A Comparison of Conventional and Tracking Filter Systems for Launch Vehicle Stabilization

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This paper extends a prior study on applications of an adaptive tracking filter to bending mode stabilization of large flexible boosters. The relative merits of fixed and tracking filters are evaluated for a variety of bending mode stabilization applications. The results motivated the design and evaluation of a tracking filter system for the Saturn V launch vehicle number 501. The principal conclusion is that better stability margins can be obtained using a tracking filter system instead of a conventional control system in certain gain stabilization applications. This improvement is accomplished at the expense of a substantial increase in system complexity, so that stability must be a critical problem in order to justify the use of a tracking filter.

Introduction

ADAPTIVE tracking filters have been proposed for bending mode stabilization in large, flexible, launch vehicles such as the Saturn V. Various filter configurations have been used such as notch filters, offset notch filters, and lag networks.[1] This paper extends a prior study[2] which consisted of a detailed analysis of tracking filter characteristics and performance, as well as some preliminary evaluation of tracking filter applications to bending mode problems. In this paper the relative merits of fixed and tracking filters are evaluated to indicate those cases where the use of a tracking filter is justified. From the results, it is seen that a tracking notch filter might be applied to the Saturn V class of launch vehicles. An adaptive control system design for the first Saturn V vehicle, 501, is presented, and it is compared with the conventional system in a real-time trajectory simulation.

Applications of Tracking Filters to Bending Stabilization

Tracking Filter Requirements

The use of a device such as a tracking filter in a launch vehicle must be justified by showing that conventional fixed filters are not capable of meeting the system specifications. There are wide classes of systems that are easily compensated by fixed filters, even though lightly damped modes, lack of knowledge of the exact system parameter values, and wide variations in parameters may be inherent to these systems.

Three basic requirements must be met to insure successful application of a tracking filter to a specific bending stabilization problem.

1) Assuming that all vehicle parameters are fixed and known, it must be possible to design a fixed bending mode filter which significantly increases the stability of the mode without appreciably decreasing any other stability margin or performance measure of the system. In practice, however, this fixed filter would not be used because parameter uncertainties or variations affect the bending frequency and, hence, the frequency to which the fixed filter must be tuned in order to provide the improved stability.

2) In the transfer function relating sensor output to the disturbance force (wind), the closed-loop bending mode poles must have relatively high residue and low damping so that, when excited, the bending oscillation picked up by the sensor has sufficient amplitude and duration to permit frequency identification.

3) The predominant frequency in the vicinity of the bending mode must be the bending mode frequency itself; and the variation of this (closed-loop) frequency with bending mode filter offsets must be such as to cause the filter to track in the direction which increases the system stability. That is, any lightly damped oscillation resulting from a decreased stability margin (due to an offset error between the filter frequency and bending mode frequency) causes the filter to track so as to improve that stability margin.

Bending Mode Stabilization

When stabilizing flexible vehicles, there are two approaches which can be taken. The structural modes can be gain stabilized by having the control system provide enough attenuation at bending mode frequencies so that the open loop gain is less than unity. The bending modes can also be phase stabilized by having the control system provide the proper phase angle so that there is negative feedback at the bending mode frequency, with the loop gain being greater than unity. Gain stabilization does not appreciably change the closed-loop damping of the mode from its open-loop damping since it effectively eliminates control at the bending mode frequency. Phase stabilization actively controls the bending mode, thereby increasing the structural damping.

A phase stabilization approach is usually preferred for the predominant (lowest frequency) bending mode since an increase in the damping of this mode can effect a significant reduction in vehicle bending moments. Phase stabilization is sometimes used for the second mode, if the open-loop phase angle at the first- and second-mode frequencies is approximately the same. Higher order modes are usually

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gain stabilized because of uncertainties connected with them and to minimize control system bandwidth. In discussing the phase stabilization problem, the vehicle model to be used is the Saturn IB-201 at a flight time of 80 sec after liftoff.[3] The block diagram of the over-all system is given in Fig. 1. The fixed filter provides phase lag to phase stabilize the first mode and attenuation to gain stabilize the high frequency bending modes. A gain-phase plot of this system with the tracking filters omitted is shown in Fig. 2a.

The following definitions are used for the various stability margins. Reference is made to the distances labeled A, B, C, and D in Fig. 2a. The aerodynamic gain margin (A) is the low frequency gain margin (the amount the gain must be reduced to obtain an instability). The rigid body phase margin (B) is the amount of phase shift at the unity gain frequency (frequency locus passing to the right of the 180° point) − 180°. The rigid body gain margin (C) is the amount the gain must be increased at the 180° phase shift frequency (below the first mode frequency) in order to produce unity gain. The first bending mode phase margin (D) is the phase margin to the left of the 180° point caused by the peaking of the phase-stabilized, first bending mode. The terms crossover (phase crossover) and crossover gain are used for the intersection of the gain-phase locus with the 180° phase coordinate and for the gain margin at that intersection, respectively. (No bending mode crossovers occur in Fig. 2a.)

Phase Stabilization

The tracking filter can be used to phase stabilize the first mode by designing the filter to provide phase lag near the first mode frequency. The use of a sharp lag reflects the requirement of maintaining the rigid body gain margin. The amount of phase shift required from the lag network is that amount necessary to shift the first mode peak to zero degrees phase. Since the lag network is lightly damped, it would appear necessary to track the first mode frequency to ensure that proper phase shift occurs. However, the following data shows that this is not a critical requirement.

A lag network which gives a maximum of 80° phase lag has the transfer function

$$G(s) = \frac{[s^2/(1.18\omega_n)^2] + [2(0.1)s/(1.18\omega_n)] + 1}{[s^2/\omega_n^2] + [2(0.1)s/\omega_n] + 1}$$

This network shifts the first mode peak toward zero degrees. Figure 2b shows the result of adding this lag network to the system of Fig. 2a with ω_n at the nominal bending mode frequency. Note that the addition of this network improves the first mode phase margin while it slightly degrades the rigid body gain margin.

Table 1 shows the rigid body gain margin and the damping ratio of the most lightly damped pole in the vicinity of the open-loop bending frequency, for both nominal and off-nominal cases, with the sharp lag network assumed to be at the bending mode or offset from it by a certain percentage. A tracking filter designed to provide maximum damping would yield the values in italics in the table. A fixed system, designed for maximum damping at the nominal bending frequency, would provide the damping ratios and gain margins indicated by the table values in parenthesis. Note that the best closed-loop damping occurs with the filter set 20% above the open-loop bending frequency. When the bending frequency is low, there is a direct trade-off between rigid body gain margin and first mode damping. Tracking the mode increases the damping ratio and first mode phase margin, but it decreases the rigid body gain margin.

The main conclusion to be drawn from Table 1 is that the closed-loop system is relatively insensitive to the indicated changes in bending mode or tracking filter frequency. This conclusion is justified by the conventional sensitivity theory of linear systems. A closed-loop system is relatively insensitive to open-loop parameter changes if these changes affect the open-loop transfer function in a frequency range where the open-loop transfer function has relatively high negative feedback. This is exactly the case with a phase stabilized bending mode. The first bending mode in Fig. 2b peaks to approximately +15 db at approximately zero degrees phase. Therefore, the closed-loop system will be relatively insensitive to parameter changes that affect frequencies near the first bending mode.

The above discussion on the application of a tracking filter to phase stabilize the first bending mode indicates that the

Table 1 Variations of closed loop damping ratio and rigid body gain margin with compensator offset

Bending mode frequency (open loop)	Compensator frequency			
	−20%	Nominal	+20%	+40%
	a) Closed-loop damping ratio			
−20%	0.0356	*0.0374*	(0.0261)	0.0228
Nominal	0.0171	0.0275	(*0.0420*)	0.0278
+20%	0.0150	0.0150	(0.0211)	*0.0409*
	b) Rigid-body gain margin			
−20%	6.6	*7.4*	(7.9)	8.0
Nominal	8.6	10.0	(*10.6*)	11.0
+20%	9.5	11.2	(12.0)	*12.5*

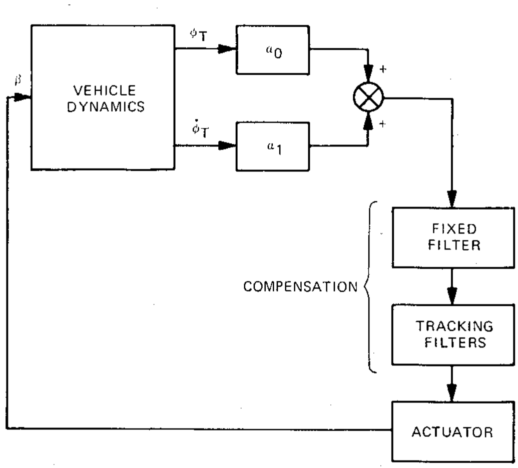


Fig. 1 Saturn IB-201 control system.

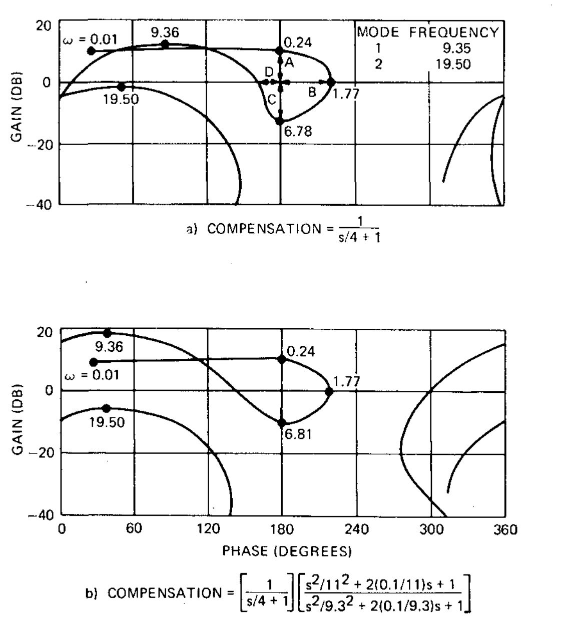


Fig. 2 Gain-phase plot, Saturn IB-201, T = 80 sec.

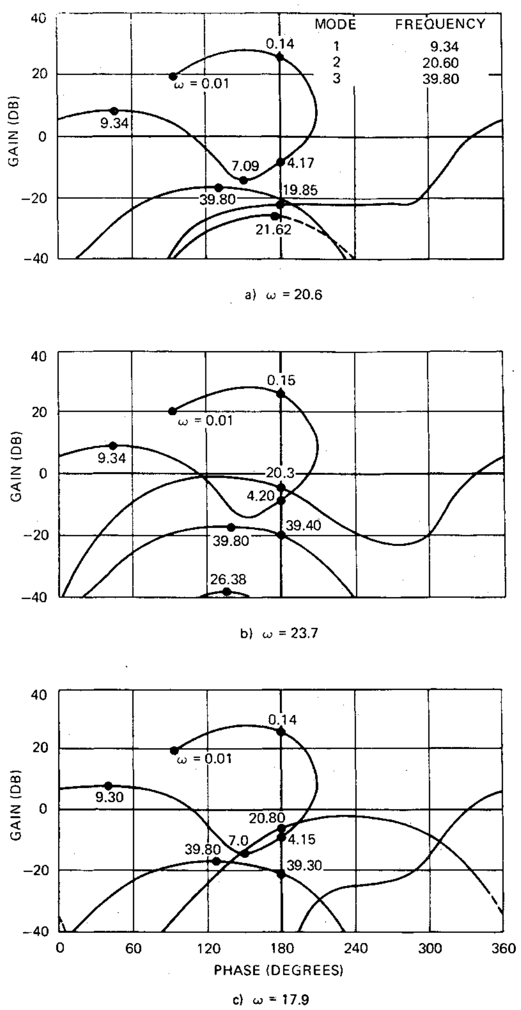


Fig. 3 Gain-phase plot, Saturn IB-201, T = 120 sec; second mode slope increased 12 db, compensation =

$$\left[\frac{1}{s/3 + 1}\right]\left[\frac{1}{s/26.4 + 1}\right]\left[\frac{s^2/\omega^2 + 1}{s^2/\omega^2 + 2(0.2\omega)s + 1}\right].$$

improvements obtained by tracking the first mode are marginal. A slight increase in modal damping is obtained at the expense of rigid body gain margin. There does not appear to be a great requirement for tracking the mode. In addition, the fact that the bending mode is phase stabilized means that the bending mode is actively damped by the control system. Consequently, tracking a phase stabilized bending mode is more difficult to achieve than tracking a gain stabilized mode. If an offset error of the filter frequency from the first mode frequency caused a significant increase in bending activity, then tracking could be achieved. Since this is not the case, it does not appear that there is a good application for tracking filters in phase stabilizing bending modes. Any slight improvements provided by the tracking filter are outweighed by the additional complexity of implementation.

Gain Stabilization

Tracking filters configured as notches can be used to gain-stabilize bending modes. This application will be discussed with the help of an off-nominal vehicle model. The Saturn IB-201 at 120 sec after launch is the basic model, but the slope of the second bending mode has been increased by a factor of four. This creates an instability at the second mode. A lag network breaking at 3 rad/sec is needed to phase stabilize the first mode and roll off the high frequency gain.

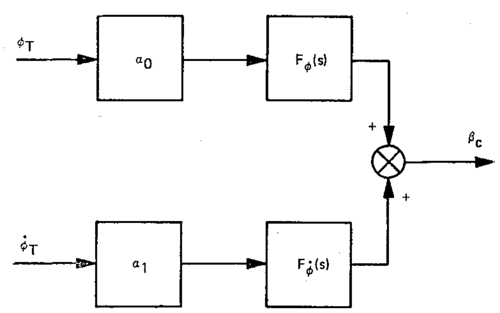
The need for a notch filter to stabilize this system is due entirely to the fact that the second mode peaks near 180° phase. If the second mode peaks near zero degrees (as in the vehicle model considered for the phase stabilization discussion), it would be phase stabilized. In this case (Fig. 2b) there is no need to notch out the second mode, since the control system is feeding back the second mode signal with the proper phase relationship to increase the damping of the mode. The notch would eliminate this signal, thereby decreasing the damping. However, when the mode peaks near 180°, positive feedback results and notch filtering improves the system stability.

In order to best meet the tracking requirements for the notch, a lag network is added with a break frequency of 26.4 rad/sec. This network shifts the second mode peak so that it occurs at exactly 180°. The addition of a notch filter at the second mode frequency of 20.6 rad/sec stabilizes the system as shown in Fig. 3a. The damping factor of the notch pole is 0.2. The gain margin at the second mode is now greater than 20 db.

The need for a tracking notch is demonstrated in Figs. 3b and 3c. In these cases, the notch has been offset above and below the mode, respectively. Notice that the gain margin has been considerably reduced in each case. Therefore, this stability margin is critically affected by whether or not the notch is at the second mode frequency. The other important point to notice is that the frequency at the 180 point is approximately the second mode frequency, so that if the bending mode is excited, the filter tracks in such a way as to increase the stability margin of the system. This case fulfills all the requirements for applying a tracking filter.

The notch needs to track because it is a narrow notch filter. By increasing the damping factor of the notch denominator, the notch could be made broad and, therefore, the system would not be as sensitive to frequency offsets between the notch and the second mode. However, there is a trade-off involved here. A broad notch causes more phase lag at low frequencies than a narrow notch, thereby decreasing the rigid body gain margin.

A lag network near the second mode frequency to provide phase stabilization and/or attenuation does not work for the same reason. So much lag is required that it degrades the



SYSTEM GAINS

GAIN CONSTANT	T ≤ 100	T > 100
a_0	0.82	0.45
a_1	0.657	0.438

TRANSFER FUNCTIONS

$$F_\phi(s) = \frac{\left(\frac{s}{0.095}+1\right)}{\left(\frac{s}{0.0378}+1\right)\left(\frac{s}{31.7}+1\right)}$$

$$F_{\dot\phi}(s) = \frac{\left(\frac{s^2}{11.7^2}+2\,\frac{0.136}{11.7}\,s+1\right)\left(\frac{s^2}{46.7^2}+2\,\frac{0.1}{46.7}\,s+1\right)}{\left(\frac{s}{2.25}+1\right)\left(\frac{s}{6.5}+1\right)\left(\frac{s}{14.1}+1\right)\left(\frac{s}{62.7}+1\right)}$$

Fig. 4 Block diagram of conventional compensation.

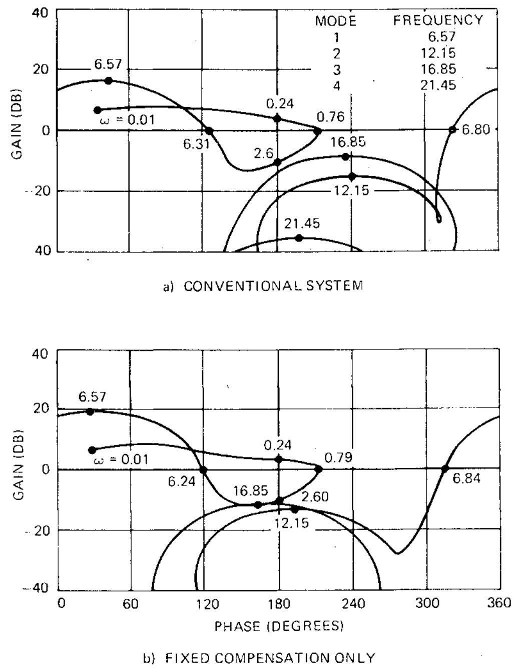


Fig. 5 Gain-phase plot, Saturn V-501, T = 80 sec.

rigid body gain margin. If a sharp lag network is used, the peaking of the lightly damped lag network causes the gain margin between the first and second modes to be small. Therefore, the notch filter is the best way of stabilizing this configuration.

There are other variations of the two cases discussed above, but the same conclusions apply: phase stabilized modes do not offer a good application for the tracking filter, while gain stabilization offers a good application for the tracking filter if the bending mode to be tracked peaks near ±180°.

Application to Saturn V-501

The preceding section indicated that substantial increases in system stability margins could be realized when a sharp tracking notch filter was used to gain stabilize a structural mode when that mode peaked near 180° phase. The second bending mode in the Saturn V-501 vehicle has this phase characteristic; and, since a conventional design is already in existence for this booster, it provides an opportunity for a direct comparison between tracking and fixed designs.[4] In addition, the third mode of the Saturn V-501 also peaks near 180° phase with a relatively low gain margin. An adaptive control system was designed which uses two tracking notch filters to gain stabilize the second and third bending modes.

The control sensors of the Saturn V-501 are located in the Instrument Unit. Because of the large magnitude and the phase of the first bending mode signal sensed at this location, and the greater uncertainties associated with the higher frequency bending modes, some form of lag compensation is required for bending mode stability. The conflicting requirements of rigid body response and high frequency roll-off are best satisfied by phase stabilizing the first bending mode and gain stabilizing the second and higher structural modes. Both conventional and tracking filter systems are based on this approach.

Compensation Design

The block diagram of the conventional system is shown in Fig. 4. In designing the tracking filter system, this conventional system is used as a basic part of the system in order to maintain the same rigid body response and to allow meaningful comparisons between the two systems. The tracking filter system consists of fixed compensation which essentially stabilizes the rigid body, phase stabilizes the first mode, and gain stabilizes the fourth and higher order bending modes; and two tracking filters which gain stabilize the second and third bending modes. To obtain the same rigid body response with both systems, the attitude and attitude rate gain schedules used in the conventional system are retained in the tracking filter configuration.

The fixed compensation for the tracking filter system is obtained by removing the poles and zeros above 14.1 rad/sec and the 11.7-rad/sec zero from the conventional filter and by adding a fixed compensator to cause the second mode to peak at 180° phase. Gain-phase plots of the conventional system and the fixed portion of the adaptive system at the 80-sec flight condition are shown in Figs. 5a and 5b, respectively. Note that the second and third modes in Fig. 5b peak at 180° phase. The rigid body stability margins of both systems are approximately equal except that the first mode phase margin of the conventional system is greater. The addition of the tracking notch compensation will improve this margin in the tracking system.

Both broad fixed compensation and tracking filters are, by design, insensitive to expected parameter variations affecting the frequency range that they control. The disadvantage in using a broad fixed filter for bending mode compensation is the attendent loss in low-frequency stability margins. Figure 6 illustrates this trade-off by showing the loss in rigid body gain margin with increasing notch filter damping ratio. The plot was made assuming two notch filters located at the second and third bending mode frequencies of the Saturn V-501 vehicle at 80 sec. A loss in rigid body phase margin occurs in addition to the decrease in gain margin. The damping ratio of both notch filters selected was 0.15, which results in a small loss of 0.6 db rigid body gain margin. (See Fig. 6.) This loss is justified in terms of the much higher gain margin realized at the bending frequencies. A block diagram of the complete Saturn V-501 control system using second and third mode tracking notch filters is shown in Fig. 7.

The gain-phase plot of the tracking filter system with the two notches set to nominal frequency is given in Fig. 8. Comparison with the conventional system shown in Fig. 5a reveals that the rigid body and first mode stability margins are approximately the same while the tracking filter system provides substantially higher second and third mode gain margins.

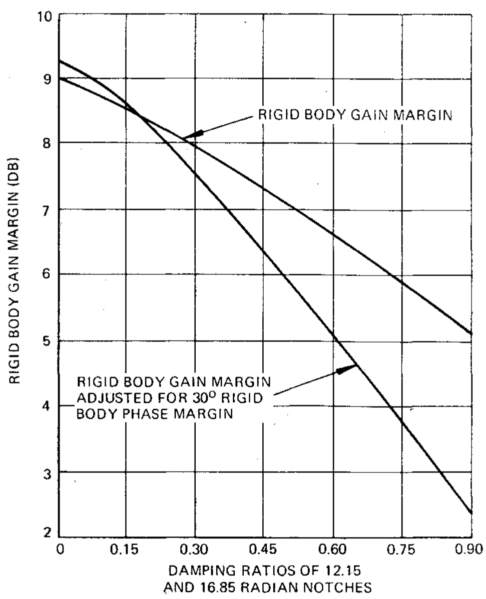
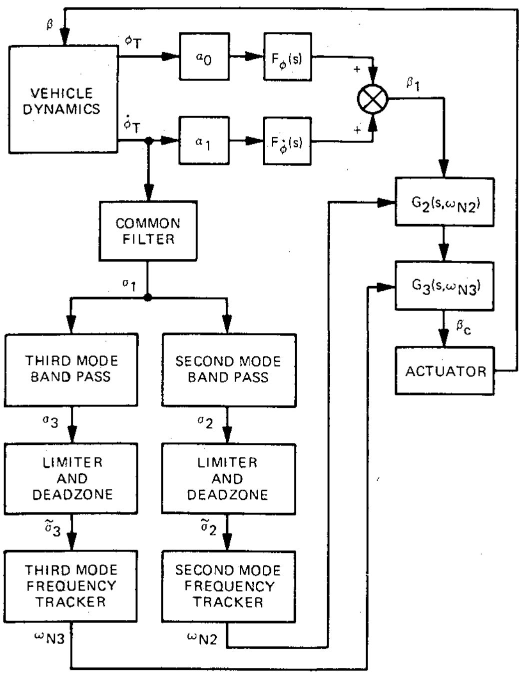


Fig. 6 Decrease in rigid body gain margin with increasing notch filter damping ratio.



FIXED COMPENSATION

$$F_{\phi}(s) = \frac{\frac{s}{0.095}+1}{\frac{s}{0.0378}+1}$$

$$F_{\dot\phi}(s) = \frac{1}{\left(\frac{s}{2.25}+1\right)\left(\frac{s}{6.5}+1\right)\left(\frac{s}{14.1}+1\right)}$$

TRACKING NOTCHES

$$G_2(s,\omega_{N2}) = \frac{\frac{s^2}{\omega_{N2}^2}+1}{\frac{s^2}{\omega_{N3}^2}+2\frac{0.15}{\omega_{N2}}s+1}$$

$$G_3(s,\omega_{N3}) = \frac{\frac{s^2}{\omega_{N3}^2}+1}{\frac{s^2}{\omega_{N3}^2}+2\frac{0.15}{\omega_{N3}}s+1}$$

Fig. 7 Saturn V-501 tracking notch filter system.

Analytical and analog simulation studies were performed at critical flight times to determine the relative stability margins of both conventional and tracking filter systems. The analytical studies compared gain-phase plots of the open-loop frequency response, assuming (for the tracking notch system) that the notches were fixed at the bending mode frequencies. These plots verify that the rigid body stability margins are essentially the same with both systems, and that the second and third mode crossovers are much lower with the notches. This is summarized in Fig. 9 which shows the crossover gains of both systems as a function of flight time. Figure 9 shows that the second mode crossover is a maximum at liftoff, gradually decreasing with flight time until 100 sec, at which time the second mode no longer represents a stability problem. The improvement in second mode crossover gain varies between 14 and 20 db. Third mode crossover gains summarized in Fig. 9 show that the minimum stability margin occurs at 100 sec, and the crossover gain improvement is approximately 27 db at all flight times.

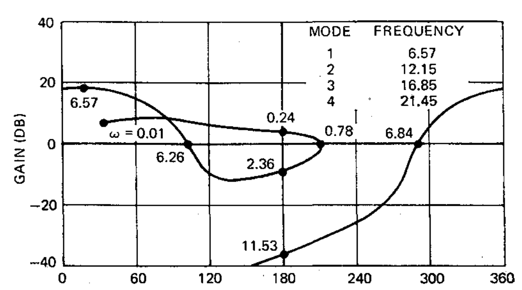


Fig. 8 Gain-phase plot, Saturn V-501, T = 80 sec, tracking notch system.

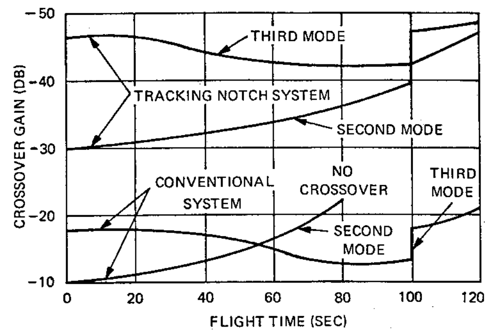


Fig. 9 Comparison of second- and third-mode crossover gains, conventional and tracking notch systems.

Fixed-Point Studies

System sensitivity to bending mode frequency variations was investigated at the flight times when the crossover gains were a minimum. For both the second and third modes, lowering the bending frequency decreases the stability margin. Figure 10a is a gain-phase plot for the conventional system at liftoff with the second bending mode frequency 20% low. Note that the crossover gain margin decreases from 9.8–1.3 db. A gain-phase plot is shown in Fig. 10b for the same conditions using the notch system (which was assumed to have tracked down to the bending frequency). The second mode crossover gain margin decreased from 30.4–24.9 db. Figures 11a and b illustrate the same sensitivity to the third mode frequency at 100 sec (before switching). With the conventional system (Fig. 11a), a 20% decrease in third mode frequency lowers the crossover gain margin from 12.2–6.2 db. Figure 11b shows that the third mode crossover gain margin with the notch decreased from 41.7–33.8 db.

Analog computer simulation was used to determine the bending mode slope margins realized by both systems with nominal and off nominal bending frequencies. As used in this paper, slope margin refers to the amount of increase in a bending mode slope (at the attitude and rate sensor location) required to cause instability. Table 2 compares the second and third mode slope margins of both systems for various frequency offsets at 0, 80, and 100 sec (before the gain

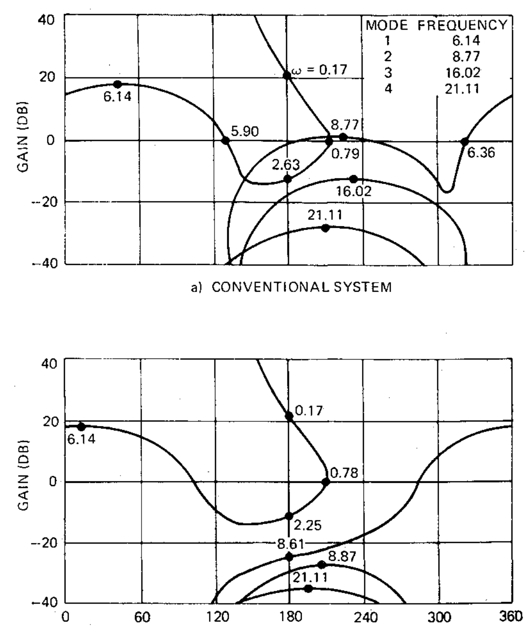


Fig. 10 Gain-phase plot, Saturn V-501, T = 0 sec, second-mode frequency reduced 20%.

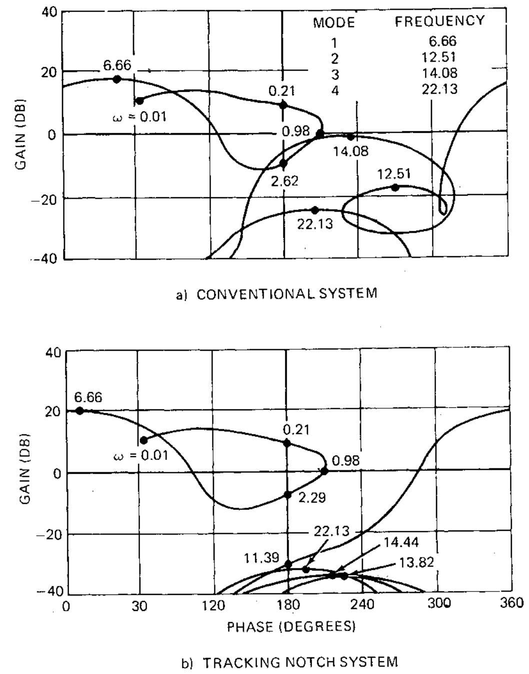


Fig. 11 Gain-phase plot, Saturn V-501, T = 100 sec before switching, third-mode frequency reduced 20%.

change). In both cases, tracking notches increased the slope margins by 10–15 db.

Trajectory Simulation

A real-time trajectory simulation was conducted to evaluate the performance of the conventional system and tracking notch system. The simulation was from launch to first stage burnout and included the first four bending modes, the S-II LH_2 tank and the S-IVB LH_2 tank. The tracking filter configurations used for both second and third mode notches employed conventional multiplier demodulators driven by their respective high pass reference outputs.[2] A block diagram of this tracking filter configuration is shown in Fig. 12. Separate tracking and compensating networks (as shown in Fig. 7) are used to achieve higher sensitivity by using the rate gyro output as the tracker inputs. This configuration also simplified the inclusion of prefiltering and limiting in the tracker circuitry.

Table 2 Comparison of Saturn V-501 second- and third-mode slope margins, conventional (C) and tracking notch (TN) systems

Flight time, sec	Frequency offset, %	Second mode C	Second mode TN	Third mode C	Third mode TN
0	−20	6.3	21.6	17.6	28.0
	10	9.5	30.0	24.9	39.7
	Nominal	14.3	31.8	30.6	43.5
	+10	19.5	33.8	35.6	49.5
	+20	24.6	39.6	>40	54.0
80	−20	16.2	36.5	15.3	28.0
	−10	21.9	39.6	21.9	35.1
	Nominal	27.4	41.6	26.1	38.0
	+10	32.9	47.6	30.2	42.9
	+20	37.8	50.2	>40	48.0
100	−20	34.2	55.9	16.4	30.9
	−10	40.3	58.7	23.5	36.3
	Nominal	45.8	>60	25.2	40.8
	+10	51.4	>60	30.4	45.1
	+20	56.0	>60	>40	>40

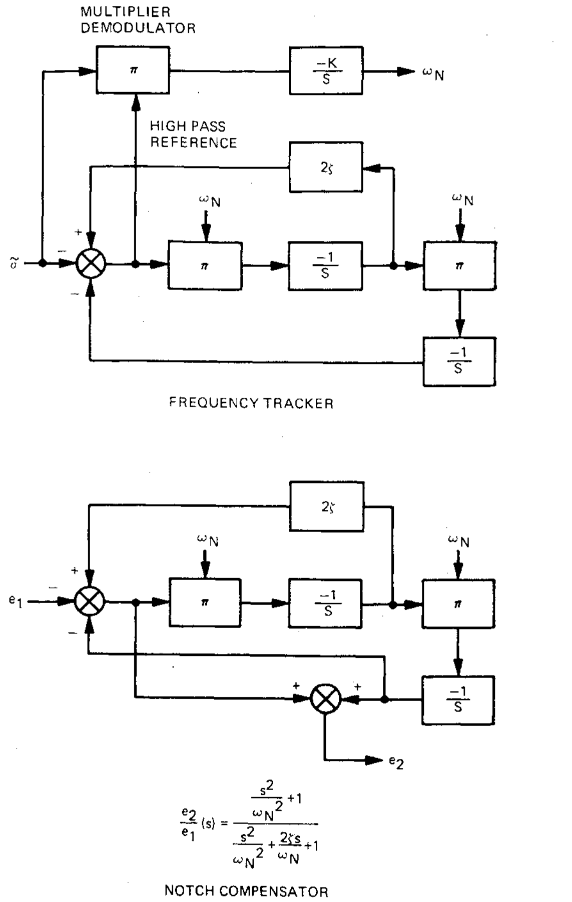


Fig. 12 Block diagram of tracking notch filter using separate tracking and compensation circuits.

Because of the small frequency separation between the bending modes, some form of bandpass filtering is required for both trackers. A compromise between the required selectivity and the added system complexity was made by using two second-order band-pass filters and a complex, second-order, lead-lag filter common to both trackers. Although a total of six integrations is required to implement the two prefilters, the use of the common section results in effectively two fourth-order prefilters. These filters are defined by the

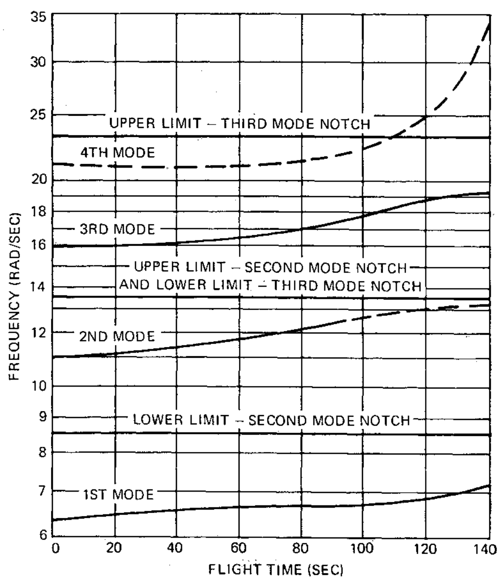


Fig. 13 Variation of bending mode frequencies with flight time.

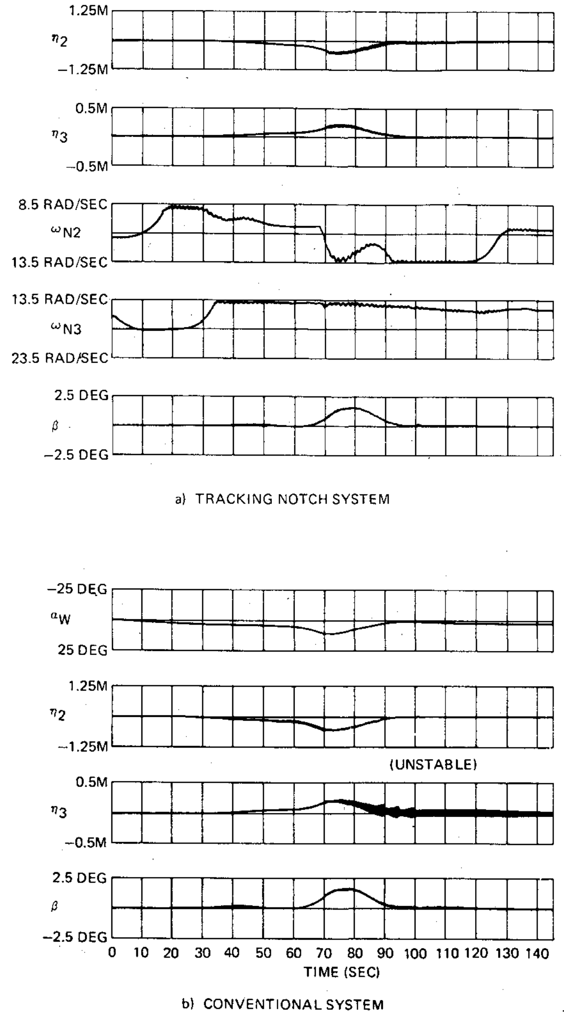


Fig. 14 Saturn V-501 launch trajectory, second- and third-mode frequencies reduced 20%, second and third slopes increased 12 db.

following transfer functions:

$$\frac{\sigma_j}{\dot{\phi}_T}(s) = \left[\frac{\dfrac{s^2}{6.5^2}+\dfrac{2(0.2)s}{6.5}+1}{\left(\dfrac{s}{10}+1\right)\left(\dfrac{s}{17}+1\right)}\right]\left[\frac{\dfrac{2\zeta_j s}{\omega_j}}{\left(\dfrac{s^2}{\omega_j{}^2}+\dfrac{2\zeta_j s}{\omega_j}+1\right)}\right]$$

where $\zeta_2 = 0.13$ and $\omega_2 = 10$ for the second-mode prefilter; and $\zeta_3 = 0.16$ and $\omega_3 = 17$ for the third-mode prefilter.

Limiter-deadzone circuits were used with both frequency trackers to limit the tracking rate and to provide a threshold to prevent tracking small inputs. Limits on the frequency tracking authority of the notches and design of the bandpass filters were based on the variation of the bending frequencies with time given in Fig. 13. The dashed portion of these curves represents the flight time over which the respective bending modes are insignificant and no tracking requirement exists. The limits were chosen to enable the notches to track approximately ±20% from the nominal bending frequencies over the flight times when the respective bending modes were significant. The bandpass filter center frequencies correspond to the center of these frequency limits, and the bandpass damping ratios were selected to make the frequency limits correspond approximately to the −6 db points on the amplitude characteristics.

Trajectories with all parameters at their nominal value show no discernable difference in vehicle response between the conventional and the tracking systems. The off-nominal cases show that the tracking system has much greater stability margins. If the second- and third-mode frequencies are assumed to be below their nominal values, the stability margins are decreased. If, in addition, the bending mode slopes are assumed to be greater than nominal, then the conventional system diverges while the tracking system remains stable. Typical trajectory runs are shown in Figs. 14a and 14b. These runs illustrate that the conventional system is unstable with the second- and third-mode frequencies 20% low and the mode slopes increased by 12 db, whereas the tracking system is stable. This is typical of all trajectory runs taken; the tracking system is never unstable when the conventional system is stable, but the conventional system is often unstable in off-nominal conditions when the tracking system is stable. The wind profile used to excite the vehicle can be seen in these figures.

In summary, the trajectory study confirmed the ability of two tracking notch filters to stabilize the second and third bending modes with large variations in the bending frequencies and slopes. With nominal bending slopes and frequencies, the vehicle response to the wind profile was the same using the conventional system and the tracking notch system. The notch system, however, provided higher slope margins with nominal and off-nominal bending frequencies.

Conclusions

This study shows that better stability margins can be obtained using a tracking filter system instead of a conventional control system in certain gain stabilization applications. This improvement is accomplished at the expense of a substantial increase in system complexity so that stability must be a critical problem in order to justify the use of the tracking filter.

A necessary condition for a successful application of the tracking filter for the purpose of gain stabilization is that the mode to be gain stabilized must peak close to an open-loop phase shift of 180°. The tracking filter is not recommended in a phase stabilization application due to the minimal improvements in stability margins obtainable and the poor tracking characteristics associated with phase stabilized modes.

An additional comment should be made about the design of an adaptive control system. Often, one gets the general impression from the literature on the subject that, if a control problem has large variations in system parameter values or great uncertainty in the knowledge of certain system parameters, then the design problem is made easier by going to adaptive control. Based on experience gained on this project, the opposite conclusion is reached; i.e., in order to insure that an adaptive system does not (or cannot) revert to a destabilizing mode of operation, a great deal more care and effort must be put into its design than would be required with a conventional system.

References

[1] Borelli, M. T. and Carroll, S. N., "Advanced Control Systems for the Saturn V Launch Vehicle," AIAA Paper 67-591, Huntsville, Ala., 1967.

[2] Gaylor, R., Schaeperkoetter, R. and Cunningham, D., "An Adaptive Tracking Filter for Bending Mode Stabilization," *Journal of Spacecraft and Rockets*, Vol. 4, No. 5, May 1967, pp. 573–577.

[3] "Preliminary Vibration Analysis of the Saturn IB, SA-201 Vehicle," Internal Memorandum R-P and VE-SLA-64-28, Nov. 1964, NASA.

[4] "AS-502 and AS-501, S-1C Burn, Pitch, Yaw, and Roll Control Gains, Shaping Network Characteristics and Control Sensor Locations," Internal Memorandum R-ASTR-F-66-69, April 1966, NASA.