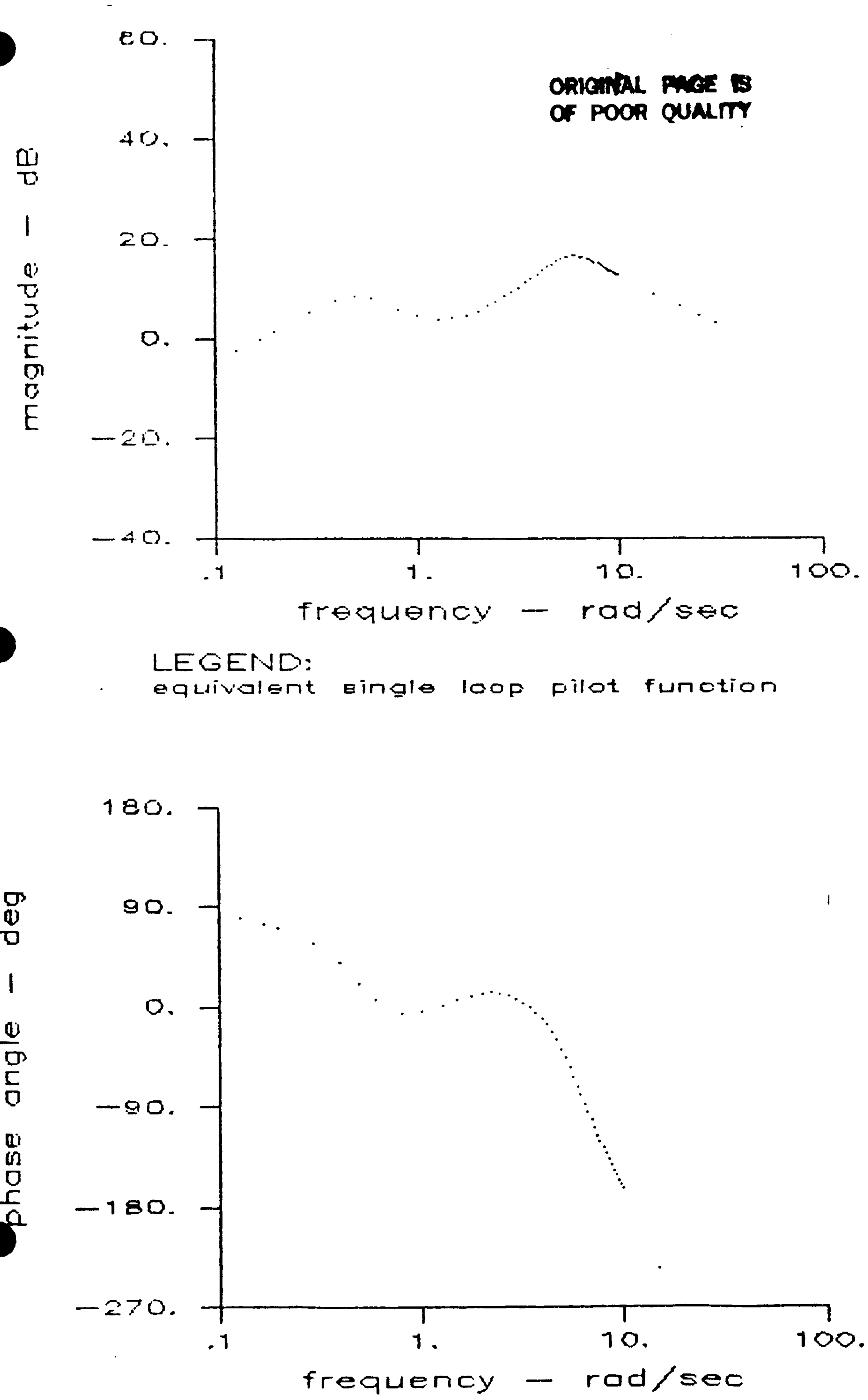
[illegible] Configuration E-4 : Theta Tracking



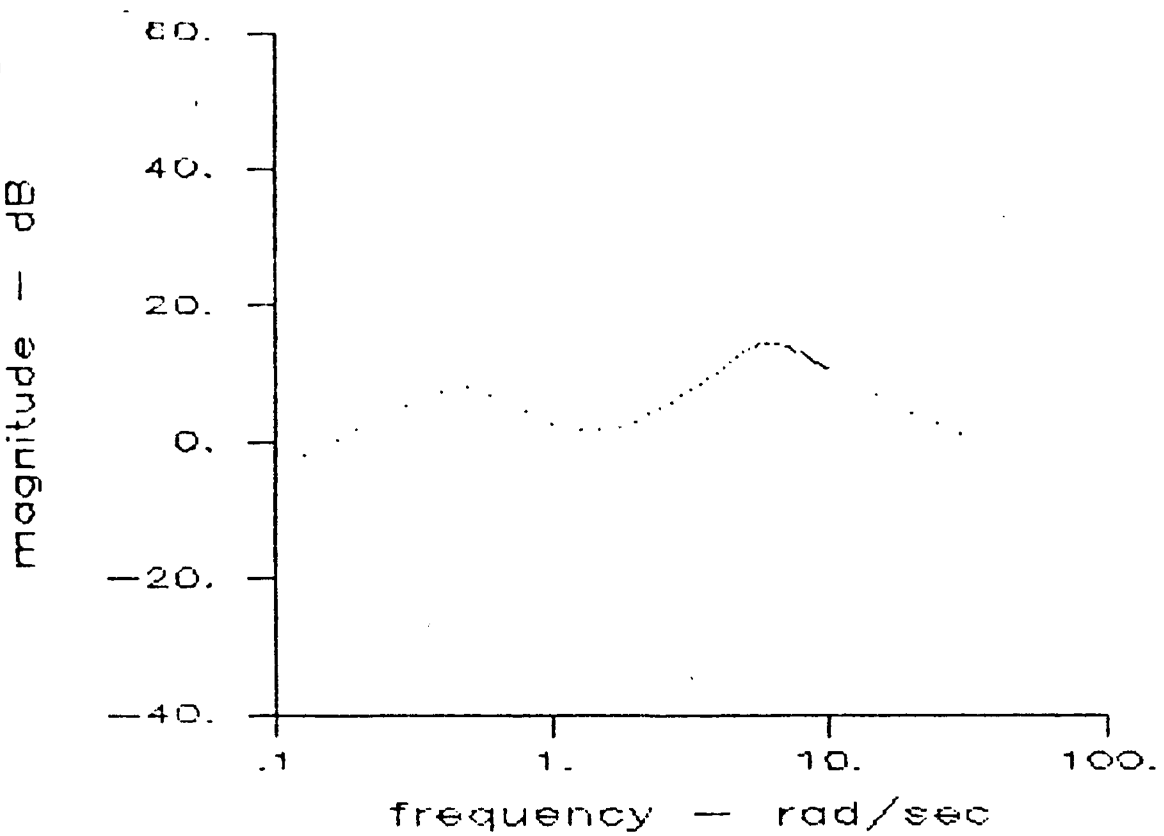
LEGEND:
· equivalent single loop pilot function



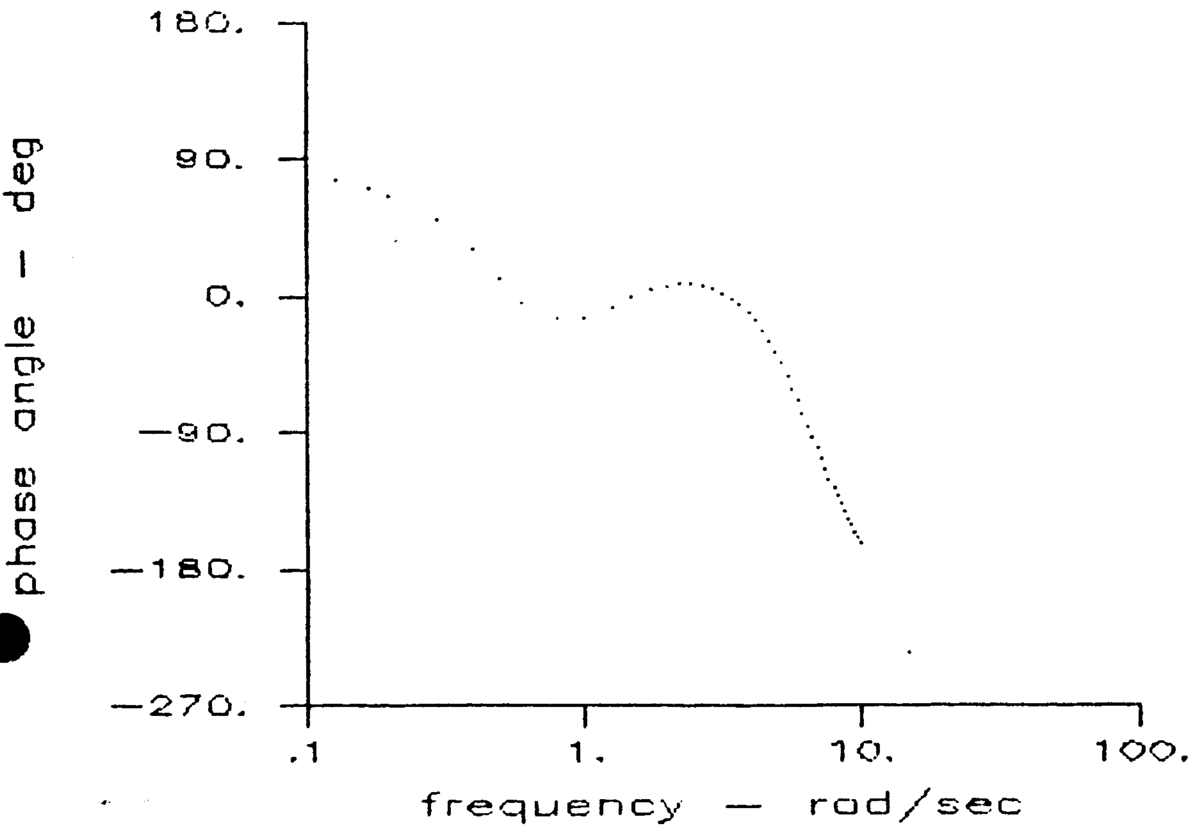
NLR Configuration E-5 : Theta Tracking



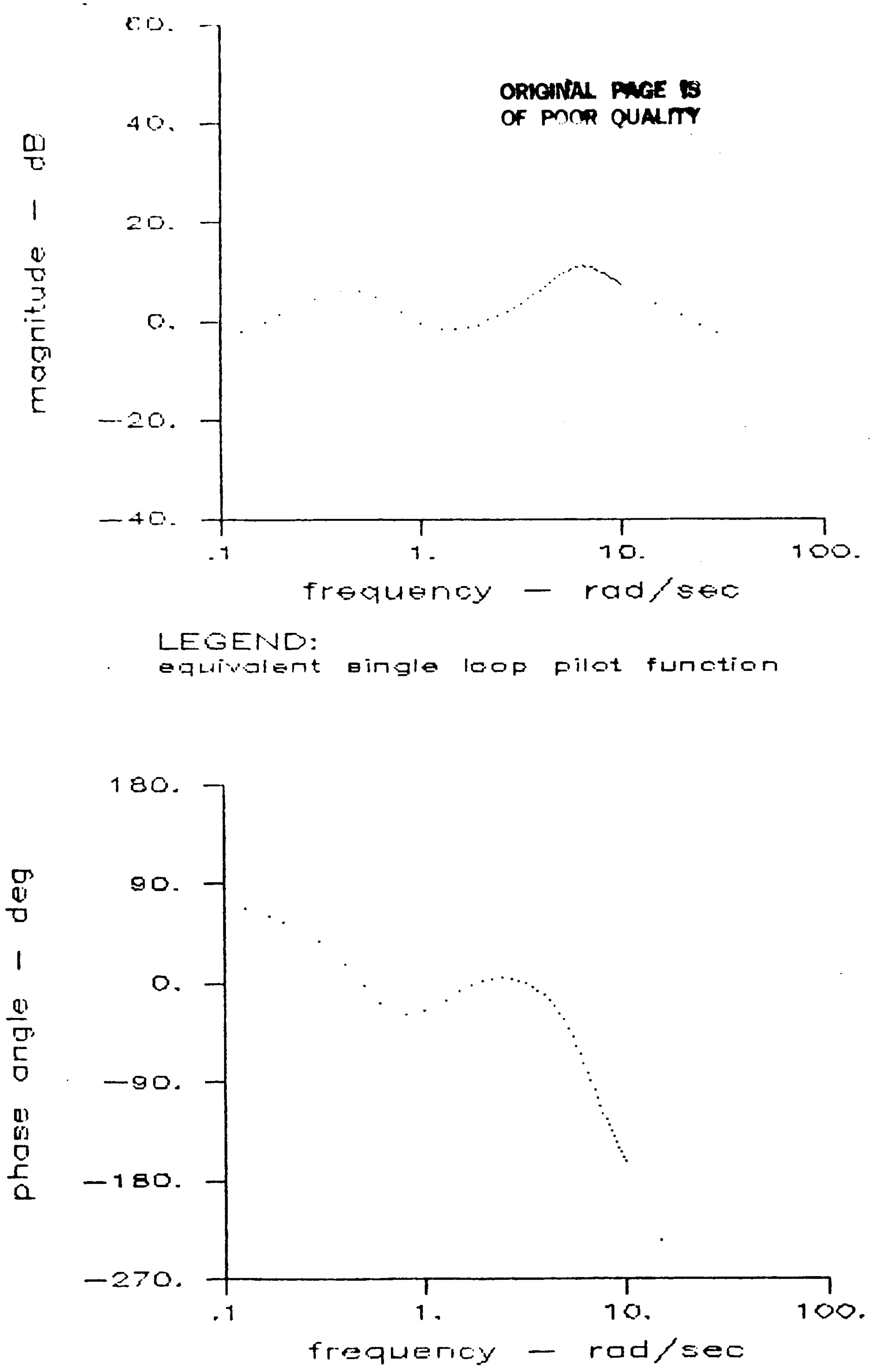
NLR Configuration F-3 : Theta Tracking



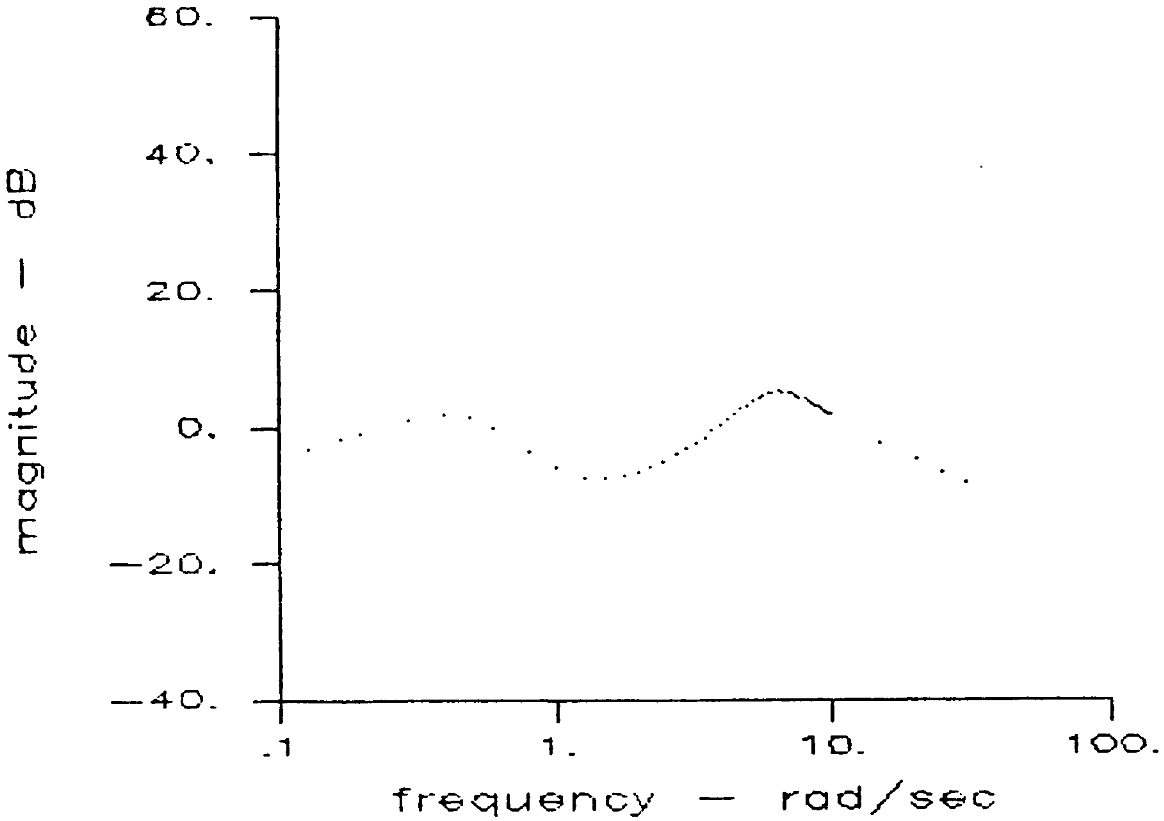
LEGEND:
· equivalent single loop pilot function



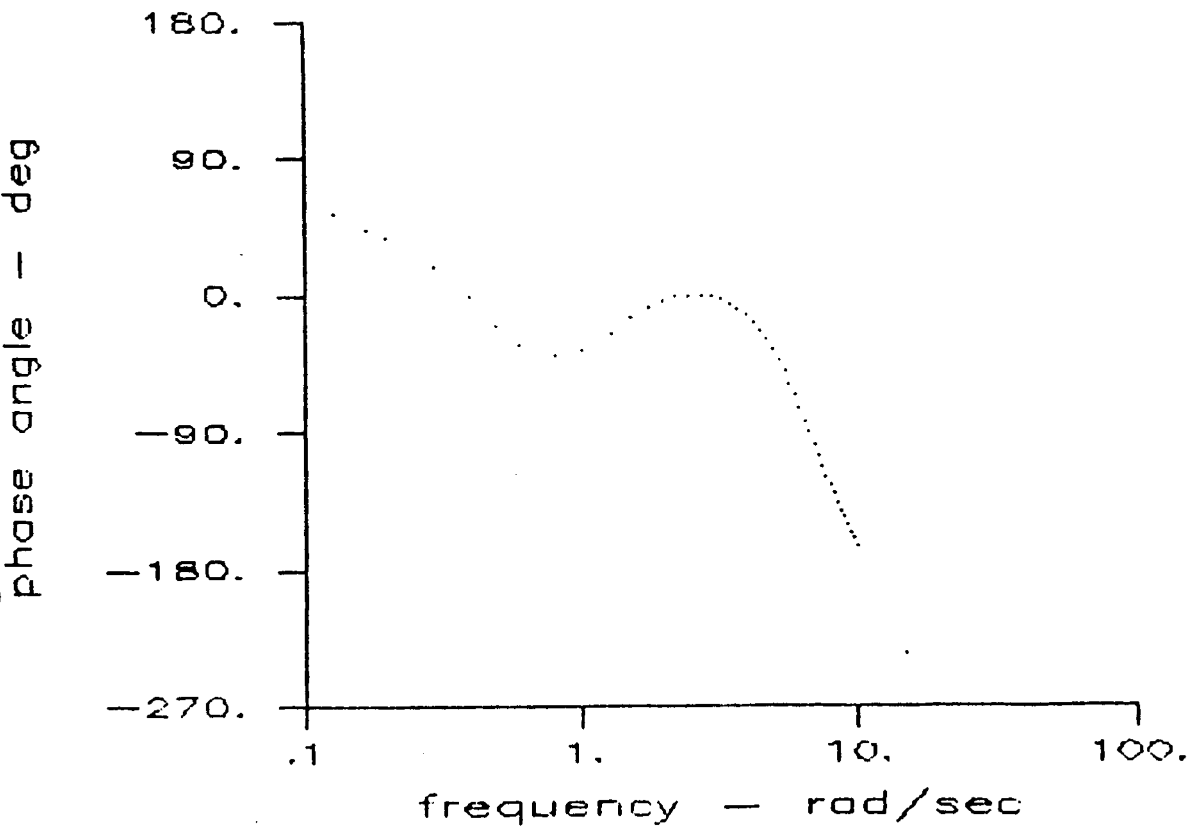
NLF Configuration I-2 : Theta Tracking



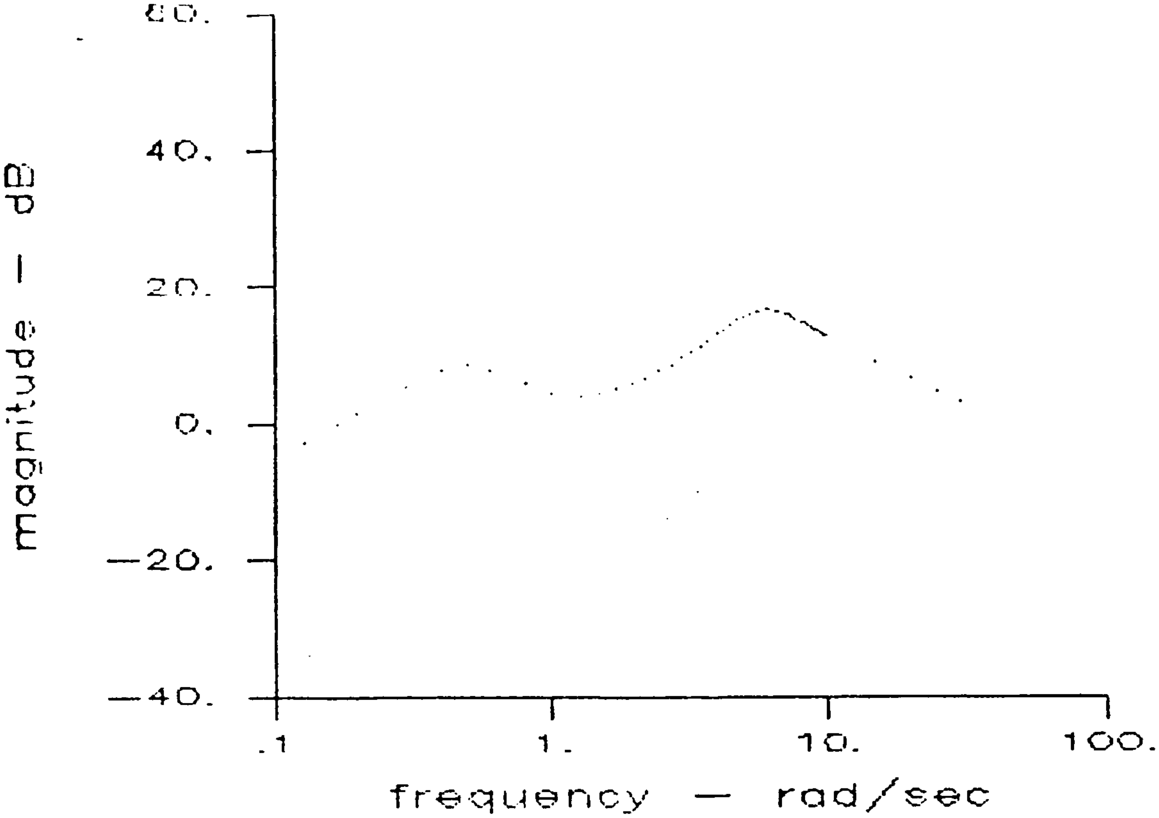
NLR Configuration F-1 : Theta Tracking



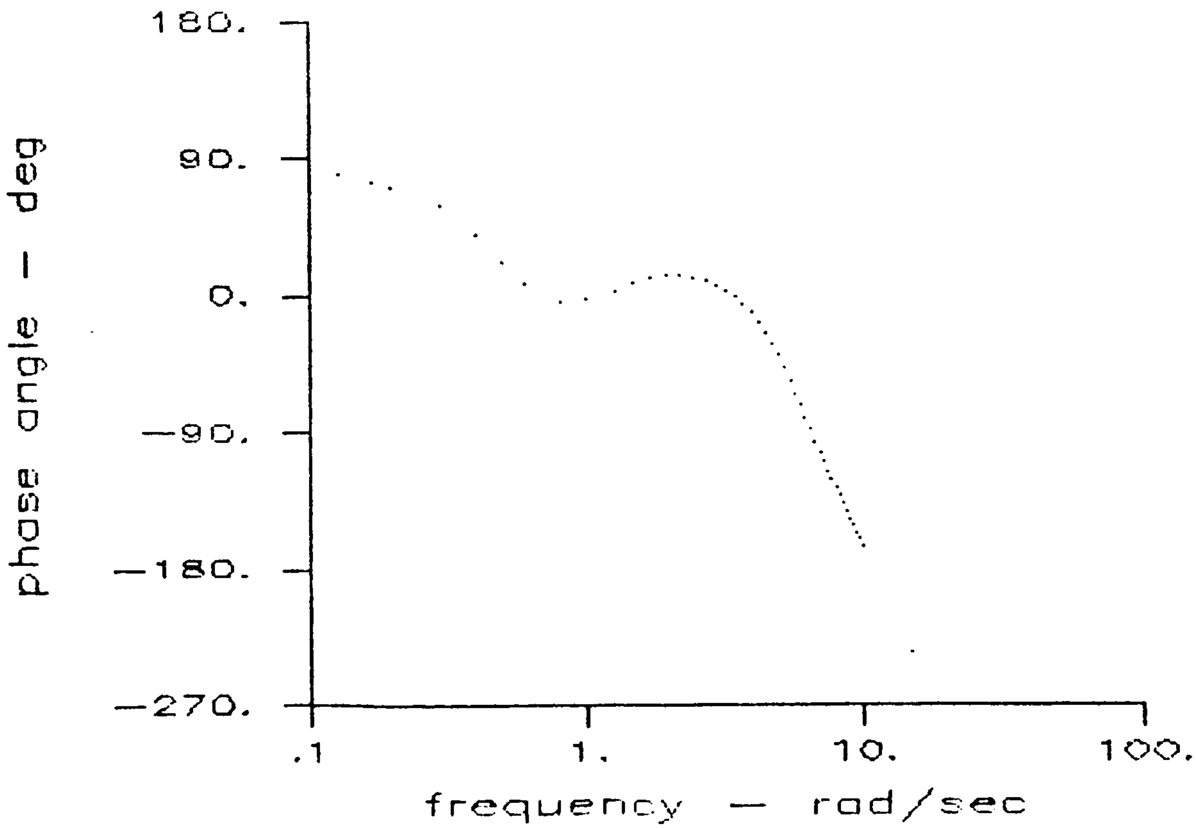
LEGEND:
· equivalent single loop pilot function



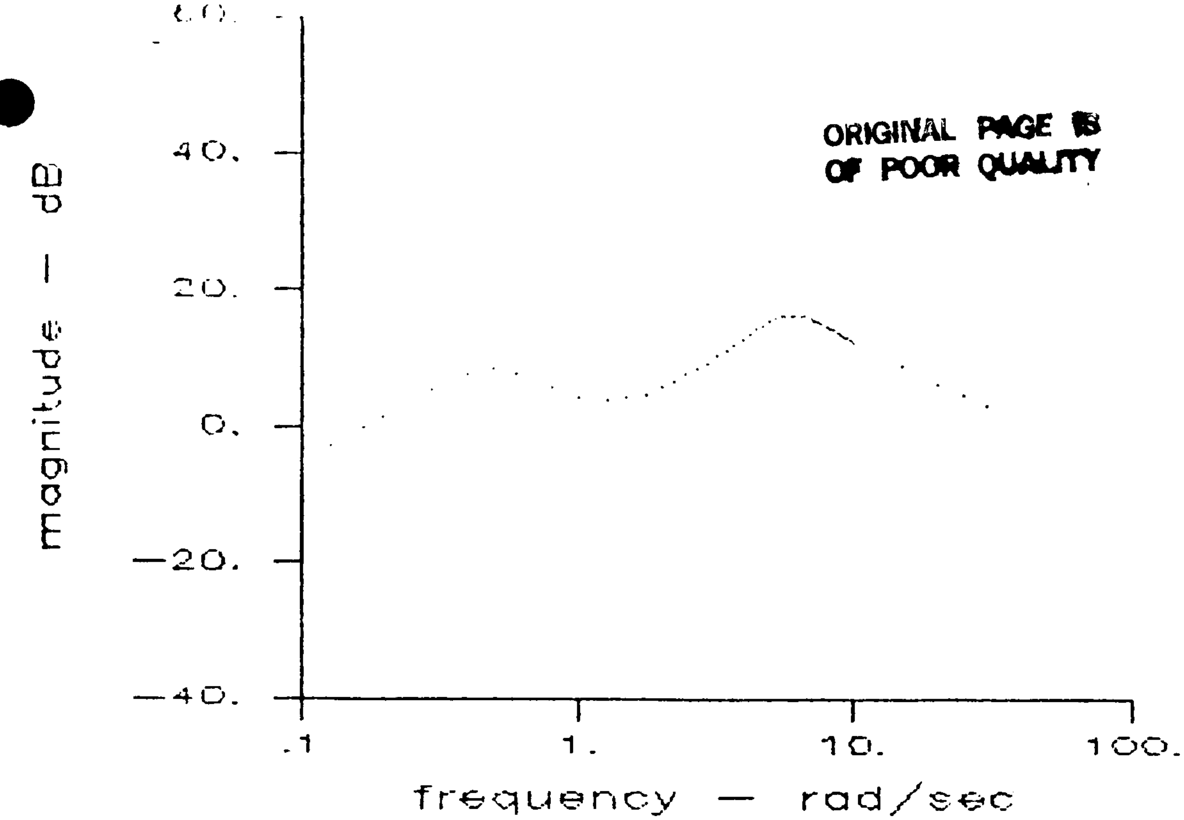
NLF Configuration G-1 : Theta Tracking



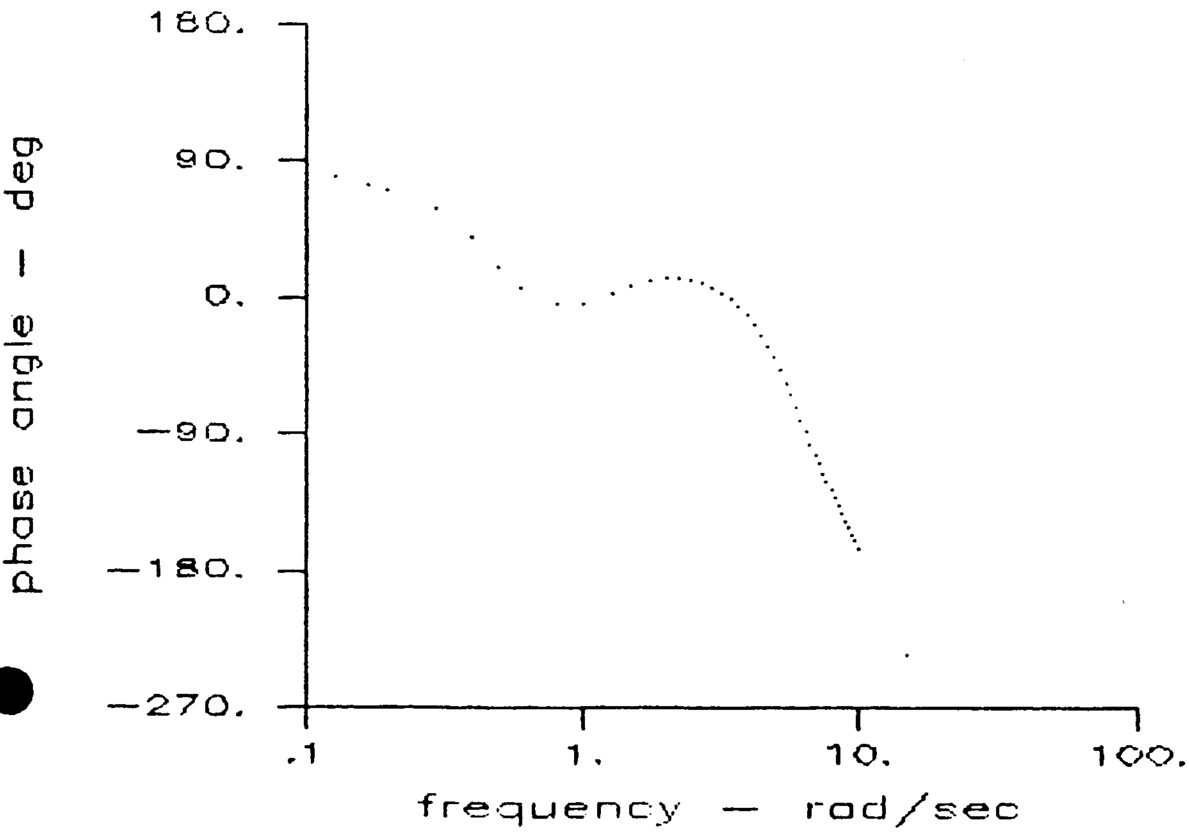
LEGEND:
· equivalent single loop pilot function



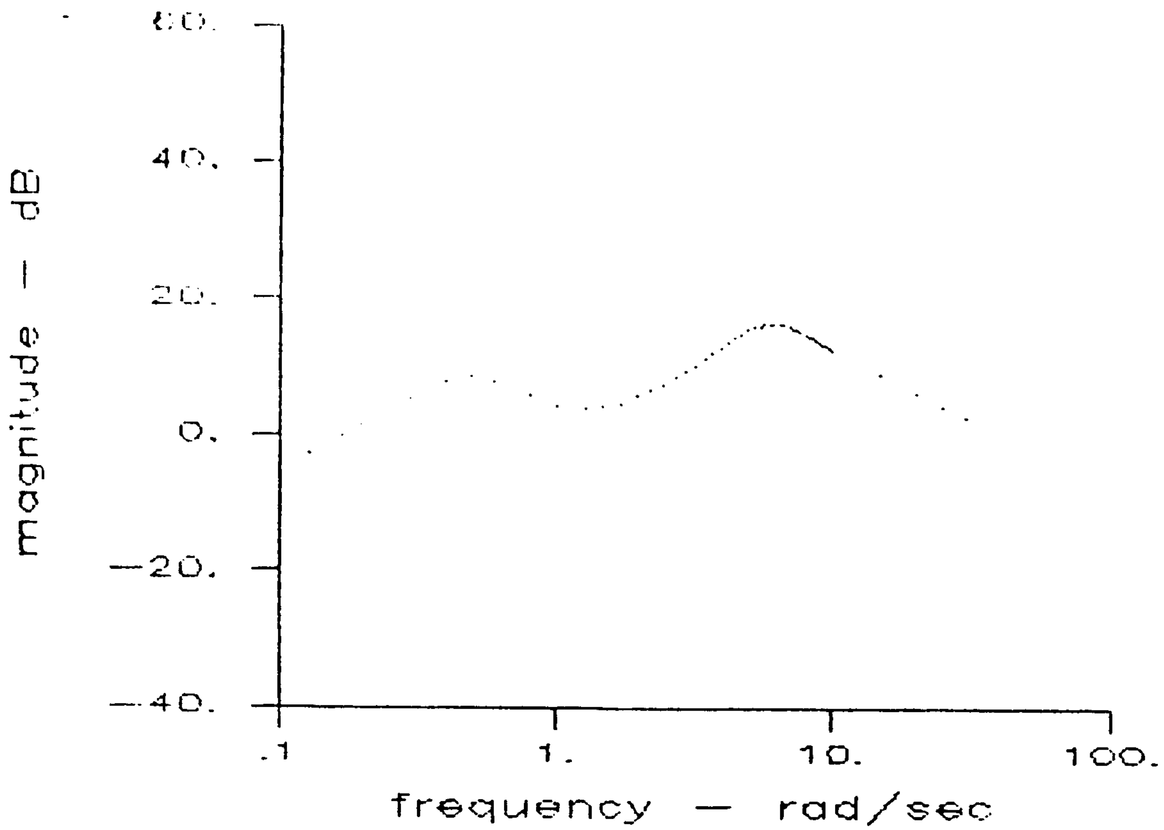
NLR Configuration G-2 : Theta Tracking



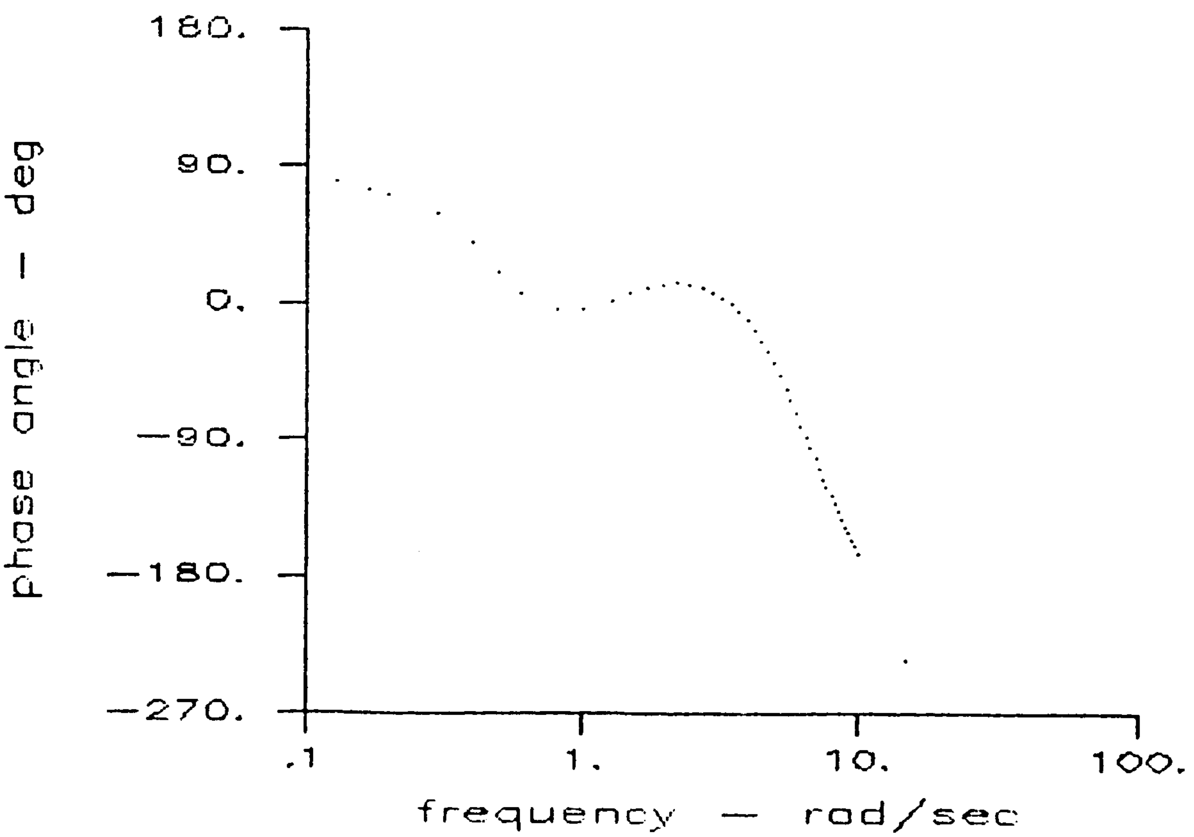
LEGEND:
equivalent single loop pilot function



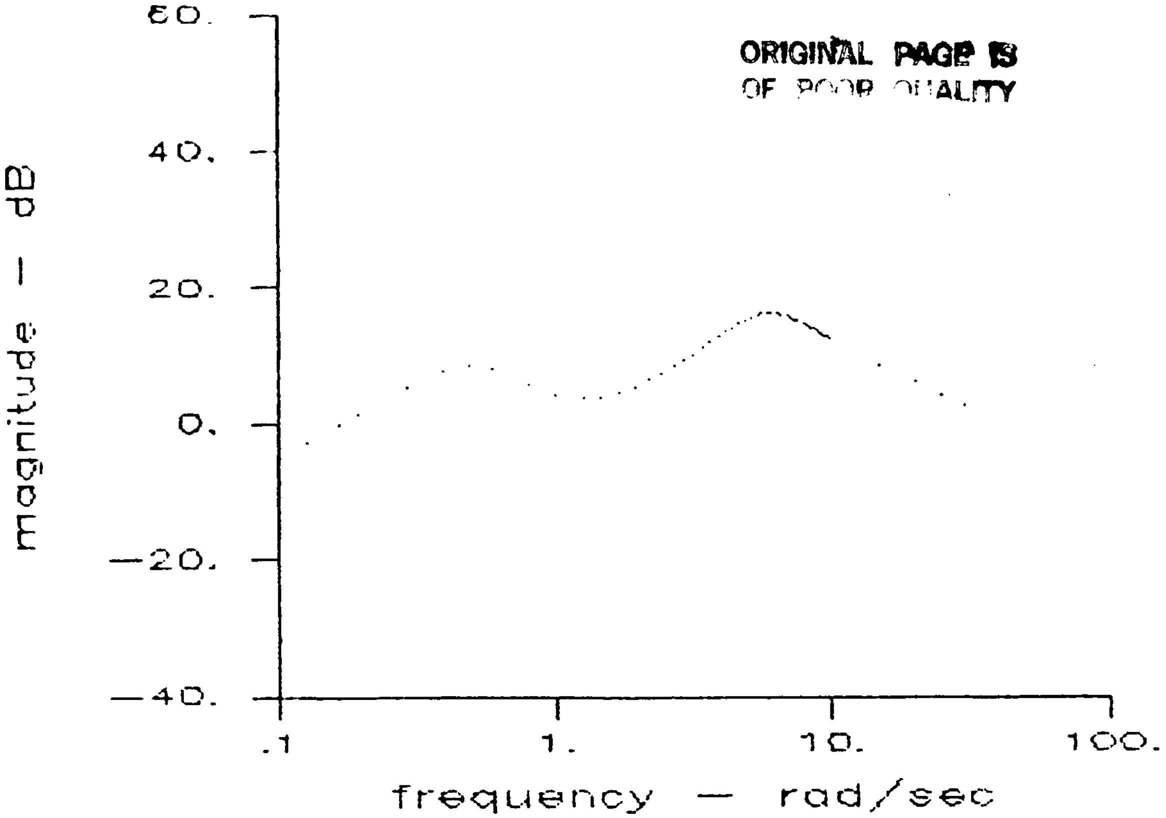
NLF Configuration G-3 : Theta Tracking



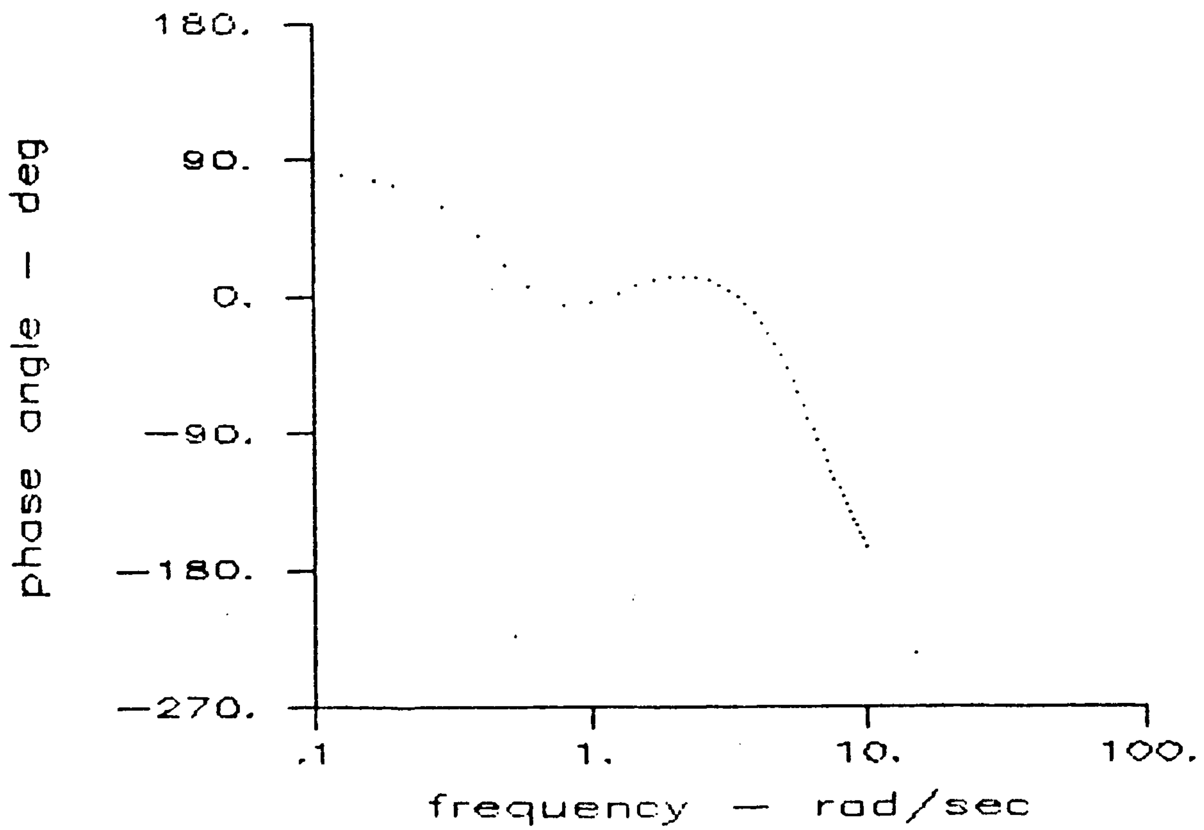
LEGEND:
equivalent single loop pilot function



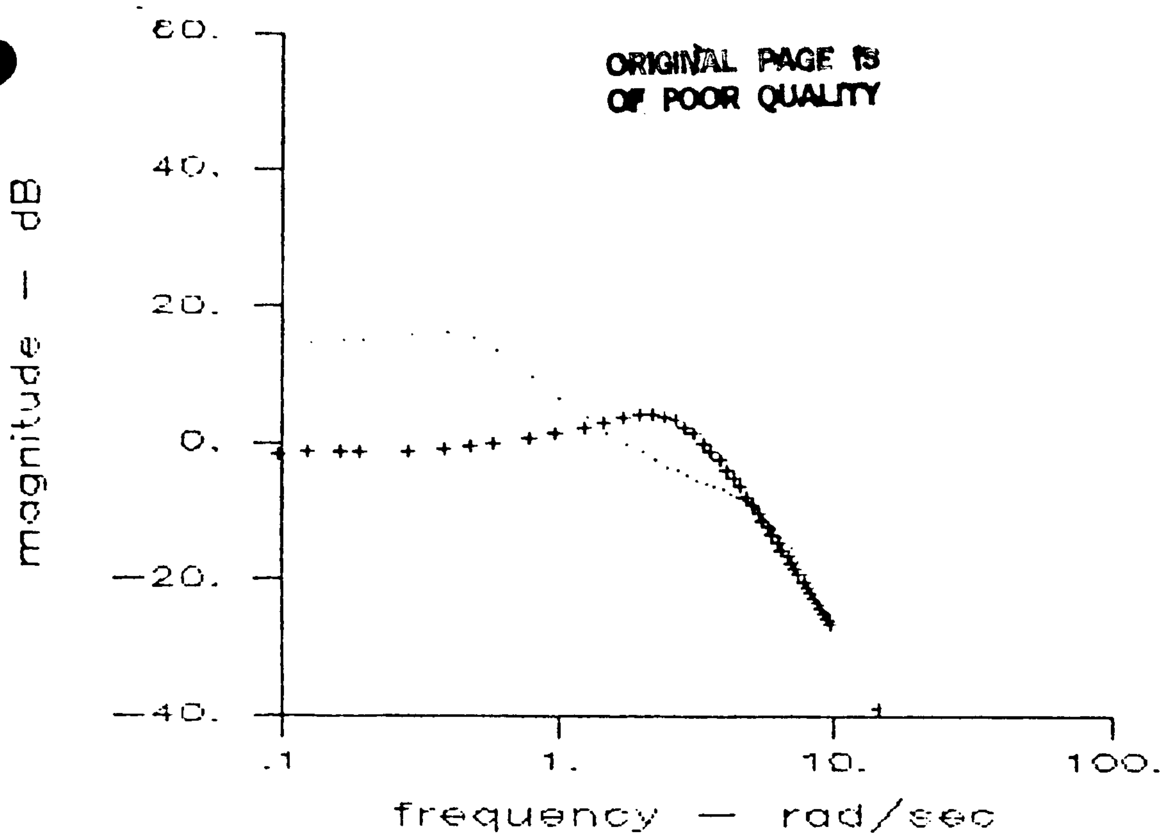
NLR Configuration G-4 : Theta Tracking



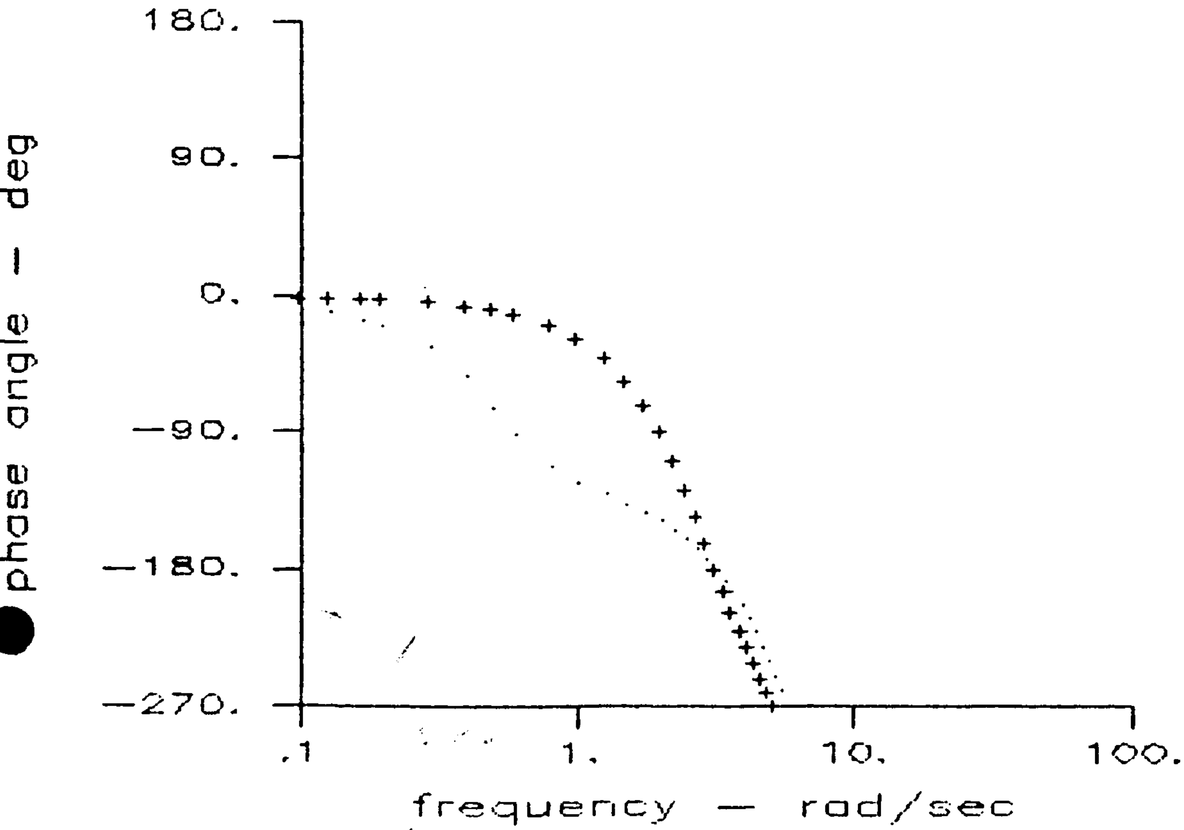
LEGEND:
equivalent single loop pilot function



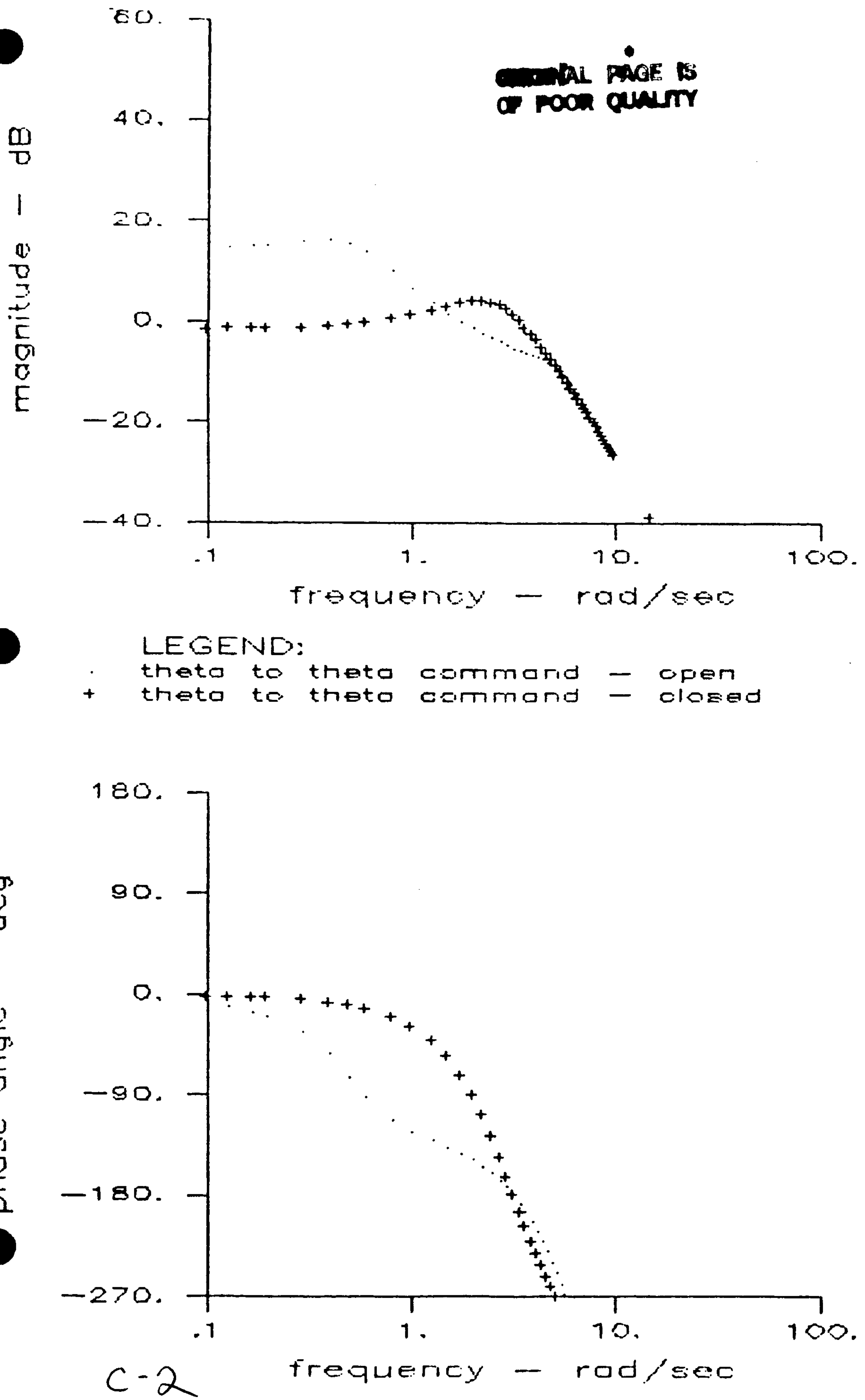
HUD Configuration E-1 : Theta Tracking



LEGEND:
· theta to theta command - open
+ theta to theta command - closed

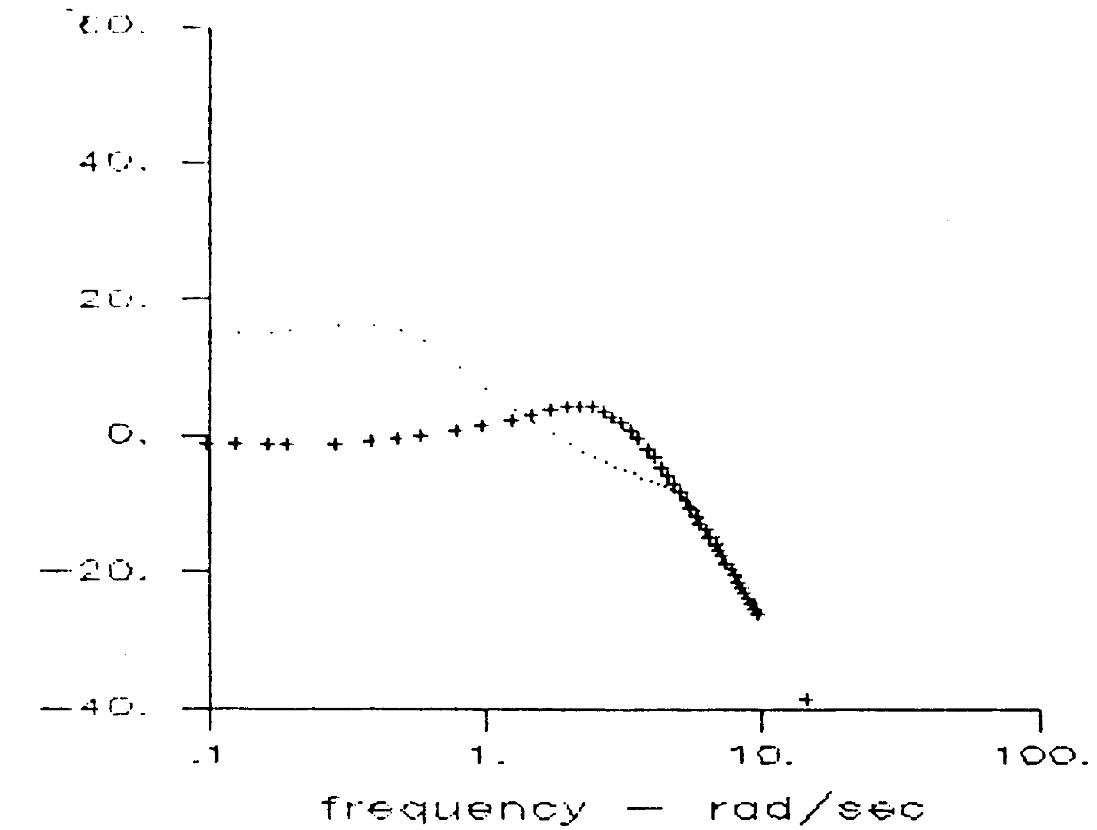


MLF Configuration C-2 : Theta Tracking

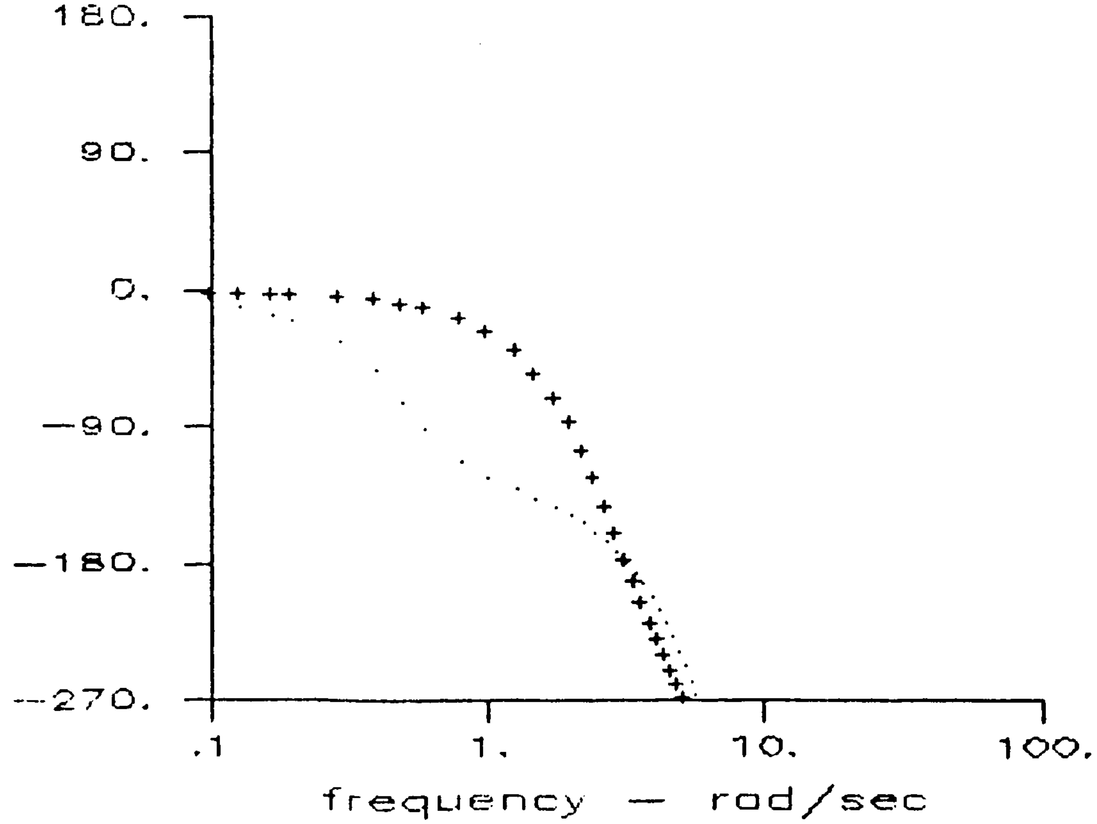


C-2

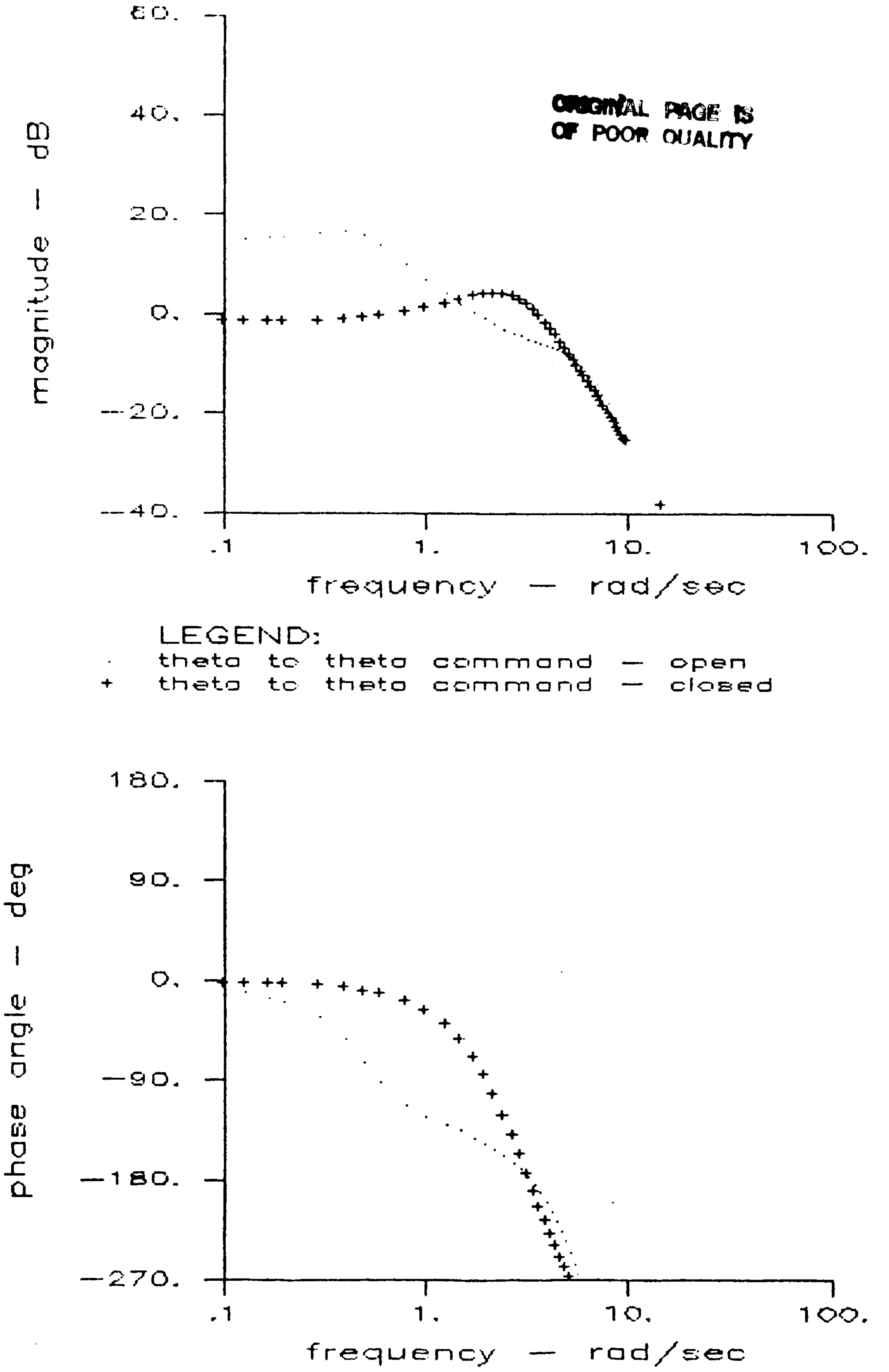
HLF Configuration F-3 : Theta Tracking



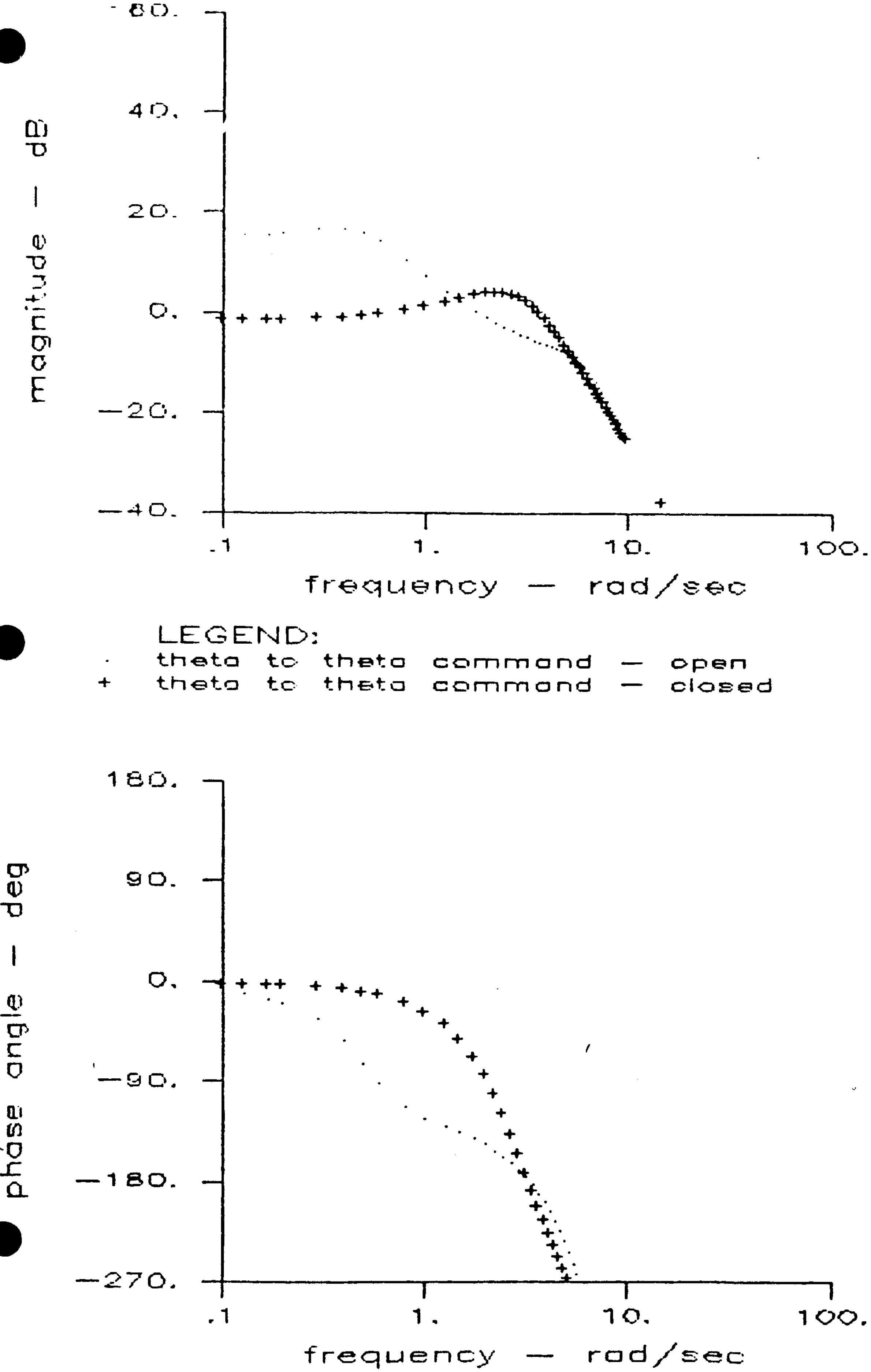
LEGEND:
· theta to theta command — open
\+ theta to theta command — closed



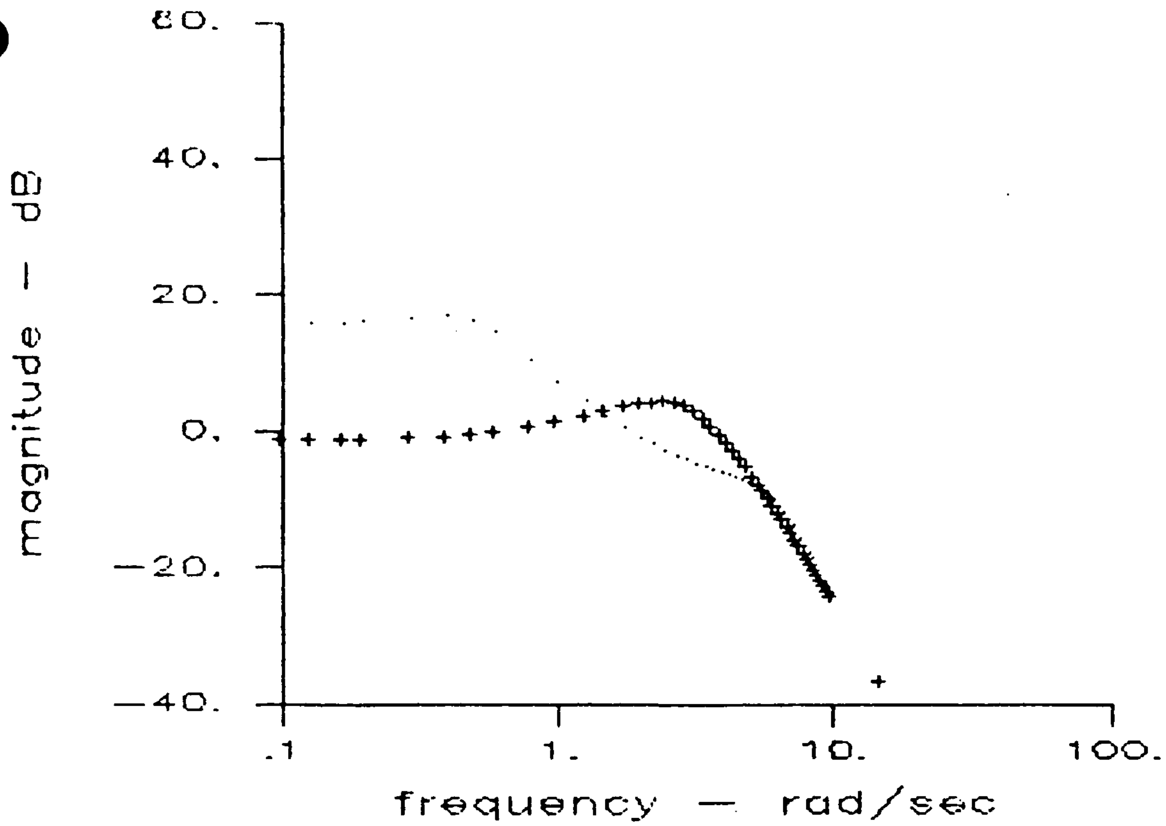
[illegible] Configuration E-4 : Theta Tracking



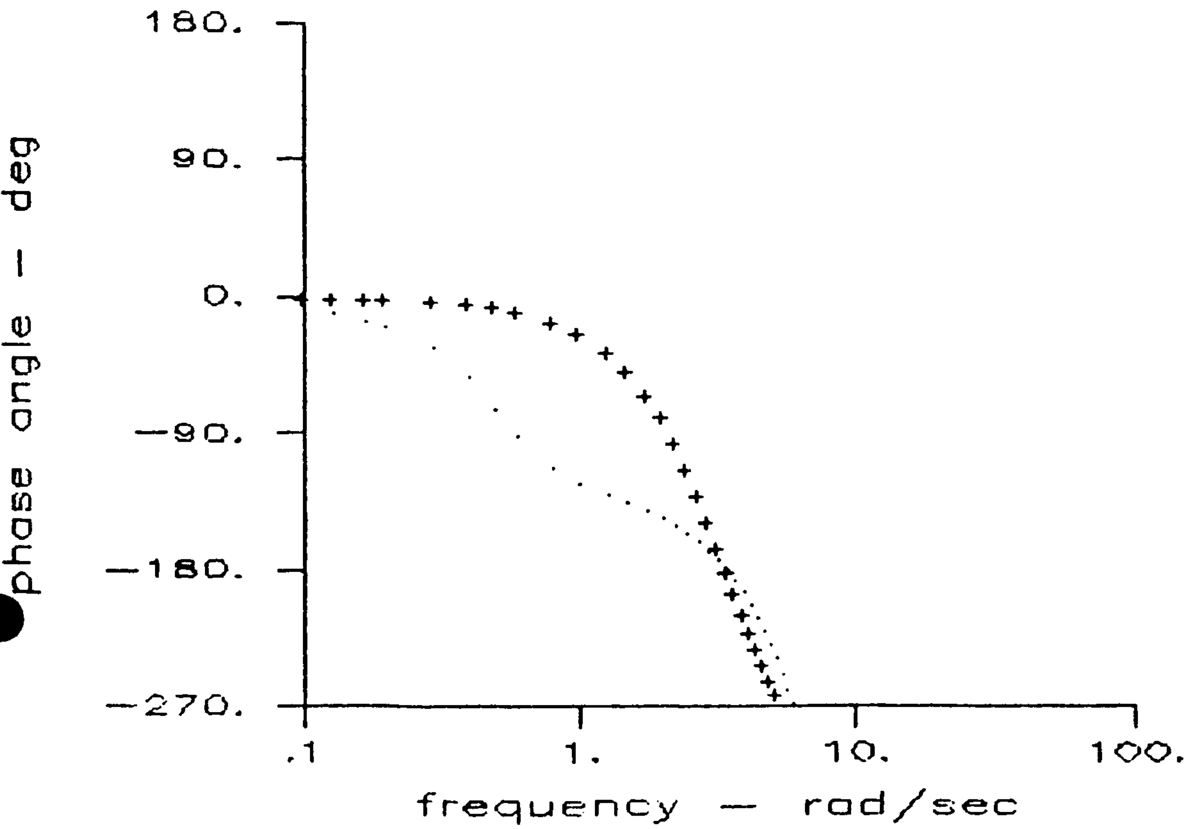
NLR Configuration E-5 : Theta Tracking



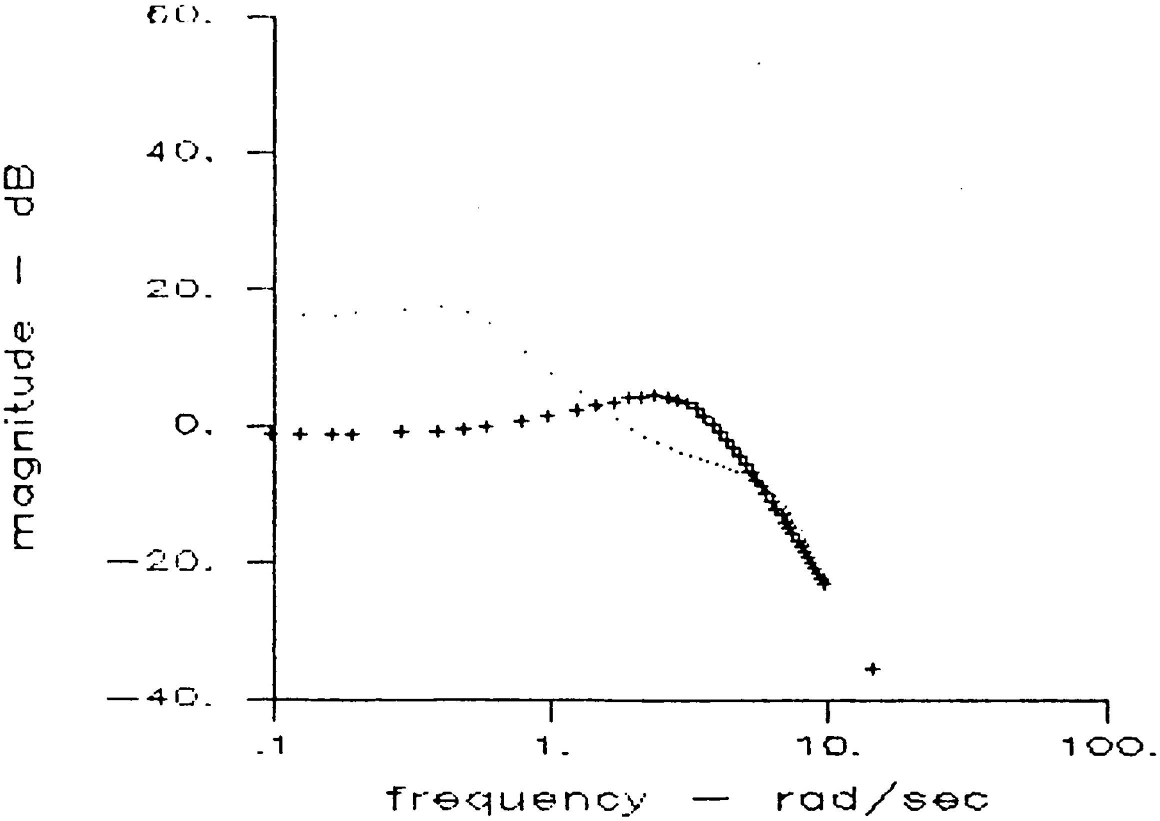
NLR Configuration 1-3 : Theta Tracking



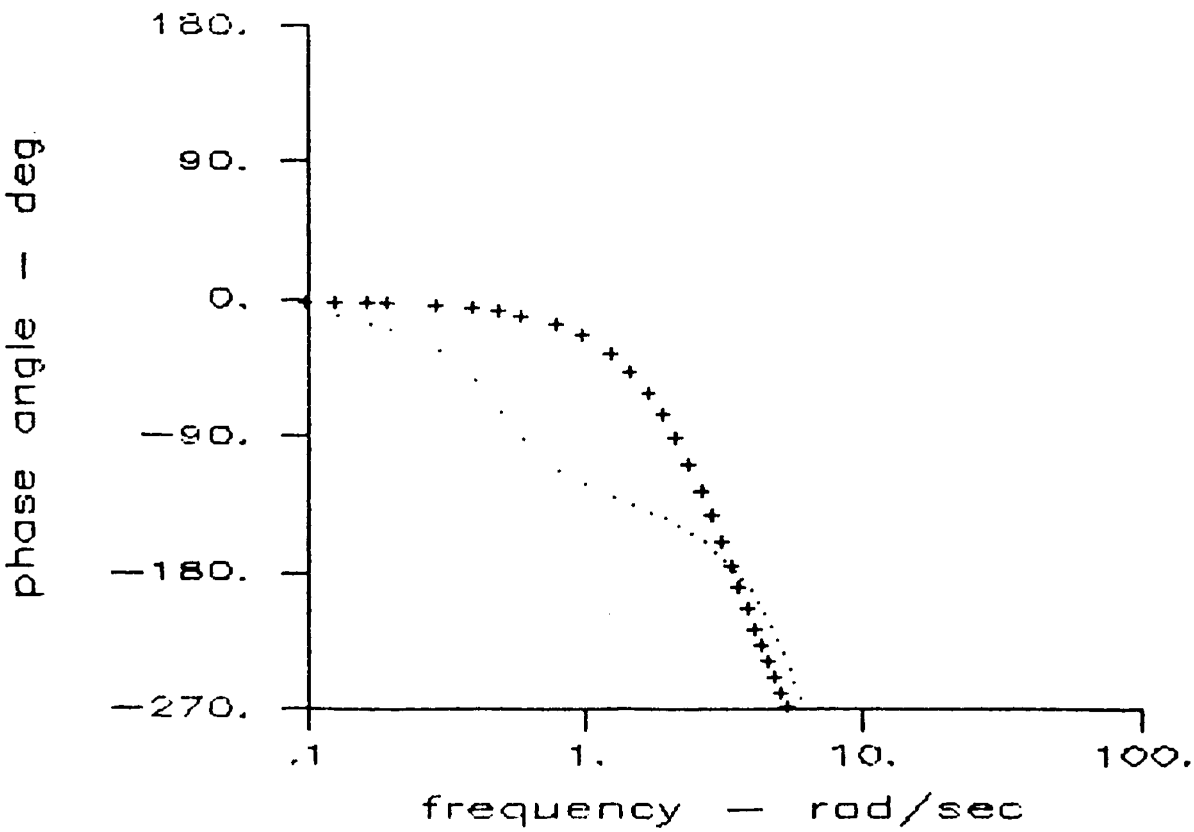
LEGEND:
· theta to theta command — open
+ theta to theta command — closed



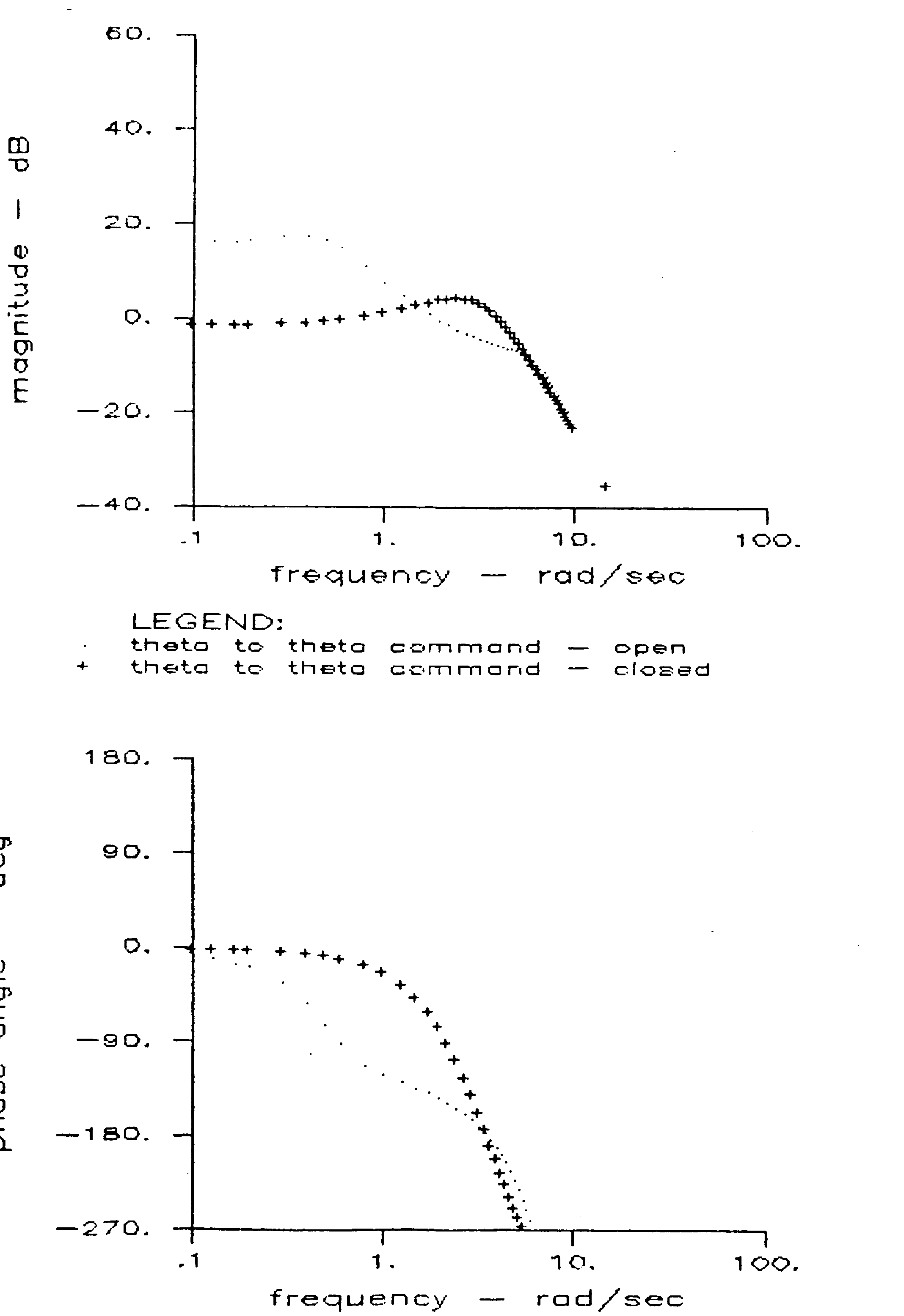
NLR Configuration F-2 : Theta Tracking



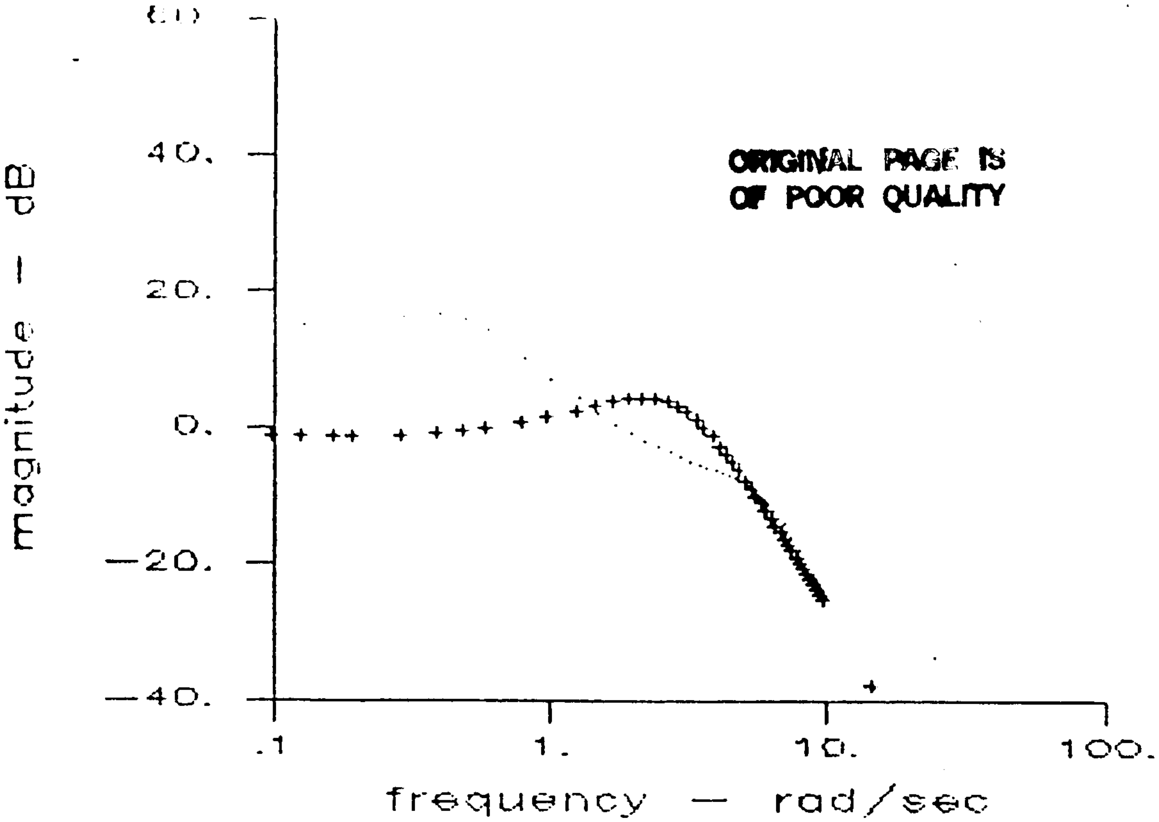
LEGEND:
· theta to theta command — open
\+ theta to theta command — closed



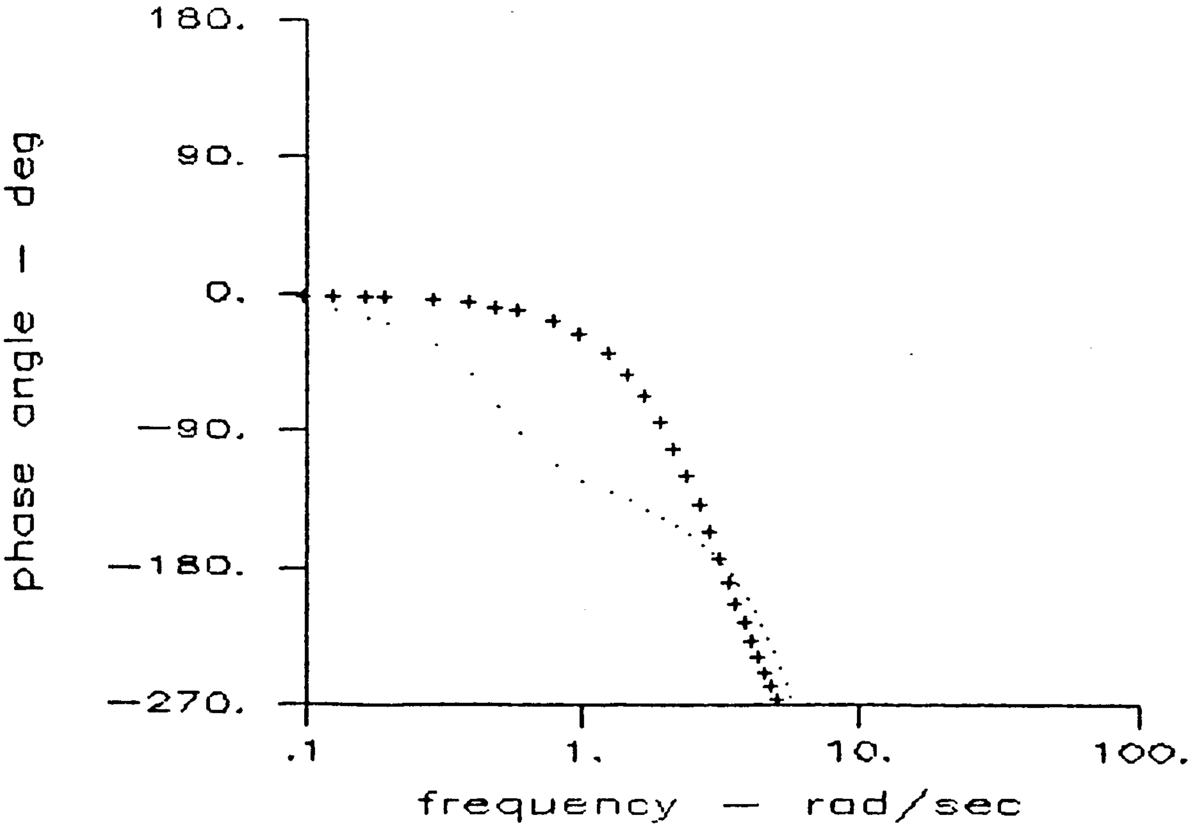
NLR Configuration F-1 : Theta Tracking



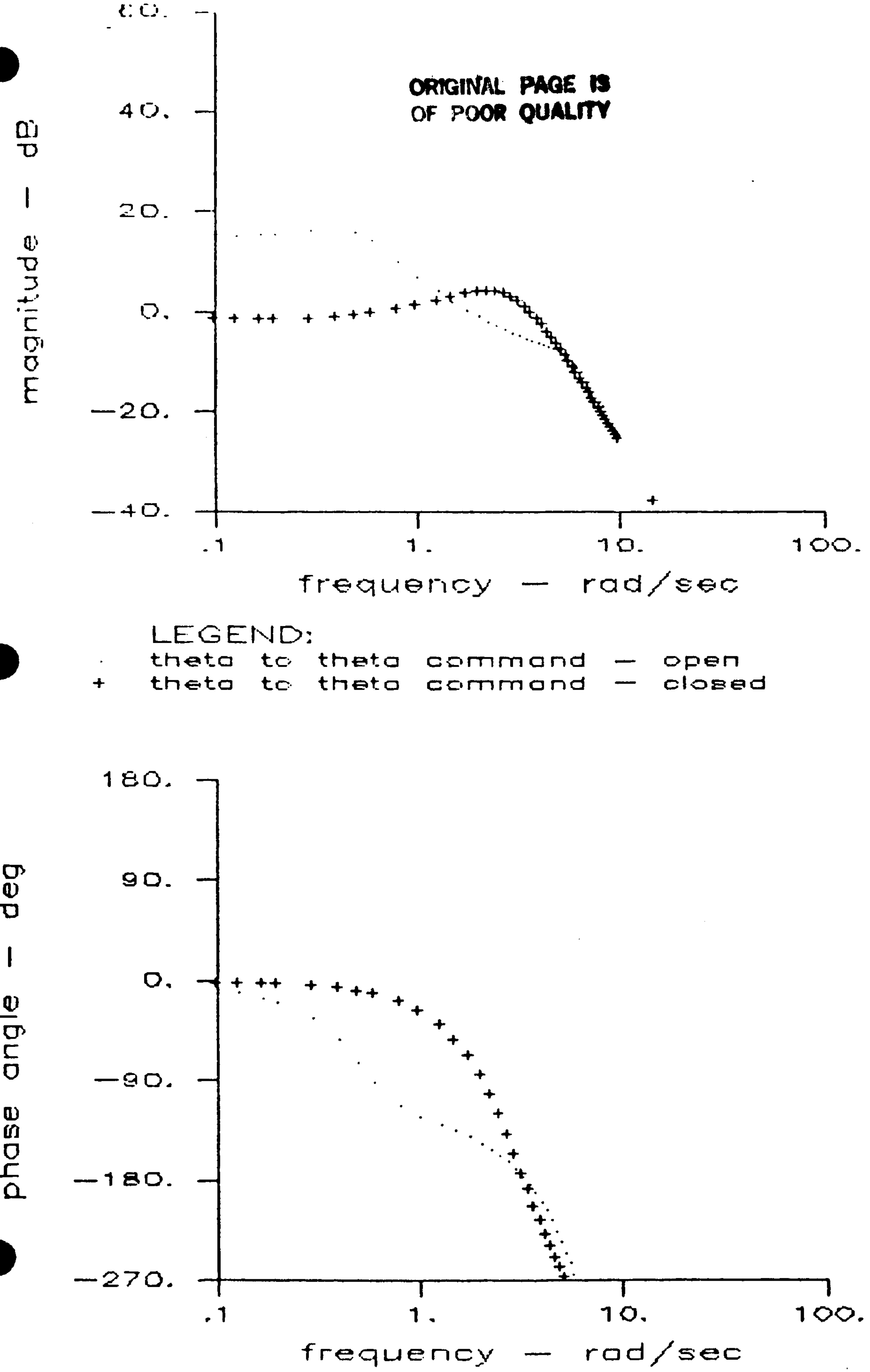
[illegible] Configuration G-1 : Theta Tracking



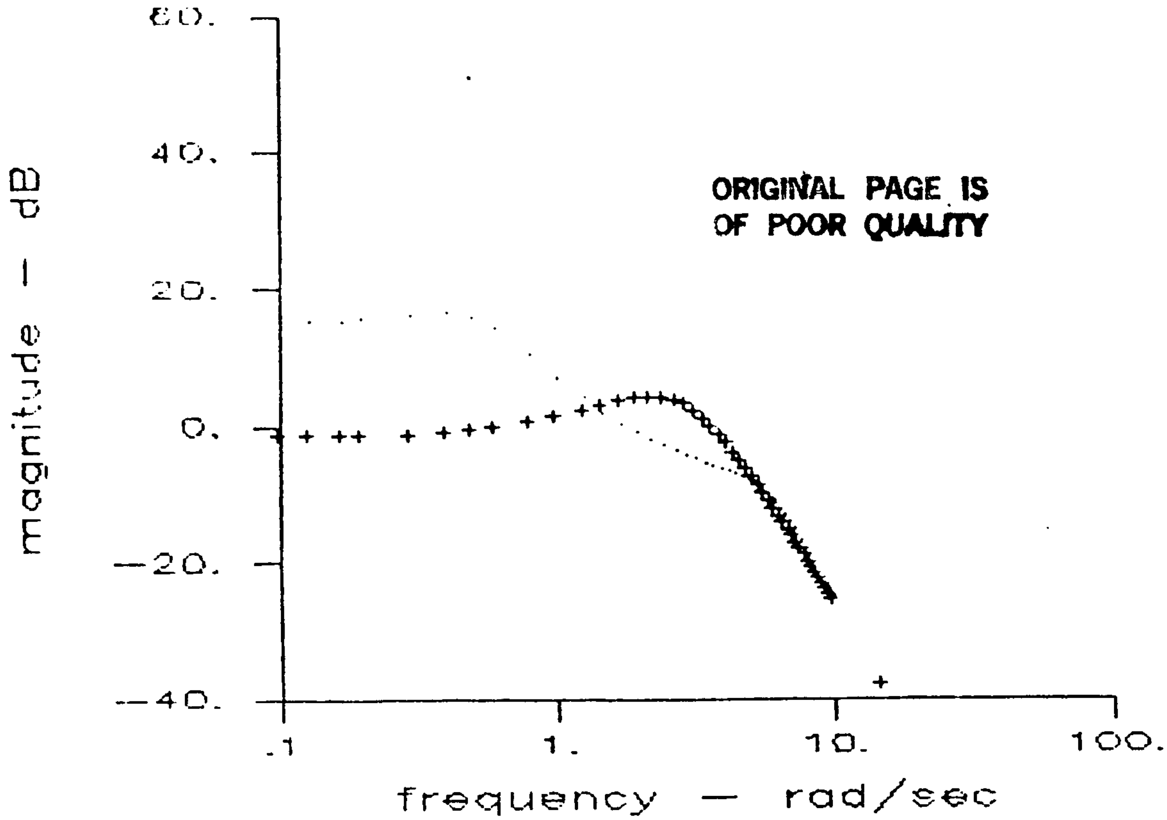
LEGEND:
· theta to theta command — open
+ theta to theta command — closed



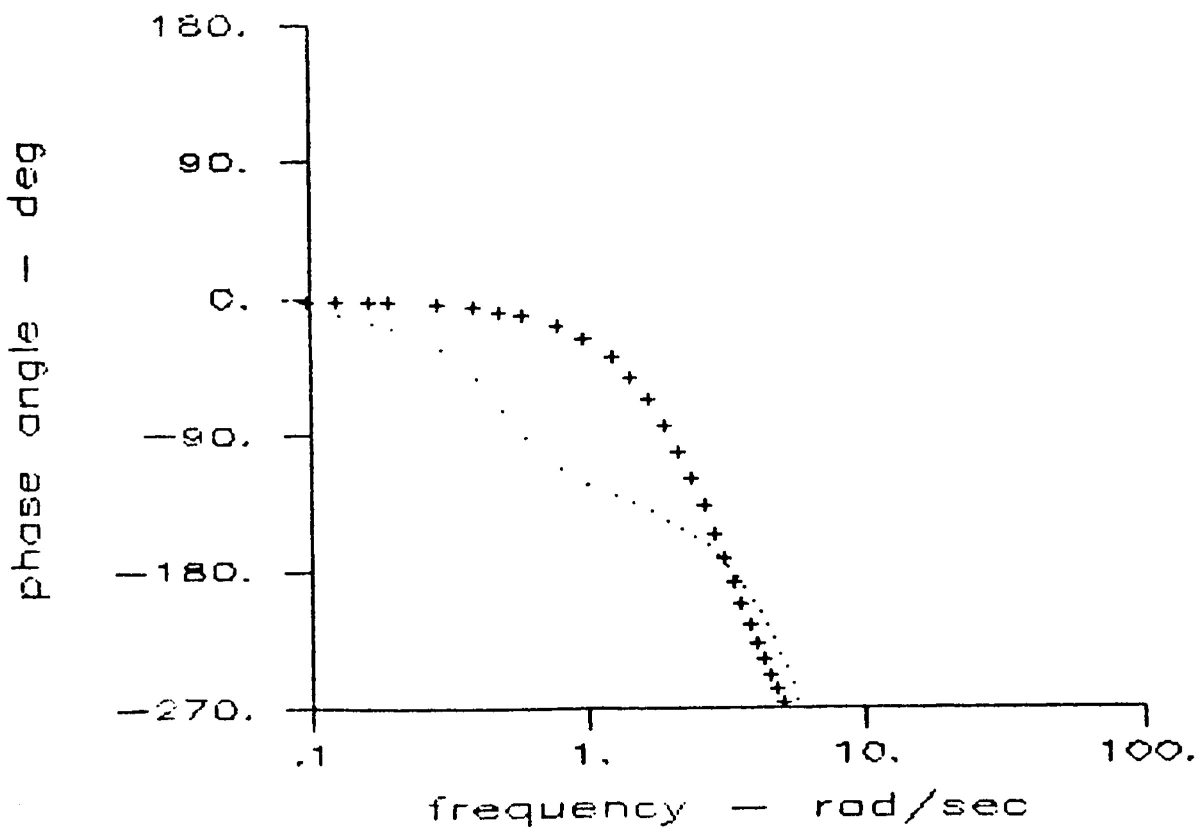
NLR Configuration G-2 : Theta Tracking



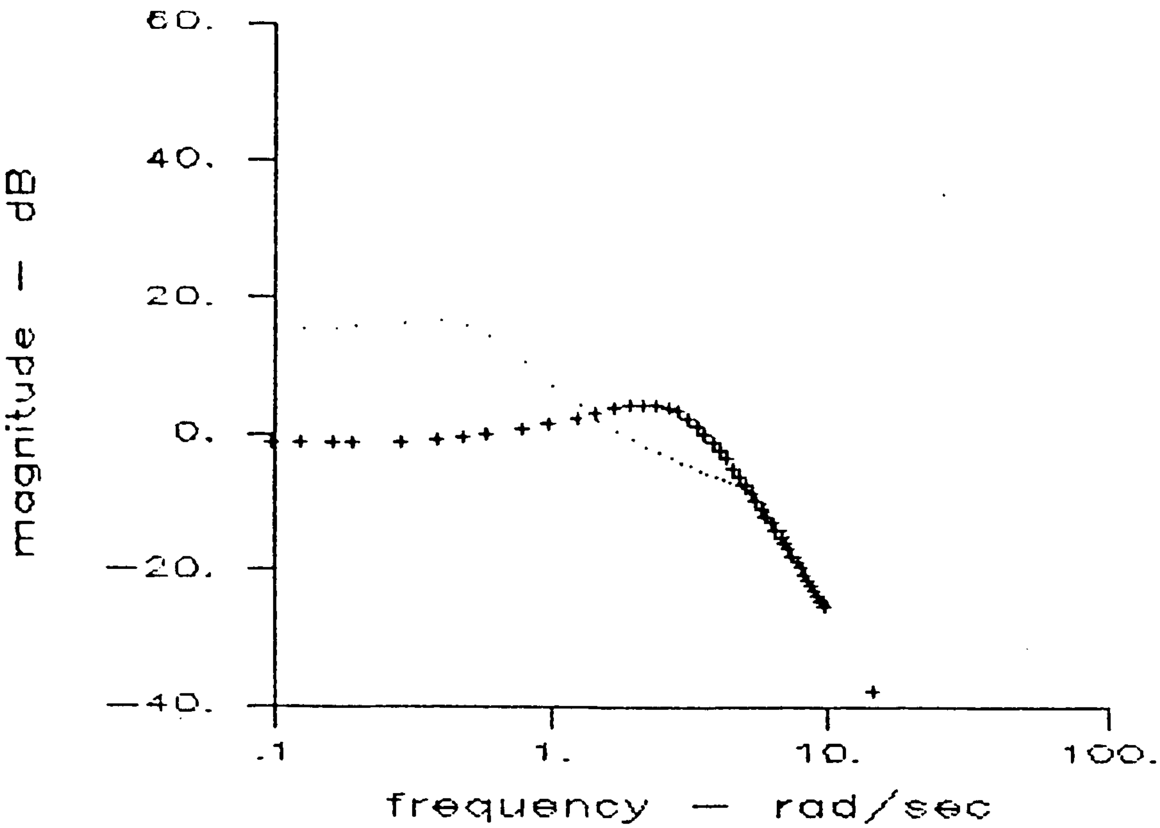
NLF Configuration G-3 : Theta Tracking



LEGEND:
· theta to theta command - open
+ theta to theta command - closed



NLR Configuration G-4 : Theta Tracking



LEGEND:
· theta to theta command - open
+ theta to theta command - closed