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Drago MATKO*, and Motoki HINADA**,

ABSTRACT: This paper presents an effective method for redesign of the M-V third stage attitude control algorithm. The fundamental aspect of the redesign is featured by introduction of an integral term into the controller in order to reduce steady state error caused by offset of the centre of gravity of the vehicle and thrust axis misalignment. The proposed method is based on the idea to utilize the existing controller as the inner loop (attitude angular velocity) controller of the cascade control. Adding the velocity-position integrator into the controller leads to the desired integral characteristics. The dynamic character of the entire closed syetem and its robustness in the gain and phase margins are investigated for five representative controllers, which are switched at the specified time marks, and corresponding nominal and deviated dynamic models.

1. INTRODUCTION

During the first ever flight of the M-V vehicle ([3-8]), a steady state error in the attitude control of the third stage was observed. This error is due to the offset of the centre of gravity of the vehicle and the thrust axis misalignment. In terms of control engineers, this offset and asymmetry represent a step and drifting disturbances at the input of the controlled system, which the existing controller of the Proportional Derivative (PD) type can not eliminate. In order to reduce this steady state error, an integral term can be introduced into the controller. For this purpose, the existing controller is redesigned by an idea of the cascade control which is given in detail in the next section. The advantage of this idea is to use the well-designed existing controller as a part of the redesigned controller and thus to reduce the associated redesign effort.

The dynamic characteristics of the rocket change during the flight, thus the entire flight is divided into the seven phases, an independent controller designed for each phase. The notations of them are specified by the corresponding time marks after launching and they are: 218, 238, 258, 278, 298, 318 and 328. To cope with this varying characteristics of the vehicle dynamics, the controllers are switched every 20 sec. There are 5 independent controllers designed and the first four of them have to be tested for the dynamic models of two, while the fifth one for the models of three successive flight phases.

Besides the nominal model, two deviated models have to be examined for every phase. The first deviated model is one having the lowest bending frequency and the second one the model with the minimum gain and phase margins when using the existing controller.

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2. IDEA OF APPLICATION OF THE CASCADE CONTROL

The existing controller is redesigned by an idea of the cascade control ([1], [2], [10-12]). The essential point of this idea is the interpretation of the control law as the series of an outer (attitude) and an inner (attitude angular velocity) feedback. The existing controller has two inputs, the attitude and the attitude angular velocity. With the supposition that the attitude output of the rocket sensors is an integral of the attitude angular velocity output, the scheme shown in Fig. 1 has the same dynamics as the originally designed closed loop system. Note, the integral term in the diagram is a part of the controller rather than the part of the controlled system (vehicle). In the first step of the redesign, the existing controller is used as the inner loop (attitude angular velocity) controller with an addition of the proportional integral (PI) term, which is shown in the figure.

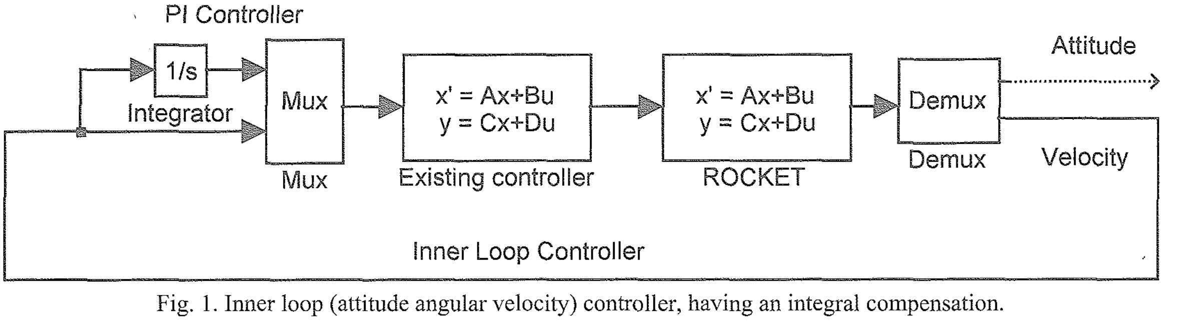

Fig. 1. Inner loop (attitude angular velocity) controller, having an integral compensation.

In the second step of the redesign, a proportional (P.gain) controller is added as an outer loop (attitude) controller. Its gain has to be determined as a compromise between the robustness and performance, which is detailed in Section 3. The resulting control scheme is shown in Fig. 2.

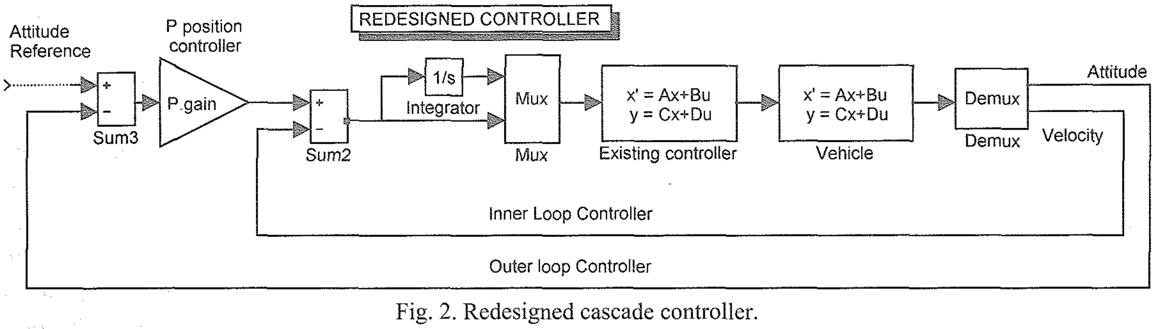

Fig. 2. Redesigned cascade controller.

The resulting control scheme can be interpreted as the new redesigned controller. However, there arises a problem in limitation of the order of the controller to be implemented in the flight model hardware. This order is limited to 6, which already is the order of the existing controller. As adding an integral term makes the order of the controller increase to 7, the next logical step in the redesign is the reduction of the order of the existing controller. This has been done by the MATLAB procedure MINREAL, which performs the minimal realization and the pole-zero cancellation. By varying the tolerance parameter of the procedure, the number of states being reduced can be varied. The tolerance parameter is determined by trial and error type effort so that the order of the existing controller is reduced by one. In this way, the redesigned controller has an order of six, which is the desired one, and this completes the redesign procedure [13].

3. THE ROLE OF THE PROPORTIONAL GAIN

The gain of the proportional part of the cascade control is the free parameter to be designed during the proposed redesign procedure. It influences the dynamic behavior as well as the stability margins and should be determined as a trade-off between both. The figure 3 depicts the time response of the attitude to the input step disturbance for the nominal 218 seconds after launching case. The response of the existing controller is depicted with solid and those of the redesigned controllers by dashed (P.gain =0.15), dotted (0.3) and dash-dotted (0.05) lines.

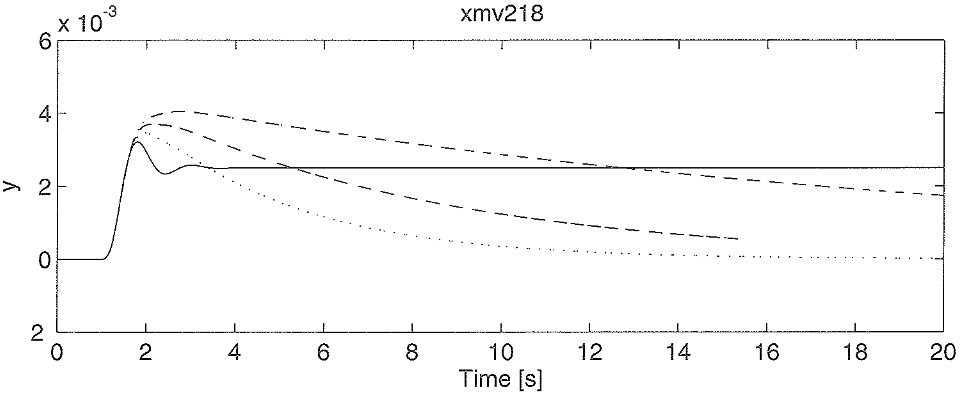

Fig. 3. Time domain response of the attitude to the input step disturbance.

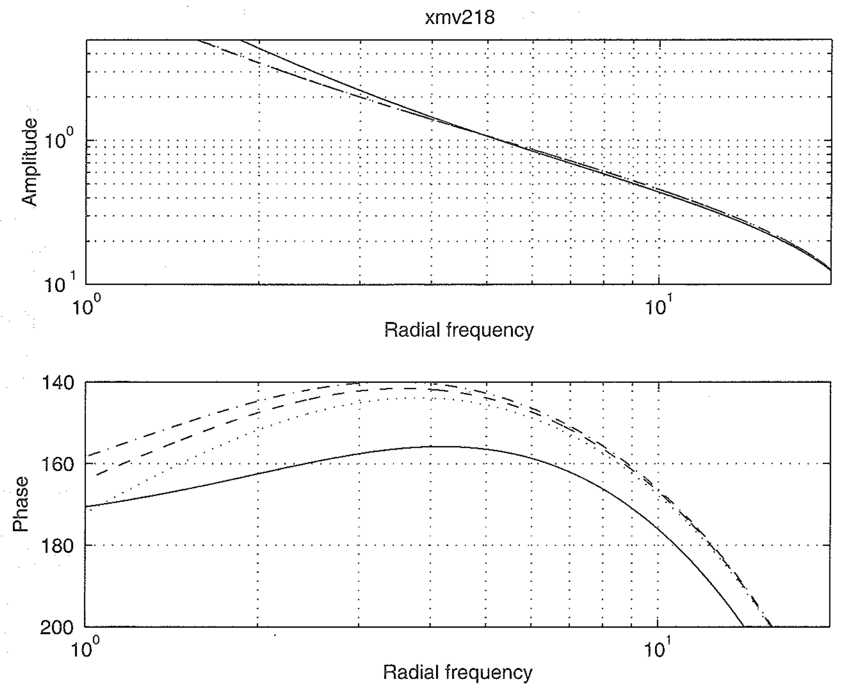

Fig. 4. Bode diagram of the entire closed system.

It can be observed that with increasing gain of the proportional part (P.gain), the dynamic response of the attitude greatly improves. However, it makes the stability margins decrease as shown in Fig. 4, where a detail of the Bode diagram is depicted for the existing controller by the solid line and for the redesigned controllers by the dashed (P.gain = 0.15), the dotted (P. gain = 0.3) and the dash-dotted (P.

gain = 0.05) lines. The stability margins of the redesigned controllers are better than those of the existing controller. They slightly decrease with increasing proportional gain. This is also confirmed in Table I, depicting the margins by different proportional gains for the nominal 218 seconds after launching case. Together with the margins, the corresponding cut-off radial frequencies are given. Note, the low frequency closed loop gain is greatly affected by P.gain as represented in Fig.3.

In the sequel of the paper the proportional gain of 0.15, which is a compromise between performance and robustness, will be used for the first four controllers and the reduced proportional gain of 0.05 for the fifth one.

Table I. Gain and phase margins for different proportional gains

Gain margins (dB):					
P. gain	Existing	Redesign.	Difference	ω exist.	ω red.
0.05	8.0178	9.5059	1.4881	10.7305	12.4456
0.15	8.0178	9.4196	1.4018	10.73051	12.3648
0.30	8.0178	9.2865	1.2686	10.7305	12.2414
Phase margins (Deg.):					
P. gain	Existing	Redesign.	Difference	ω exist.	ω red.
0.05	23.0804	36.2061	3.1258	5.2640	5.3095
0.15	23.0804	35.1222	12.0418	5.2640	5.3111
0.30	23.0804	33.4910	10.4106	5.2640	5.3164

4. COMPARATIVE CHARACTERISTICS OF THE EXISTING AND THE REDESIGNED CONTROLLERS

The existing and the redesigned controllers are compared here with respect to the pole - zero locations, the frequency responses, the robustness as tested in the gain and phase margins, and the time domain responses for the nominal and the deviated models. In Fig. 5, the pole - zero locations of the first controller (designated as e9_8a_3) are shown.

It can be observed that the redesigned procedure moves the low frequency real pole toward the origin of the complex plane, making the controller an integral type. Also the two real zeros are moved apart. All the other poles and zeros remain at the same positions. Note that the low frequency damping may become smaller through the procedure, implying that tuning the outer loop control gain (P.gain) should be proceeded carefully. It should be noted that in Fig. 4 only the pole-zero locations for the first (attitude) controller input are shown. The locations for the second (attitude angular velocity) controller input are practically the same.

The effectiveness of the integral-type redesigned controller can be observed in Fig. 6, showing the Bode diagrams for the combination of the first controller and the nominal 218 seconds after launch body dynamics. The plots of the existing (e9_8a_3) controller and its redesigned version are depicted by the dashed and solid lines respectively. It can be observed that the redesign procedure increases the low frequency gain (amplitude response) significantly while the gain in the mid-frequency range is slightly reduced. In high frequency range, both responses remains similar. The phase responses differ significantly in the low frequency range, where the redesigned controller exhibits the phase below 180 degrees due to its integral characteristics. In the mid-frequency range, the phase response by the redesigned controller is above the one by the existing controller, improving the phase margin significantly. Similar phenomena can be observed with other models (the nominal 238 seconds after launch case and the four corresponding deviated models).

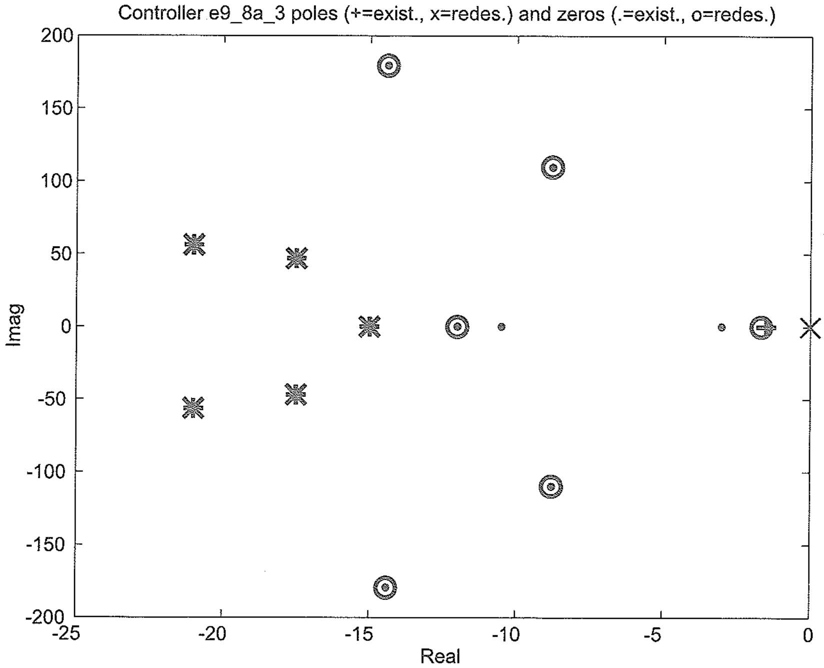

Fig. 5. Zero-pole map of the existing (e9_8a_3) controller and its redesigned version.

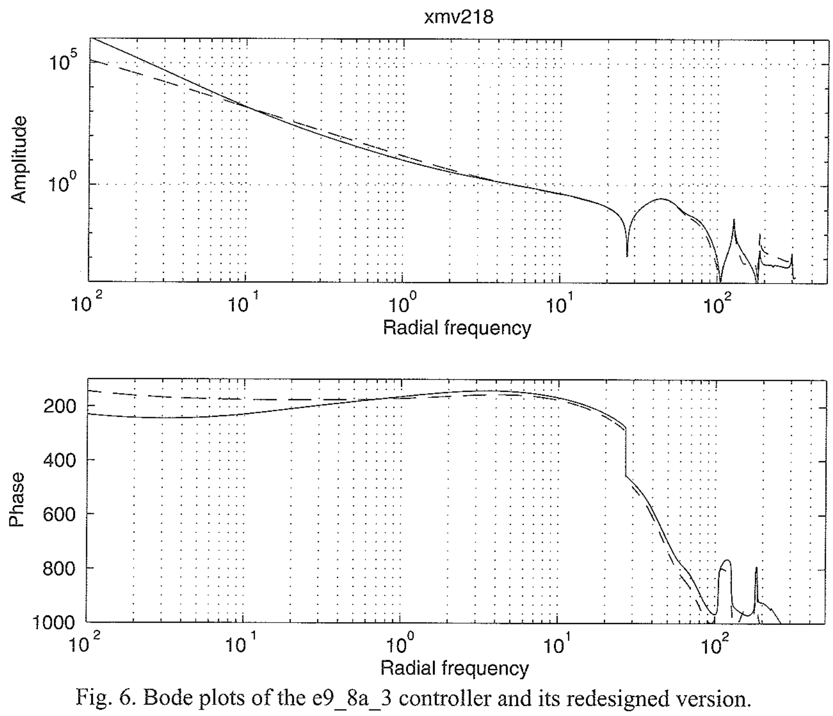

Fig. 6. Bode plots of the e9_8a_3 controller and its redesigned version.

The gain and phase margins for all six cases are given in Table II, where the corresponding cut-off radial frequencies are also given. A slight improvement of the gain margins can be observed for all cases except for the deviated "c1313_1" model, where the gain margin is decreased by the redesign procedure by 0.54 dB. On the contrary, significant improvement of the phase margins is observed for all six cases.

The time domain responses of the first controller against a step disturbance at the input are depicted for all six cases in Fig. 7. The responses with the redesigned controller (solid line) exhibit a slightly increased overshoot compared with those of the existing controller (dashed line). This is due to lower gain in the mid- frequency range

Table II. Gain and phase margins of the first controller (e9_8a_3)

Gain margins (dB):

Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv218	8.0178	9.4196	1.4018	10.7305	12.3648
xmv238	7.0358	8.4538	1.4180	10.7334	12.3672
c1313_1	5.6815	5.1425	-0.5389	9.4093	104.5784
c1313_2	4.6371	5.6611	1.0240	9.4136	10.7302
c3125_1	3.6407	5.0115	1.3709	7.4958	8.7746
c3135_2	2.6358	4.0126	1.3768	7.4990	8.7770

Phase margins (Deg.):

Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv218	23.0804	35.1222	12.0418	5.2640	5.3111
xmv238	21.9830	33.1907	11.2078	5.7583	5.8608
c1313_1	20.5732	32.3304	11.7572	5.3900	5.4562
c1313_2	18.5903	29.2658	10.6755	5.9881	6.1242
c3125_1	12.4364	24.1504	11.7140	5.3661	5.4270
c3135_2	9.9377	20.6281	10.6904	5.8863	6.0056

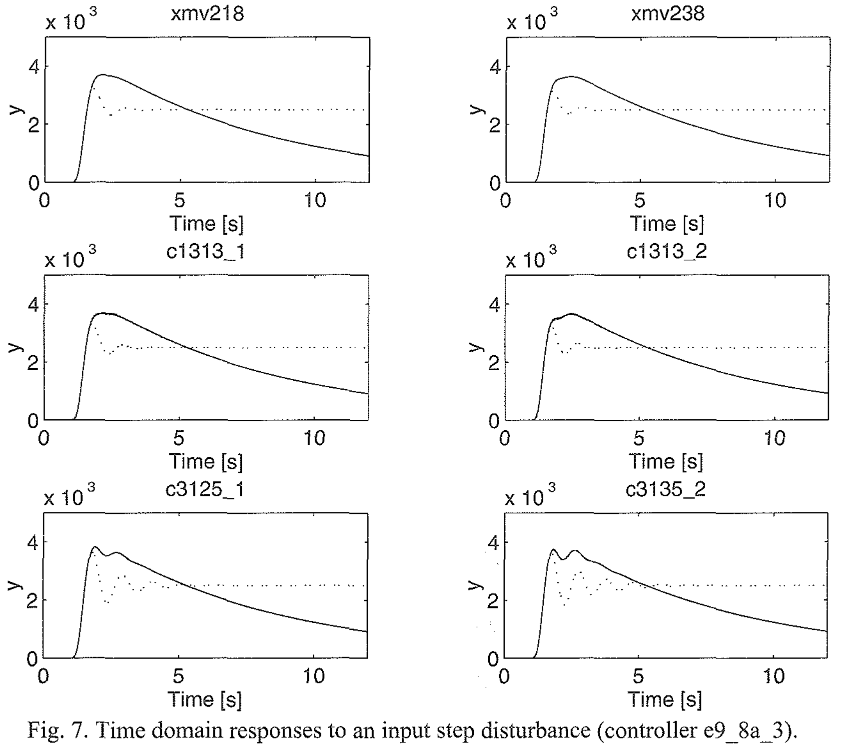

Fig. 7. Time domain responses to an input step disturbance (controller e9_8a_3).

However a high reduction of the steady state error can be observed with the redesigned controller. This is due to the increased gain in the low - frequency range. It can be concluded that the reduction of the steady state error is achieved at the cost of a slightly increased overshoot.

In the same way, all five controllers are tested. The tables III to VI depict the gain and phase margins for all treated cases. A slight increase (with a few exceptions) of the gain margin and a significant increase of the phase margin can be observed.

Table III. Gain and phase margins of the second controller (e9_7b_3).

Gain margins (dB):					
Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv238	9.7407	11.3642	1.6235	11.3684	13.2816
xmv258	7.0425	8.5655	1.5231	1.3734	13.2858
c1313_2	4.9955	3.2278	-1.7678	107.7648	107.8391
c1313_3	4.0285	4.4928	0.4643	111.1202	111.3337
c3135_2	4.8756	6.4356	1.5600	7.7045	9.2221
c3135_3	2.3014	3.8162	1.5148	7.7101	9.2259
Phase margins (Deg.):					
Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv238	23.1866	39.0474	15.8609	4.8889	4.9202
xmv258	21.4684	34.3940	12.9256	6.0965	6.2959
c1313_2	21.1330	36.5885	15.4555	5.0250	5.0805
c1313_3	17.6536	29.6558	12.0022	6.3763	6.6278
c3135_2	13.6212	29.1556	15.5344	4.9720	5.0175
c3135_3	8.5280	20.5498	12.0218	6.2417	6.4637

Table IV. Gain and phase margins of the third controller (e9_6c_3)

Gain margins (dB):					
Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv258	11.1140	12.7676	1.6535	11.7724	13.8434
xmv278	7.7934	9.3296	1.5363	11.7816	13.8511
c1313_3	3.4222	3.6608	0.2385	111.1431	111.3761
c1313_4	3.3917	3.7810	0.3894	115.3587	115.8355
c3135_3	6.0584	7.6754	1.6171	7.8184	9.4561
c3135_4	2.8816	4.4445	1.5630	7.8287	9.4629
Phase margins (Deg.):					
Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv258	22.5048	0.9755	18.4707	4.4900	4.4694
xmv278	21.9537	36.4546	14.5009	5.8696	6.0708
c1313_3	20.9151	39.0608	18.1457	4.5971	4.5955
c1313_4	18.6375	32.1947	13.5572	6.1196	6.3736
c3135_3	13.9802	32.2726	18.2924	4.5551	4.5459
c3135_4	9.7366	23.3059	13.5693	6.0037	6.2290

Table V. Gain and phase margins of the fourth controller (e8_6d_3)

Gain margins (dB):

Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv278	10.7778	2.3049	1.5272	11.6009	13.6485
xmv298	7.0398	8.4857	1.4460	11.6206	13.6648
c1313_4	8.0604	7.5836	-0.4768	9.9488	115.2359
c1313_5	4.3573	5.3576	1.0003	9.9680	11.5895
c3135_4	5.9508	7.5188	1.5679	7.7705	9.4110
c3135_5	2.3155	3.8367	1.5212	7.7930	9.4259

Phase margins (Deg.):

Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv278	22.8122	41.8625	19.0503	4.4756	4.4566
xmv298	21.5877	35.6901	14.1024	6.1281	6.3765
c1313_4	21.2113	39.9120	18.7006	4.5822	4.5831
c1313_5	17.7591	30.7165	12.9574	6.4190	6.7304
c3135_4	14.3055	33.1559	18.8505	4.5412	4.5344
c3135_5	8.5622	21.5441	12.9818	6.2798	6.5548

Table VI. Gain and phase margins of the fifth controller (e8_5e_3)

Gain margins (dB):

Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv298	8.3059	8.8157	0.5098	11.1996	13.0172
xmv318	12.5033	13.6795	1.1762	11.2400	13.0456
xmv328	10.4049	10.8537	0.4489	26.9968	28.2607
c1313_5	3.2020	6.5944	3.3924	194.1377	11.4169
c1312_6	4.6224	12.5152	7.8928	126.2263	256.4704
c1115_7	13.5782	13.3298	-0.2484	23.4997	24.3735
c3135_5	4.8615	5.8220	0.9605	7.8625	9.5331
c1115_6	8.3336	9.6213	1.2877	7.9144	9.5662
c3144_7	3.6648	3.2052	-0.4596	25.2186	26.0928

Phase margins (Deg.):

Model	Existing	Redesign.	Difference	ω exist.	ω red.
xmv298	24.8861	46.6525	21.7664	4.7266	4.8643
xmv318	24.8111	51.7815	26.9704	3.7060	3.5776
xmv328	28.7099	27.4720	-1.2380	0.2006	0.1036
c1313_5	22.9780	43.8921	20.9141	4.8642	5.0483
c1312_6	42.6274	68.6818	26.0544	3.7896	3.6770
c1115_7	28.2517	27.2905	-0.9612	0.2015	0.1041

However, as shown in Figs. 8 and 9, depicting the amplitude parts ot the Bode plots for the fourth controller applied to the nominal 298 seconds after launch case and for the fifth to the nominal 328 seconds respectively, the region with the increased gain is moved towards very low frequencies.

The region having the decreased gain around the rigid body frequencies becomes larger. This has a negative effect on the overshoots as depicted in Figs. 10 and 11. The figure 10 compares the responses for the same case with two different (e8_6d_3 and e8_5e_3) controllers. The dynamic response by the fifth (e8_5e_3) controller is much worse than that by the fourth (e8_6d_3) controller. This is due to the limited level of robustness over a wide variety of the deviated models. The increased overshoot in the left part of Fig. 10 can be still accepted while the response by the redesigned version of the fifth (e8_5e_3) controller, depicted in the right side of the Figs. 10 and 11, cannot be considered acceptable. Thus, the proposal is to use the original controller for the last two phases of the third stage flight. This is not critical since the thrust level in these phases is low and consequently is small in disturbance magnitude.

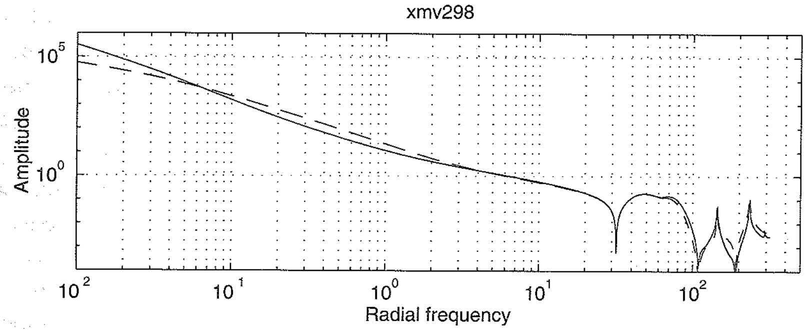

Fig. 8. Bode plots of the e8_6d_3 controller and its redesigned version.

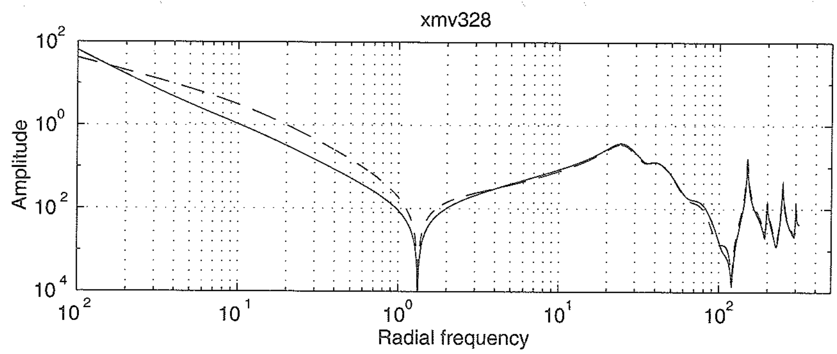

Fig. 9. Bode plots of the e8_5e_3 controller and its redesigned version.

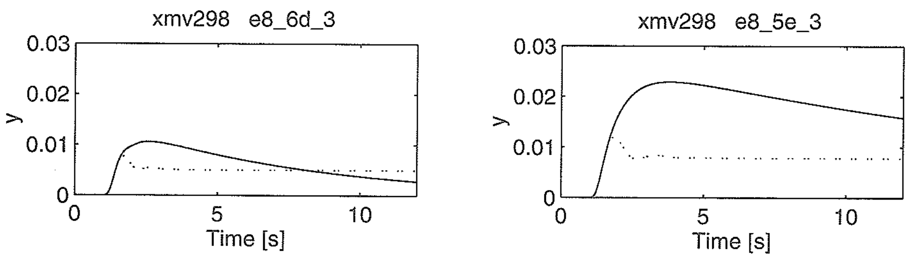

Fig. 10. Time domain responses to an input step disturbance (nominal 298 case).

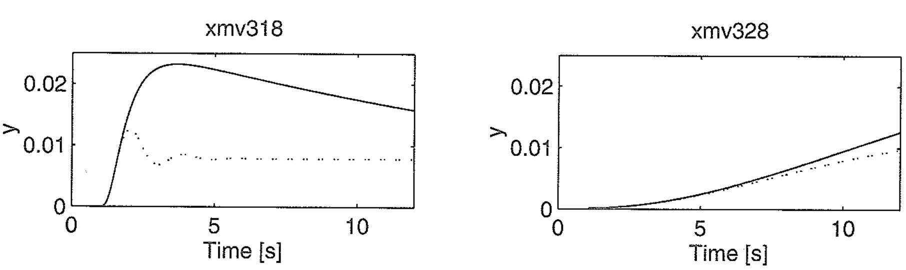

Fig. 11. Time domain responses to an input step disturbance (controller e8_5e_3).

5. CONCLUSIONS

A procedure has been proposed for redesign of the third stage control of the M-V launch vehicle. It is based on the idea of a cascade control, where the existing well designed controller of the Proportional-Derivative type is used as an inner loop (attitude angular velocity) controller. Through the procedure, the controller becomes the Proportional-Integral type, capable of reducing the low frequency input disturbances. A proportional controller is then added as the outer loop (attitude) controller. Its gain is a free parameter during the redesign procedure and is determined on the basis of a compromise between performance and robustness. The redesigned controller possesses an increased gain at the low frequencies at the cost of a slightly reduced at the rigid body mid-frequencies. In the time domain, a reduction of the steady state error caused by a step input disturbance can be obtained at the cost of a slight increase of overshoot. The investigations have shown an increase of gain margins (with a few exceptions having a minor decrease) over the examined models (nominal and two deviated per flight phase) using the redesigned versions of the first four controllers. With these controllers, the phase margins have been significantly increased for all (nominal and deviated) models. The redesign procedure is effective for these four controllers while the fifth one suffers from the poor dynamic response. Since the disturbance magnitude is relatively low during the phase, the existing controller can be still used. It is believed that the proposed control strategy can improve the accuracy of the trajectories of the future M-V rocket missions although it should be highly remarked that the integral characteristics is susceptible to satilation phenomenon.

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