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THRUST VECTOR CONTROL REQUIREMENTS FOR LAUNCH VEHICLES USING A 260-INCH SOLID ROCKET FIRST STAGE

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16. Abstract

Gimbaled nozzle and liquid injection thrust vector control requirements are derived for a family of 260-in. (6.61-m) solid rocket launch vehicles with two different second stages. The use of biased pitch programs is assumed. Also, the use of fins in reducing requirements is investigated. It is shown that the use of fins is not warranted for the gimbaled nozzle system unless the deflection angle for winds is much greater than that required for pitchover. Also, the use of fins does not reduce liquid injection system requirements significantly.

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SUMMARY

Gimbaled nozzle and liquid injection thrust vector control requirements are determined for a family of launch vehicles having 260-inch (6.61-m) solid first stages with different propellant loadings. Maximum deflection angle, rate, and acceleration requirements are determined for the gimbaled nozzle system. For the liquid injection system, the maximum deflection angle and maximum deflection impulse requirements are determined. These requirements are derived for vehicles with and without base fins. It is shown that if biased pitch programs are used, the use of fins is not warranted for the gimbaled nozzle system unless the deflection required during the high wind region is much greater than the deflection required during pitchover. Since fins do not reduce requirements resulting from misalinement, their use on a vehicle with a liquid injection system is also not warranted.

INTRODUCTION

The potentialities of the 260-inch (6.61-m) solid motor as the first stage of a future launch vehicle have been examined in recent analyses (e.g., ref. 1). However, no definite payload weight has yet been defined for these missions; thus, in order to determine preliminary thrust vector control (TVC) requirements, one method is to assume a launch vehicle having a 260-inch (6.61-m) solid first stage with a range of propellant loadings. The purpose of this study, therefore, is to determine TVC system requirements for a family of launch vehicles with 260-inch (6.61-m) solid motor first stages. Two second stages were considered - a modified S-IVB (J2S engine) and a larger hydrogen-oxygen (H-O) stage with 400 000 pounds force (1.78 MN) of thrust and 400 000 pounds mass (182 000 kg) of propellant. TVC requirements were derived for solid propellant loadings ranging from 1.7 million pounds mass (0.77×10^6 kg) to 5.0 million pounds mass

(2.3×10^6 kg) for the launch vehicle with the S-IVB second stage. Also considered was a clustered 260-inch (6.61-m) solid launch vehicle which consisted of six 260-inch (6.61-m) solid motors for the first stage. The second stage was composed of a cluster of six of the larger H-O stages.

Two basic TVC systems were considered: gimbaled nozzle and liquid injection. Also, the effect of adding fins to the vehicles was studied to determine the possible reduction in TVC requirements for both systems. Finally, tail-off problems were investigated for the clustered vehicle. Attitude and attitude rate errors were calculated as a function of tail-off duration and variation of web action time. In order to reduce these errors to an acceptable limit, the effects of nozzle canting and increased deflection capability were investigated.

Most of the results presented are obtained by assuming a required launch availability of 90 percent. Thus, the wind velocities used are those which are not exceeded 90 percent of the time. However, since design criteria may show a need for higher launch availability, requirements for 95 and 99 percent peak wind velocities are also presented.

ASSUMPTIONS

Some of the assumptions and ground rules of the study are listed below.

(1) The data for all the vehicles studied are based on a conceptual design study conducted at the Lewis Research Center.

(2) The nominal pitch program was designed to fly zero angle of attack through the atmosphere after a rapid initial pitchover phase. The unbiased pitch programs were designed with no wind disturbance present, while the biased pitch programs were designed to maintain zero angle of attack through a mean wind profile, as described in appendix B. The upper stages used a steering program generated by the calculus of variations in order to maximize payload capability into a 185-kilometer circular orbit. The magnitude of the initial pitchover maneuver, which determines the amount of trajectory lofting, was optimized in order to maximize payload, but with the constraint that the dynamic pressure should not exceed 47 kilonewtons per square meter.

(3) Vehicle aerodynamic data (center of pressure and normal force coefficients) were obtained by using the analytical techniques presented in reference 2.

(4) Aerodynamic data for the base fins were taken from a work entitled "Aerodynamics of the Saturn IB Redesigned Fin" by Bob G. Dunn of NASA Marshall Space Flight Center.

(5) An Eastern Test Range launch was assumed with a launch azimuth sector of 45° to 115°.

(6) Synthetic wind data were used in calculating TVC requirements. The peak ve-

locities used are based on 90, 95, and 99 percent probability of occurrence is the worst monthly period. These velocities were derived from reference 3.

Since most conventional autopilots are designed to fly the nominal pitch program (trimmed) in the presence of disturbances, the TVC requirements quoted herein are based on trim requirements. The results presented in reference 4 show that for the type of vehicle presented herein at least 80 percent of the fully trimmed requirement must be provided for vehicle stability. It is assumed that the vehicle is maintained trimmed up to its maximum TVC capability.

The TVC requirements for the gimbaled nozzle system for a given wind disturbance are calculated by superimposing the wind disturbance on the nominal trajectory and assuming the trajectory does not drift from the nominal due to the presence of the disturbance. These assumptions lead to a slightly conservative estimate of TVC requirements because the actual trajectory drifts in a direction which tends to reduce the angle of attack and, hence, the deflection angle. The drift effect can reduce the TVC requirements by as much as 30 percent as shown in reference 2.

RESULTS AND DISCUSSION

An investigation was made of five different vehicles to determine the control requirements for gimbaled nozzle and liquid injection thrust vector control (LITVC) systems. The vehicles are

(1) 260 (3.4)/MS-IVB vehicle
(2) 260 (1.7)/MS-IVB vehicle
(3) 260 (5.0)/MS-IVB vehicle
(4) Single 260 (5.0)/H-O (0.4) vehicle
(5) Clustered 260 (30.0)/H-O (2.4) vehicle

The numbers in parentheses represent total stage propellant loadings in millions of pounds. A schematic of all the vehicles is shown in figure 1. It is assumed here that, for the gimbaled nozzle system, the angle of the nozzle and the angle of the thrust vector are the same except for misalinement. Also, the effective gimbal point for the gimbaled nozzle was assumed to be at the throat of the nozzle; for any difference in gimbal point, moment arm ratios may be calculated and applied to the values of deflection angles given in this report to determine new requirements. The gimbal point for the LITVC system was assumed to be at a nozzle expansion ratio of 4.0.

The TVC requirements for all systems studied were calculated with and without biased pitch programs. However, the final design values were obtained by assuming the use of biased pitch programs (BPP). The use of BPP requires monitoring the winds aloft prior to the launch. This information is used to select from a predetermined family

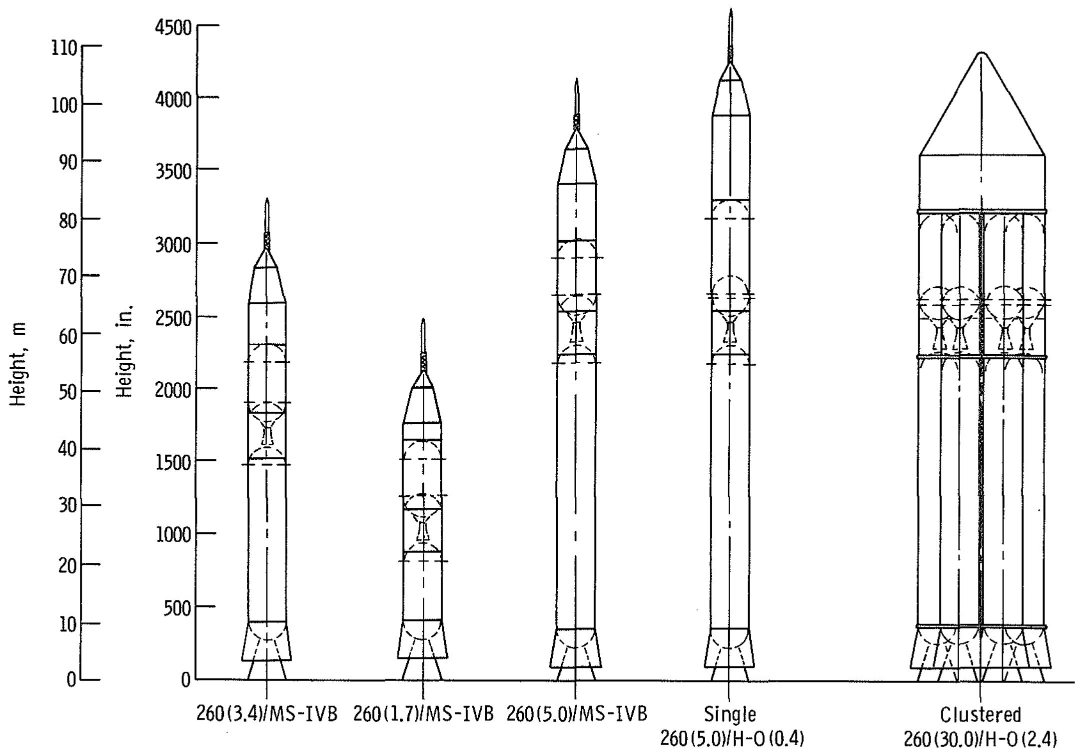
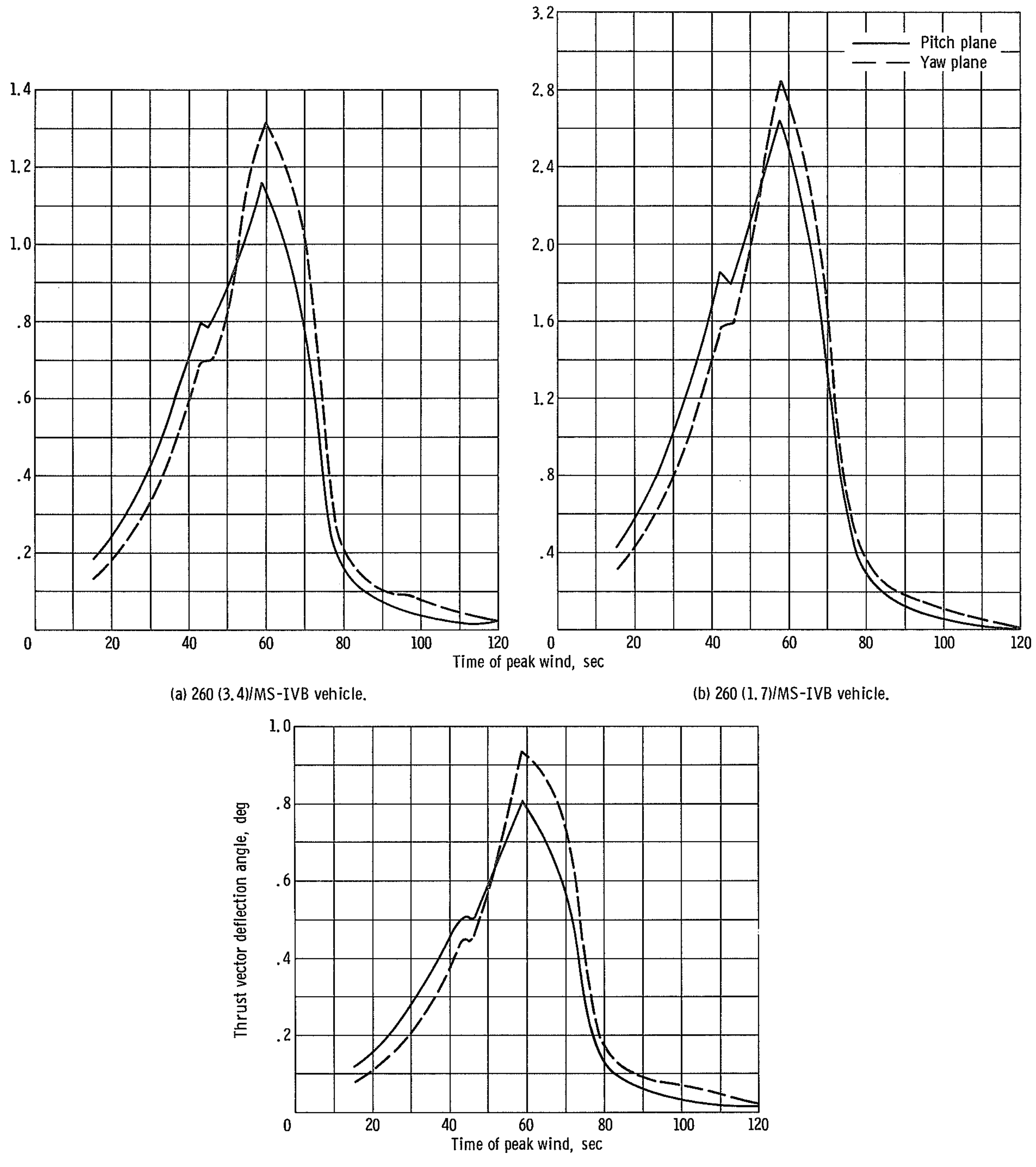


Figure 1. - Family of 260-inch (6.61-m) solid launch vehicles.

the pitch program that minimizes vehicle loads and TVC requirements. Since the preflight winds must be monitored in any case, the use of BPP is accomplished with essentially no extra effort and is therefore recommended. The use of BPP to reduce vehicle bending, maximum deflection angle, and deflection impulse (important for LITVC systems) for winds is presented in appendix B. The data show that the use of BPP can result in a reduction in vehicle bending moment of 50 percent and reductions in peak deflection angle and deflection impulse of 40 and 50 percent, respectively, for 90 to 99 percent launch availability for the 260 (3.4)/MS-IVB vehicle. These reductions apply to wind requirements only. It was assumed that these values would apply to the other vehicles as well. A detailed analysis is presented first for 90 percent winds. Later, final results are presented for 95 and 99 percent winds.

Gimbaled Nozzle System

The deflection angle required for winds for each vehicle is shown in figure 2. The data on the curves in figure 2 correspond to an envelope of maximum deflection requirements for a family of 90 percent ground and flight winds rather than to any single wind

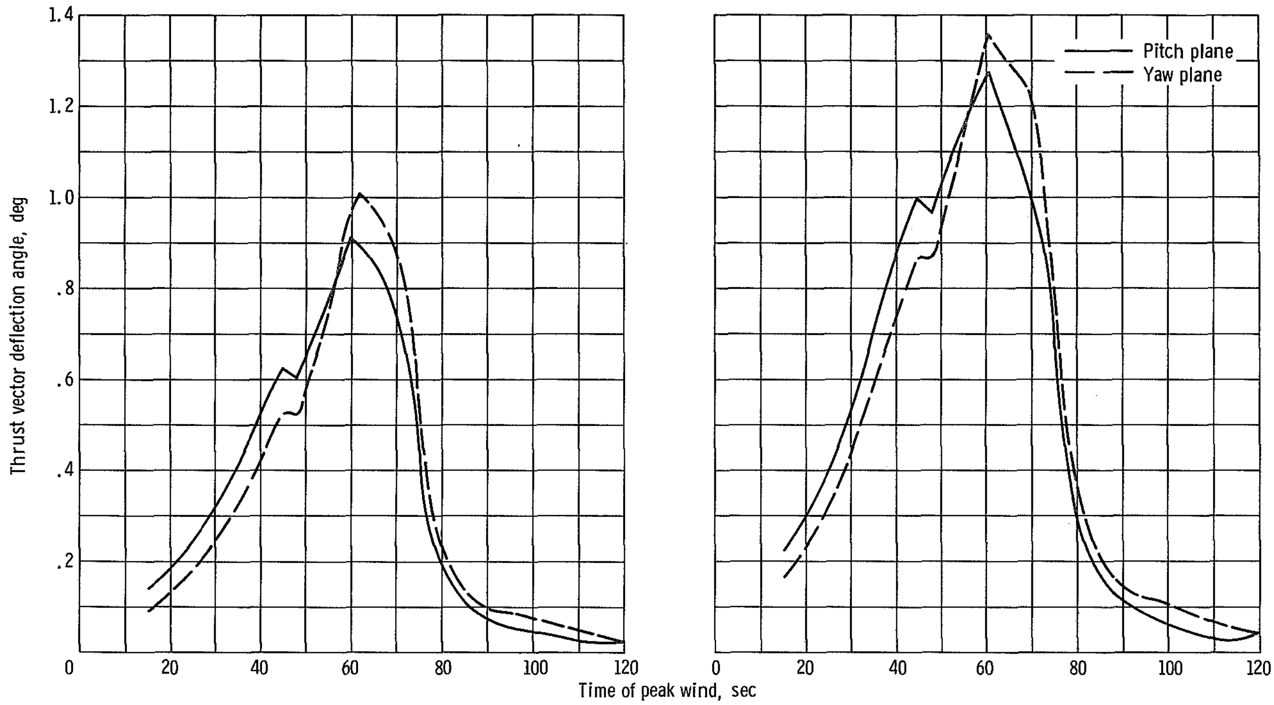


(a) 260 (3.4)/MS-IVB vehicle.

(b) 260 (1.7)/MS-IVB vehicle.

(c) 260 (5.0)/MS-IVB vehicle.

Figure 2. - Pitch and yaw deflection requirements for family of 90 percent synthetic wind profiles. Without biased pitch programs (BPP).



(d) Single 260 (5.0)/H-O (0.4) vehicle.

(e) Clustered 260 (30.0)/H-O (2.4) vehicle.

Figure 2. - Concluded.

profile. The synthetic wind profiles consist of low wind velocity regions with a wind spike occurring at some altitude. The height of the spike (maximum wind velocity) is a function of the spike altitude and the wind azimuth. The TVC required at the peak velocity corresponds to a single point on the deflection profile. The peak wind velocities used to determine these requirements were derived from reference 3. The data on figure 2 were derived by superimposing the wind disturbance on the nominal trajectory so that no drift velocity is accumulated. Since the drift tends to reduce the angle of attack and, hence, the deflection angle, the results presented are somewhat conservative (about 30 percent high as determined in ref. 2). Since the pitch and yaw requirements were obtained for different wind profiles, these requirements should not be added vectorially. Instead, it can be shown that the maximum deflection angle (regardless of wind direction) is essentially equal to the yaw requirement. The maximum wind requirements shown in figure 2 may be reduced by 40 percent by the use of BPP.

Peak TVC requirements tend to occur just prior to maximum dynamic pressure or maximum Q. (All symbols are defined in appendix A.) The winds in the pitch plane are always tail winds because of the launch azimuth sector (45^{o} to 115^{o}) and the fact that the winds tend to blow from the west in the northern hemisphere. The tail winds tend to reduce the relative velocity and Q; hence, they also reduce TVC requirements. Winds in the yaw direction result in increased relative velocity, Q and TVC requirements.

TABLE I. - THRUST VECTOR DEFLECTION ANGLE REQUIREMENTS FOR GIMBALED NOZZLE TVC SYSTEM

Parameter	Variation	Vehicle				
		260 (3.4)/ MS-IVB	260 (1.7)/ MS-IVB	260 (5.0)/ MS-IVB	Single 260 (5.0)/ H-O (0.4)	Clustered 260 (30.0)/ H-O (2.4)
		Deflection angle, deg				
1. Steady-state winds	90 percent	1.32	2.84	0.93	1.02	1.36
2. Steady-state winds with biased pitch programs[a]	90 percent	.79	1.70	.55	.61	.82
3. Wind gusts[b]	3σ	.20	.43	.14	.15	.21
4. Thrust misalinement	3σ	.40	.40	.40	.40	.40
5. Thrusts and weights	3σ	.08	.10	.06	.06	.09
6. Pitch program	Maximum	.73	.62	.98	.80	.86
7. Winds at pitchover without biased pitch programs		.18	.42	.12	.14	.21
Total[c] 1		1.78	3.44	1.36	1.45	1.82
Total[d] 2		1.25	2.30	0.98	1.04	1.28
Total[e] 3		1.31	1.44	1.50	1.34	1.47

[a]60 percent of steady-state winds.
[b]15 percent of steady-state winds.
[c]Total consists of item 1 plus root sum square of items 3, 4, and 5.
[d]Total consists of item 2 plus root sum square of items 3, 4, and 5.
[e]Total consists of sum of items 4, 6, and 7.

Total deflection requirement. - In order to determine the total maximum deflection angle, effects other than winds were also considered. All of these effects are shown in table I. An effective misalinement of 0.40° was assumed, which includes the effect of center of gravity offset as well as nozzle misalinement. For the clustered vehicle this value also includes the effect of thrust unbalance during the flight. This number is representative of gimbaled nozzle systems; however, the actual value of misalinement will be a function of the particular nozzle and gimbal design. The thrust and weight dispersions were derived from results presented in reference 1. Wind gusts dispersion was calculated by adding 7.6 meters per second to the peak wind velocity, which resulted in a maximum of 15 percent of the maximum thrust vector deflection angle for winds (calculated without BPP) for all vehicles. The deflection angle due to winds at pitchover (10 to 15 sec) was determined from figure 2 (at 15 sec) while the thrust vector deflection angle required for pitchover was determined from simulations made using a control system discussed in appendix C. In table I, three totals are presented so that the maximum deflection angle requirement can be determined. Totals 1 and 2 give the maximum deflection angle required during the high wind region, with and without BPP, while total 3 gives the total deflection angle required at pitchover. The high wind and pitchover requirements are calculated separately since they occur at different times and are not additive. Thus, the maximum deflection angle requirement is the larger of the two totals (totals 2 and 3 under the assumption that BPP will be used). For example, the 260 (3.4)/

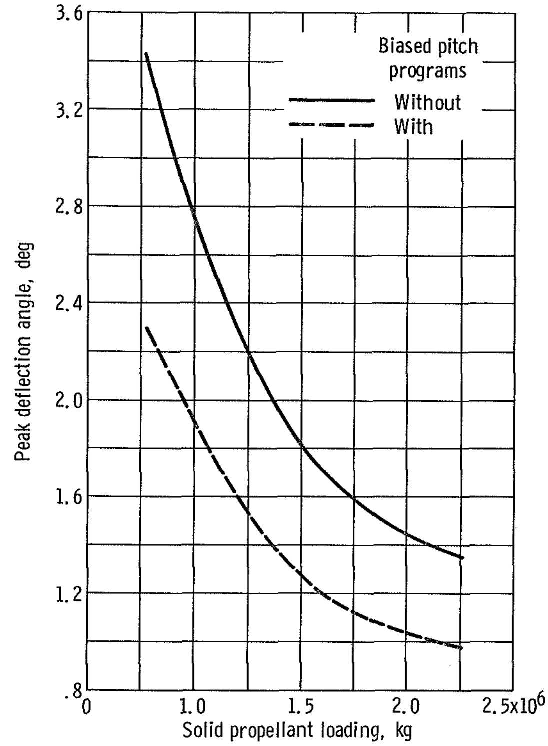


Figure 3. - Peak total deflection angle required for 90 percent winds as function of propellant loading for 260-inch (6.61-m) solid first stage with the S-IVB second stage.

MS-IVB vehicle (reference vehicle) requires a deflection angle of 1.25° from total 2 and a deflection of 1.31° during pitchover. Therefore, the design maximum deflection angle needed is 1.31°. Values for the other vehicles are also presented.

Figure 3 shows the peak total deflection angle, for 90 percent winds, as a function of propellant loading for the 260-inch (6.61-m) solid first stage and the S-IVB second stage. From this figure, the total deflection angle needed for winds for the gimbaled nozzle system may be obtained for propellant loadings other than the ones investigated in this report. It should be noted that as the propellant loading increases, the deflection angle for winds decreases because the increase in control moment arm and thrust and is slightly offset by the increase in the aerodynamic moment arm. However, the pitchover requirement (item 6, table I) tends to increase as propellant loading increases; the total pitchover requirement is larger than the wind requirement for the larger vehicles.

Rate and acceleration requirements. - The calculation of gimbal angle for pitchover (item 6, table I) and the gimbal rate and acceleration for pitchover and the high wind region was accomplished by the use of a control system described in appendix C. The results for the two regions are presented in table II. The design values for the rate $\dot{\delta}$ and acceleration $\ddot{\delta}$ are the larger of the two values presented. For the reference ve-

TABLE II. - RATE OF ACCELERATION REQUIREMENTS FOR A

GIMBALED NOZZLE TVC SYSTEM

Vehicle	Region			
	Pitchover		Maximum dynamic pressure	
	Thrust vector deflection			
	Rate, $\dot{\delta}$, deg/sec	Acceleration, $\ddot{\delta}$, deg/sec^2	Rate $\dot{\delta}$, deg/sec	Acceleration, $\ddot{\delta}$, deg/sec^2
260 (3.4)/MS-IVB	1.3	4.0	0.90	1.4
260 (1.7)/MS-IVB	1.0	3.4	2.0	3.1
260 (5.0)/MS-IVB	1.7	5.4	.65	1.0
Single 260 (5.0)/H-O (0.4)	1.4	4.4	.62	.94
Clustered 260 (30.0)/H-O (2.4)	1.5	4.2	1.1	1.6

hicle, $\dot{\delta}$ is 1.3 degrees per second and $\ddot{\delta}$ is 4.0 degrees per second^2.

Use of base fins. - Next, a set of eight fins (as described in the work by Dunn) mounted symmetrically around the base of the vehicle was assumed to determine possible reductions in TVC requirements for the gimbaled nozzle system. It was also assumed that the center of pressure of the fins was at the gimbal station on the vehicle and that the angle of attack on the fins was the same as on the vehicle. Equations to calculate TVC requirements for winds when fins are used are found in reference 2. Figure 4 shows the maximum deflection angle for 90 percent winds as a function of fin area ratio (fin area divided by vehicle reference area). The vehicle reference area S_{ref} is the cross sectional area of the vehicle and is 34.2 square meters for the single engine vehicles and 384 square meters for the clustered vehicle. The end points on the figure represent the largest possible reduction in TVC requirements for winds obtainable with base fins. A further increase in fin area ratio causes the requirements to decrease below this value during part of the flight, but also to increase above this value during a different part of the flight. This effect is shown in figure 5 for the reference vehicle (yaw plane). Thus, the maximum deflection angle for winds may be reduced from 1.32° to 0.44° for the reference vehicle by using a fin area ratio of 1.0. By using BPP, this maximum deflection angle can be reduced by 40 percent to 0.26°. Substituting this value for winds (item 2) into table I, reduces total 2 to 0.72°. However, the total deflection angle needed for pitchover would not be reduced appreciably since during this early part of the flight, the Q is low; thus, the fins are not very effective. Therefore, the use of fins on the reference vehicle is not indicated when BPP is used. However, for the 260 (1.7)/MS-IVB vehicle, the deflection angle needed during the high wind region using BPP is 1.70° (table I). This

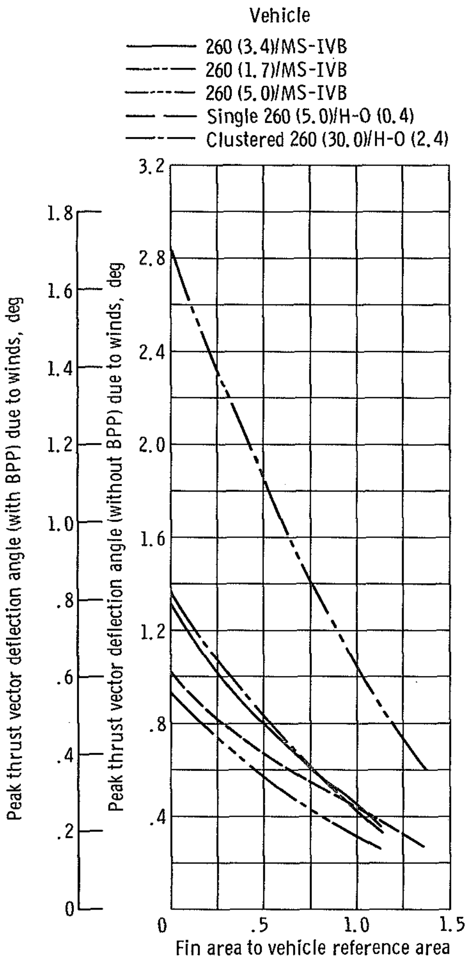


Figure 4. - Peak thrust vector deflection angle due to winds as function of fin area to vehicle reference area. (BPP denotes biased pitch program).

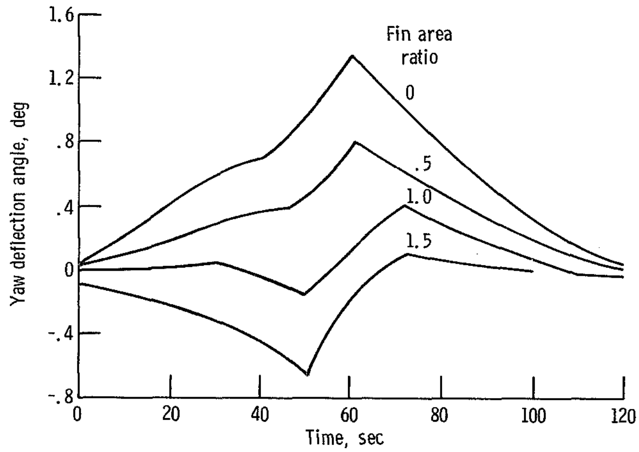


Figure 5. - Yaw deflection angle as function of time for 260(3.4)/MS-IVB vehicle. Fin area ratio varied.

can be reduced to 0.63° by using a fin area ratio of 1.0, and total 2 would be reduced to 1.23°. Since this requirement is about the same as the pitchover requirement, the use of fins on this vehicle might be worthwhile.

Liquid Injection System

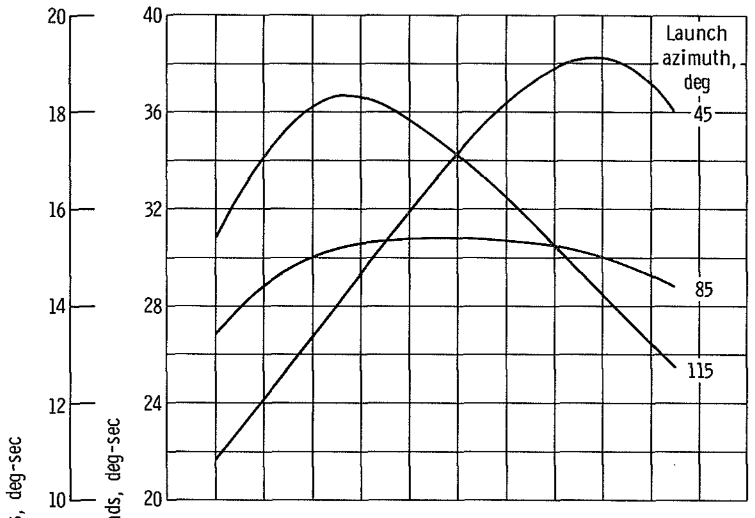
The second system studied was a LITVC system. For this system, the maximum deflection angle and the maximum deflection impulse (the integrated deflection angle-time profile) requirements are needed.

Total deflection requirement. - The maximum deflection angle required is important for the LITVC system since the system must be capable of obtaining this deflection to insure vehicle stability. The wind profiles from reference 3 were used to derive the peak deflection angle requirement. The maximum deflection angle requirements for the pitch-over and high wind regions are shown in table III for all five vehicles. These requirements are the same as shown previously for the gimbaled nozzle configurations except for a correction due to the change in moment arm. The assumed gimbal point for the LITVC

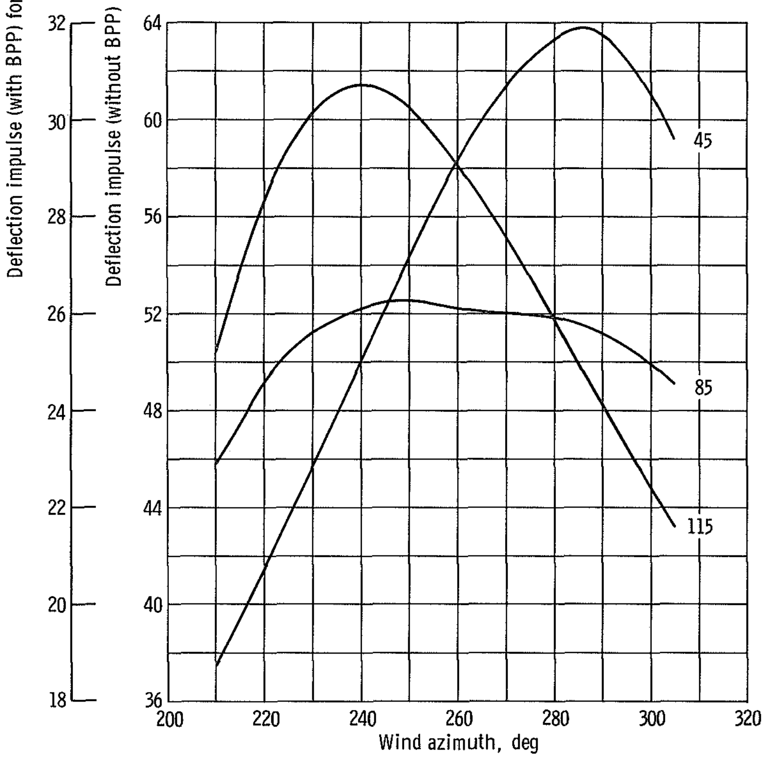
TABLE III. - THRUST VECTOR DEFLECTION ANGLE REQUIREMENTS FOR LIQUID INJECTION TVC SYSTEM

Parameter	Variation	Vehicle				
		260 (3.4)/ MS-IVB	260 (1.7)/ MS-IVB	260 (5.0)/ MS-IVB	Single 260 (5.0)/ H-O (0.4)	Clustered 260 (30.0)/ H-O (2.4)
		Deflection angle, deg				
1. Steady-state winds	90 percent	1.13	2.26	0.79	0.89	1.20
2. Steady-state winds with biased pitch programs[a]	90 percent	.68	1.36	.47	.53	.72
3. Wind gusts[b]	3σ	.17	.34	.12	.13	.18
4. Thrust misalinement	3σ	.25	.25	.25	.25	.25
5. Thrust and weight	3σ	.08	.10	.06	.06	.09
6. Pitch program	Maximum	.62	.48	.83	.69	.75
7. Winds at pitchover with biased pitch programs		.17	.37	.11	.13	.19
Total[c] 1		1.44	2.69	1.07	1.18	1.52
Total[d] 2		0.99	1.79	0.75	0.82	1.04
Total[e] 3		1.04	1.10	1.19	1.07	1.19

[a]60 percent of steady-state winds.
[b]15 percent of steady-state winds.
[c]Total consists of item 1 plus root sum square of items 3, 4, and 5.
[d]Total consists of item 2 plus root sum square of items 3, 4, and 5.
[e]Total consists of sum of items 4, 6, and 7.

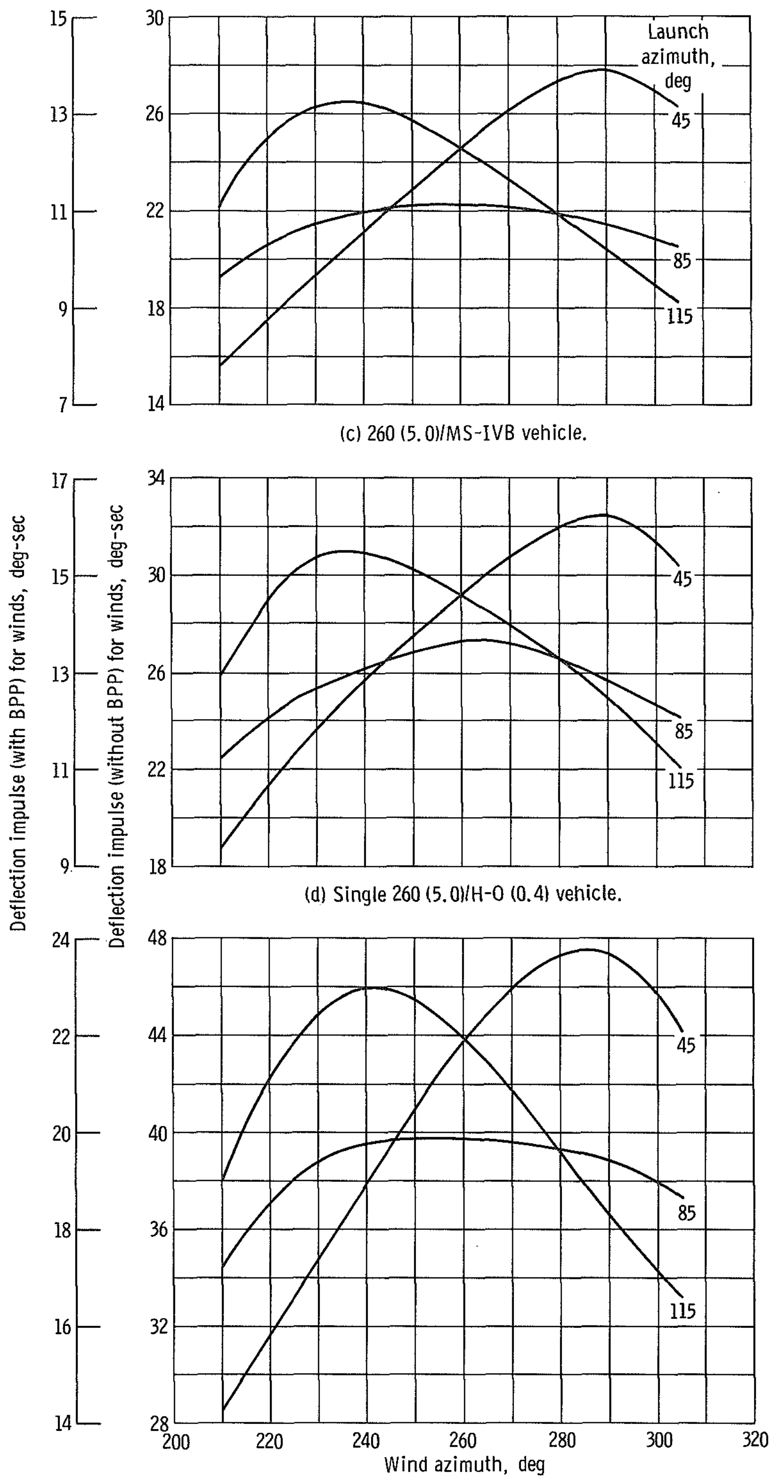


(a) 260 (3.4)/MS-IVB vehicle.



(b) 260 (1.7)/MS-IVB vehicle.

Figure 6. - Deflection impulse as a function of wind azimuth. Center of wind plateau, 10.4 kilometers; 90-percent winds. (BPP denotes biased pitch program.)



(c) 260 (5.0)/MS-IVB vehicle.

(d) Single 260 (5.0)/H-O (0.4) vehicle.

(e) Clustered 260 (30.0)/H-O (2.4) vehicle.

Figure 6. - Concluded.

system is at a nozzle expansion ratio of 4.0 which is lower than the assumed gimbal point for the gimbaled nozzle system. Thus, the deflection angles in table III are lower than the corresponding ones in table I. Since the nozzle is fixed for the LITVC system, a misalinement of 0.25° was assumed. This number is representative for LI systems but is influenced by the design of the nozzle. Totals 2 and 3 are determined by using BPP, and the greater of the two values determines the design value of maximum deflection angle needed.

Total deflection impulse requirement. - In order to determine deflection impulse requirements, a different set of wind profiles must be used. This is because the profiles generated by using reference 3 were designed with maximum shear, which results in minimum drift and maximum thrust vector deflection angles for winds. The use of these profiles is applicable for rockets when the engine is gimbaled to obtain TVC capability and maximum deflection angle is the primary consideration. However, for rocket vehicles using LITVC systems, an important consideration is the weight of liquid injectants required. This is a function of the integrated deflection-time profile (deflection impulse) rather than the maximum deflection angle. Thus, the wind profile used to determine LITVC wind requirements was taken from reference 5. The maximum deflection impulse

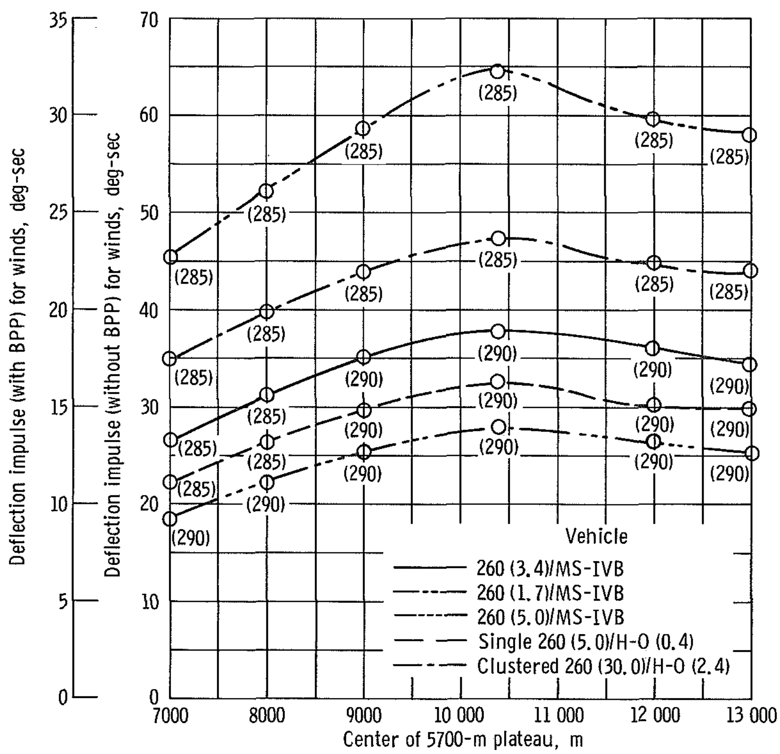


Figure 7. - Deflection impulse as a function of center of 5700 m wind plateau. 90 percent winds; launch azimuth, 45° (wind azimuth indicated in parentheses). (BPP denotes biased pitch program.)

TABLE IV. - LIQUID INJECTION THRUST VECTOR CONTROL SYSTEM DEFLECTION IMPULSE REQUIREMENTS

Vehicle	Deflection impulse, deg-sec								Weight of liquid injectant (with bias), kg
	90-Percent steady-state winds without bias	90-Percent steady-state winds with bias	Misaline-ment (0.25°)	Thrust and weights	Pitch-over	Tailoff	Total[a] 1	Total[b] 2	
	1	2	3	4	5	6			
260 (3.4)/MS-IVB	38	19	36	6	3	-	78	59	10 000
260 (1.7)/MS-IVB	64	32	33	13	3	-	103	71	6 650
260 (5.0)/MS-IVB	28	14	37	5	4	-	70	56	13 300
Single 260 (5.0)/H-O (0.4)	32	16	37	5	3	-	73	57	13 700
Clustered 260 (30.0)/H-O (2.4)	48	24	37	7	4	2	92	68	98 000

[a]Total consists of items 1, 5, and 6 plus root sum square value of items 3 and 4.
[b]Total consists of items 2, 5, and 6 plus root sum square value of items 3 and 4.

for 90 percent winds was found by varying the wind azimuth from 210° to 305°, launch azimuth from 45° to 115°, and the center of the wind profile plateau from 7.0 to 13.0 kilometers. Figure 6 presents results for three launch azimuths and for an altitude of peak wind (center of wind profile plateau) of 10.4 kilometers. Note here that the use of BPP reduces the deflection impulse due to winds by 50 percent.

Figure 7 was derived from figure 6 and other figures of the same type for different altitudes of peak wind. Figure 7 shows that for all five vehicles the deflection impulse for winds peaked at a wind azimuth of about 290° and an altitude of peak wind of 10.4 kilometers. The launch azimuth in all cases in figure 7 was 45°. The reason for the similarity is that all the vehicles had nearly the same nominal trajectory. Table IV presents the deflection impulse breakdown for a LITVC system. The thrust and weight dispersion was calculated by using the results presented in reference 1. This value is root sum squared with the misalinement requirement (0.25° times the total flight time) and added to the deflection impulse due to winds. The deflection impulse for pitchover was determined by multiplying the value for pitchover from table III by 5 seconds. For the clustered vehicle, an additional requirement of 2 degree-seconds resulted from unbalanced thrust during tail-off. The derivation of this requirement will be discussed later. To determine the weight of liquid injectant required, a nitrogen tetroxide (N_2O_4) system with overall effective side specific impulse of 275 seconds was assumed.

Figure 8 shows the thrust vector deflection angle needed to trim the vehicle for a LITVC system. The wind profile assumed in figure 8 was the one resulting in the largest deflection impulse for 90 percent winds. The bias through the whole flight is due to the root sum square of the thrust and weight dispersion and the misalinement (a bias of 0.26° for the reference vehicle). Breaking the figure into segments results in

0 to 10 seconds	Bias value
10 to 15 seconds	Bias value + pitchover requirement
15 to 90 seconds	Bias value + high wind requirement
90 to 120 seconds	Bias value + high altitude wind and drift requirement (as discussed in ref. 4)
120 Seconds to end[a]	Bias value

[a]For the clustered vehicle, this also includes the effect of thrust unbalance during tail-off.

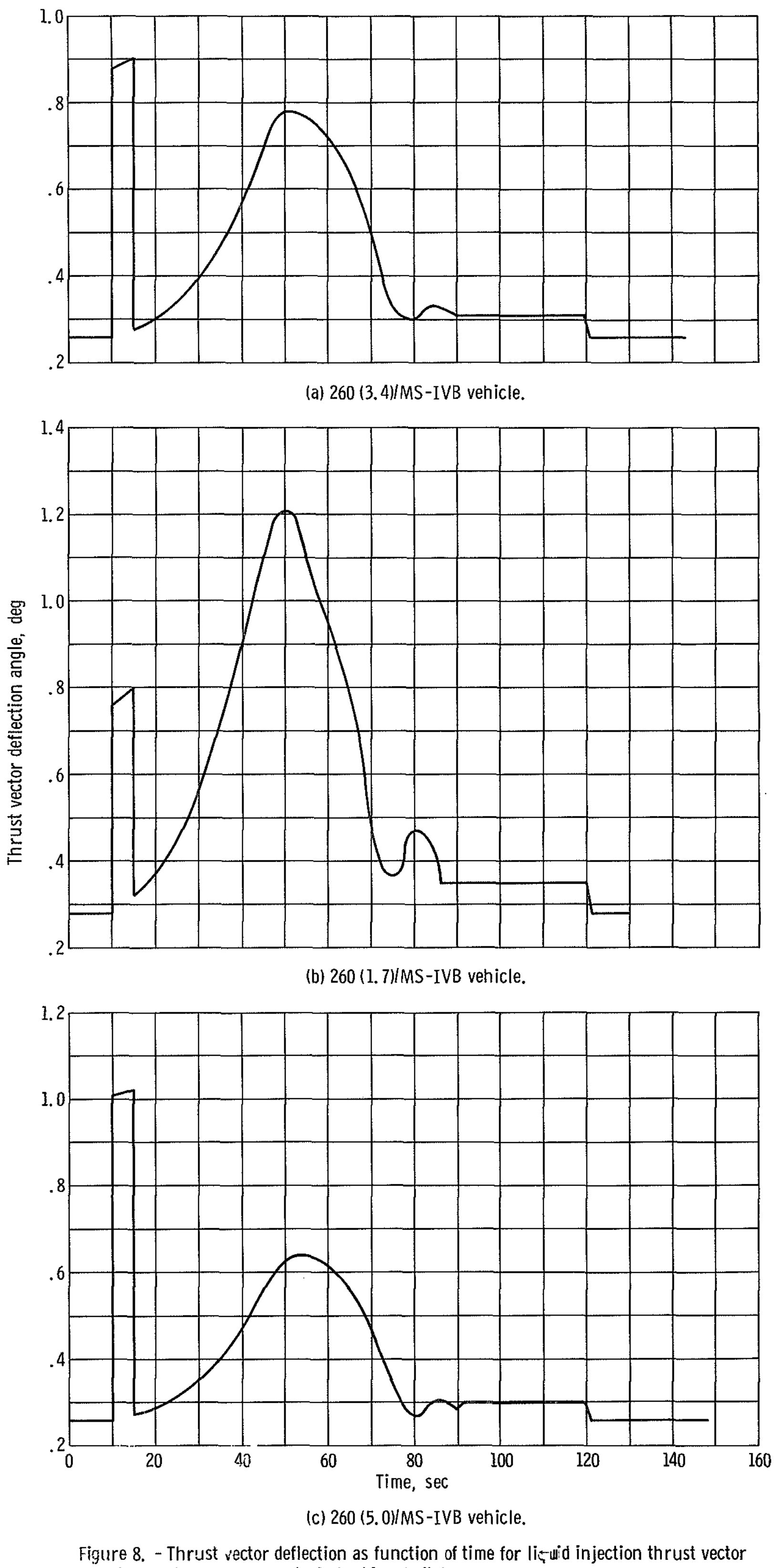
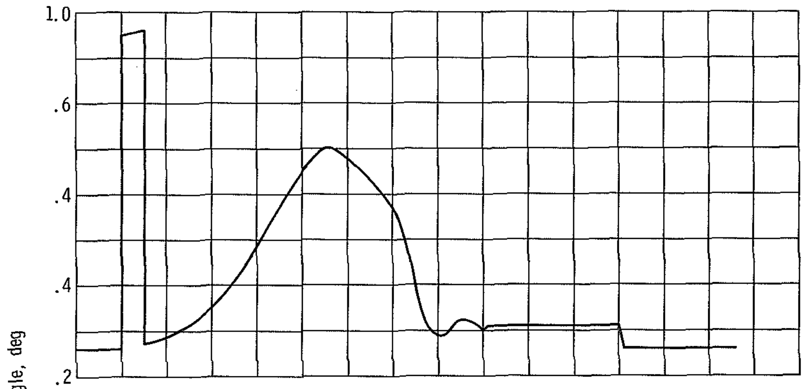
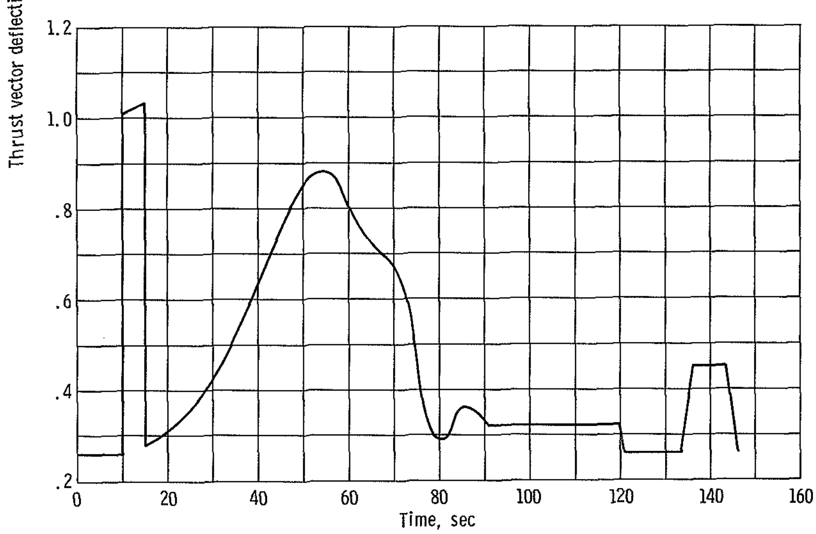


Figure 8. - Thrust vector deflection as function of time for liquid injection thrust vector control system. 90-percent winds; biased pitch programs.



(d) Single 260 (5.0)/H-O (0.4) vehicle.



(e) Clustered 260 (30.0)/H-O (2.4) vehicle.

Figure 8. - Concluded.

Note that the maximum deflection values for the pitchover and high wind regions on figure 8 were less than the corresponding values on table III. This is due to the fact that the wind profile used to derive the data on figure 8 was the one which resulted in generating the greatest deflection impulse and not necessarily the greatest deflection angle.

Figure 9 was derived from figure 8 by taking the area under the curve. A dump schedule is required for unused injectant since a severe payload penalty would result if most of the injectant is carried to first stage separation. A sample dump schedule is shown in figure 9(a). At a given time, if the amount of injectant used is less than the value shown at that time, the difference may be dumped. In figure 9(a), a linear dump schedule is assumed, and 90 percent of the N_2O_4 is dumped.

Use of base fins. - The use of base fins to reduce deflection impulse requirements for the LITVC system was also investigated. Figure 10 shows the deflection impulse for 90 percent winds as a function of fin area ratio. It should be noted that the 50 percent

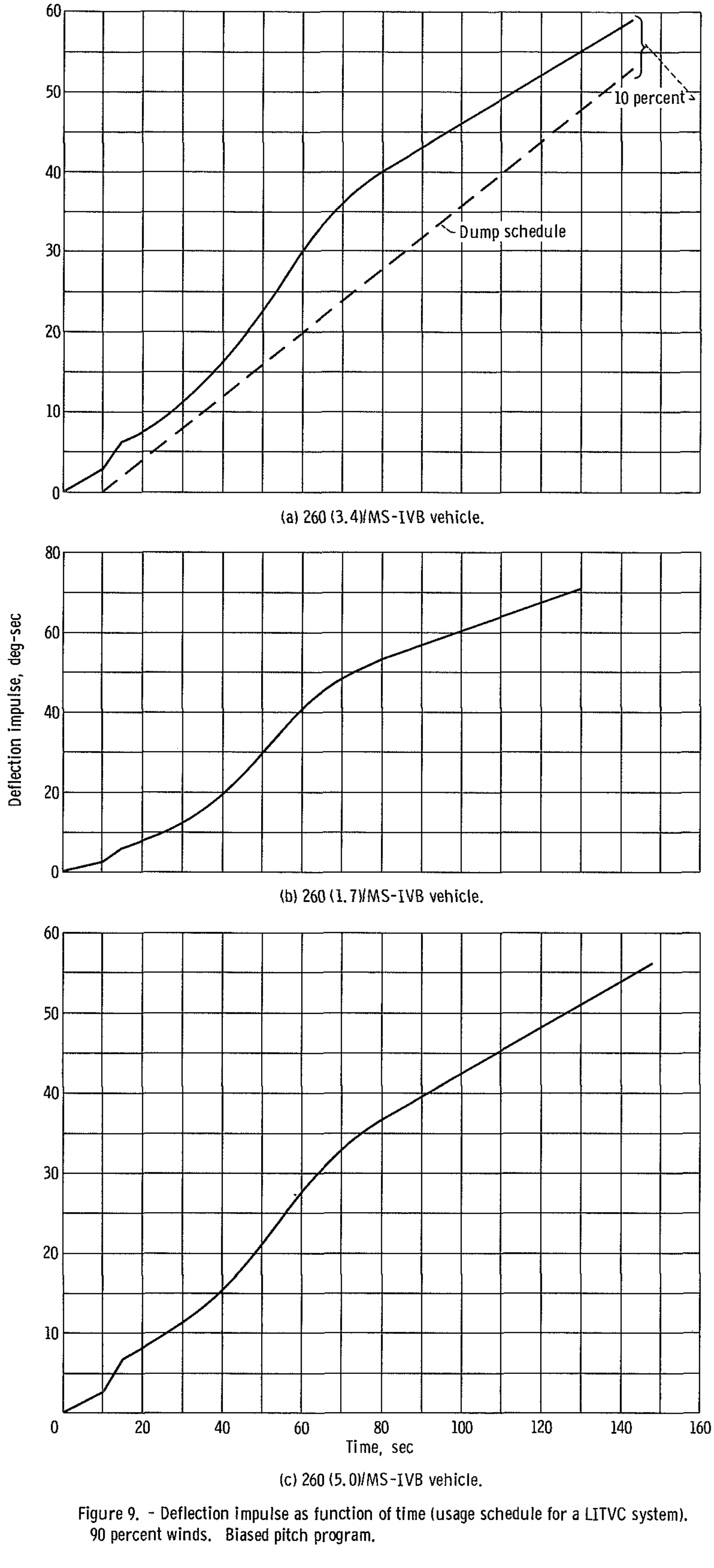
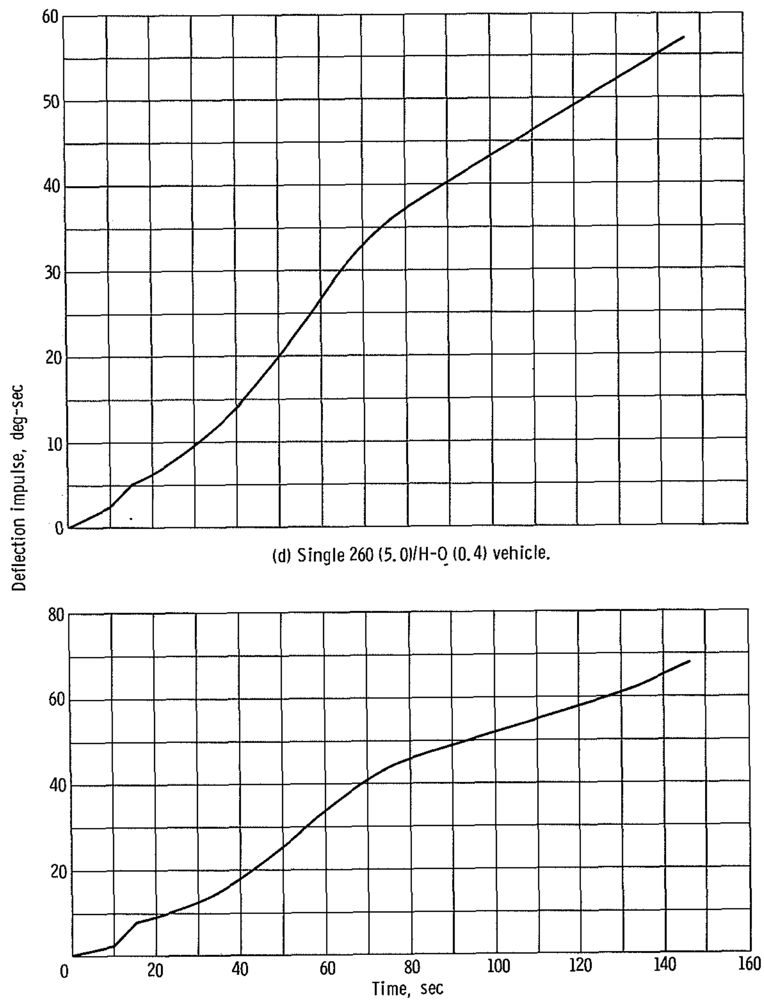


Figure 9. - Deflection impulse as function of time (usage schedule for a LITVC system). 90 percent winds. Biased pitch program.



(d) Single 260 (5.0)/H-O (0.4) vehicle.

(e) Clustered 260 (30.0)/H-O (2.4) vehicle.

Figure 9. - Concluded.

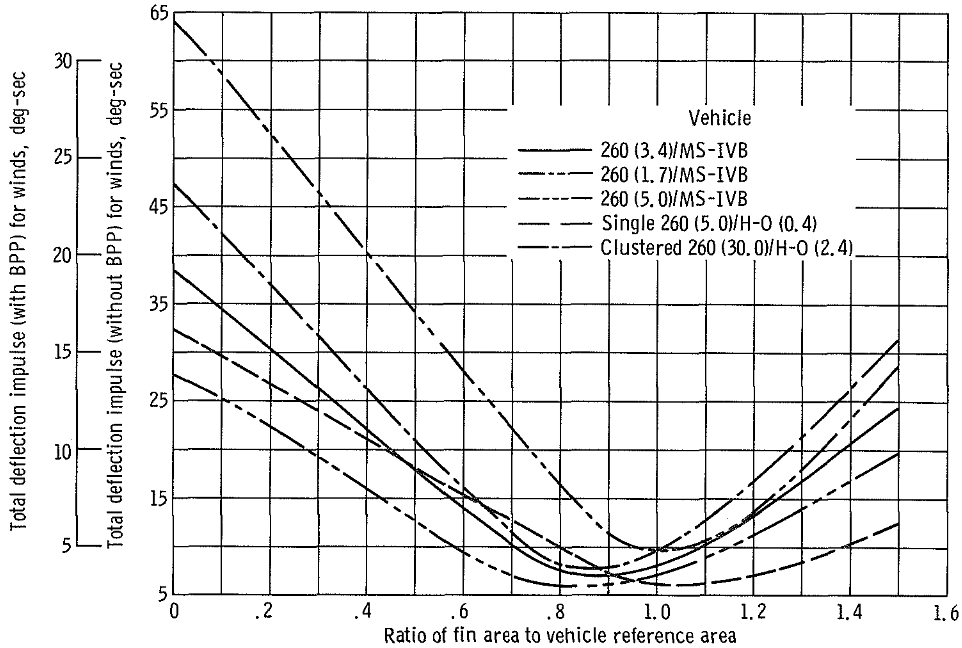
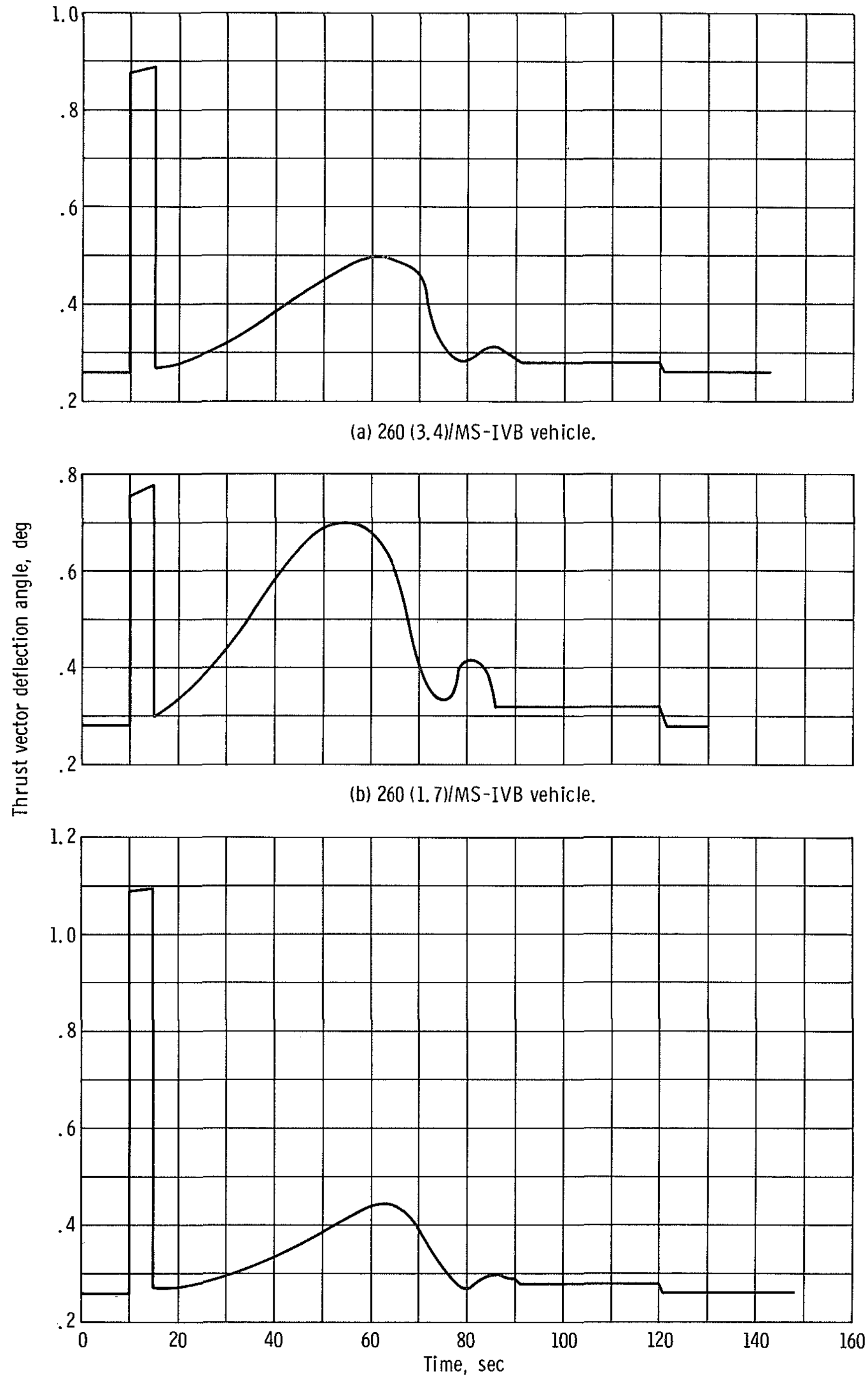


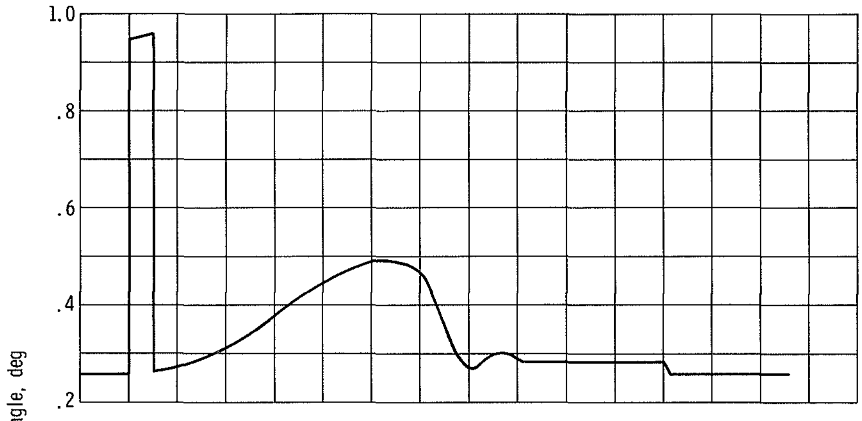
Figure 10. - Total deflection impulse for winds as function of ratio of fin area to vehicle reference area. (BPP denotes biased pitch program.)

reduction in deflection impulse for winds obtainable with BPP also applies when fins are used. Here also, as for the gimbaled nozzle system, there is an optimum fin area ratio which can be used. A fin area ratio of 0.5 was picked for analysis purposes. Figure 11 was then drawn for each vehicle in the same manner as figure 8. The area under the curve in figure 11 was calculated and figure 12 resulted. The effect of the fins can be seen by comparing figures 9 and 12. For example, from figure 12(a), the total deflection impulse needed to trim the reference vehicle is 49 degree-seconds - a reduction of 10 degree-seconds from the reference case with no fins (fig. 9(a)). The reduction in total deflection impulse is relatively small for all vehicles since misalinement rather than winds is the largest effect as seen from table IV. The fins cannot reduce the deflection impulse required for misalinement. Also, for the clustered vehicle, the fins do not reduce the tail-off requirement, since the aerodynamic surface is of little value during tail-off because of the low dynamic pressure.

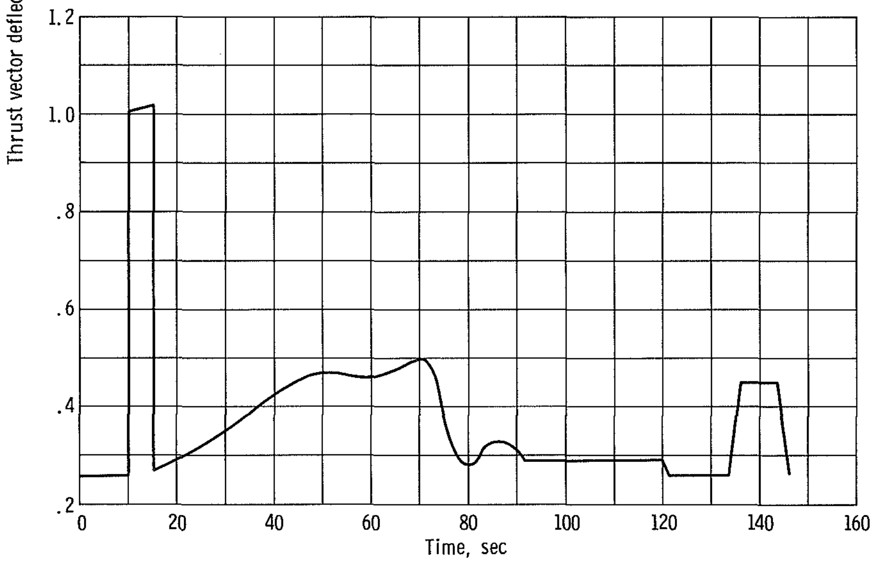


(c) 260 (5.0)/MS-IVB vehicle.

Figure 11. - Thrust vector deflection as function of time for liquid injection thrust vector control system. 90 percent winds; biased pitch program; fin area to vehicle reference area ratio, 0.5.

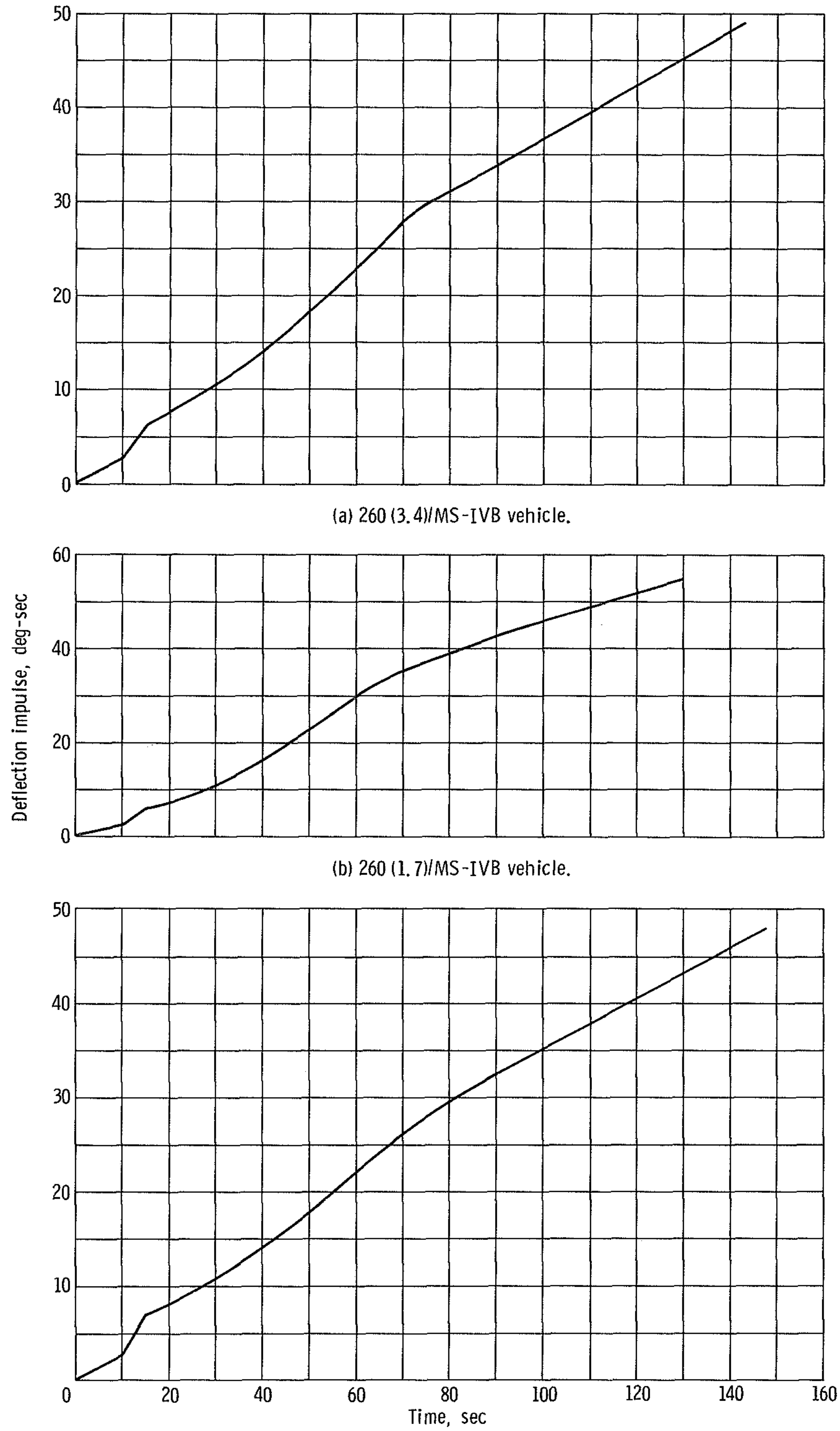


(d) Single 260 (5.0)/H-O (0.4) vehicle.



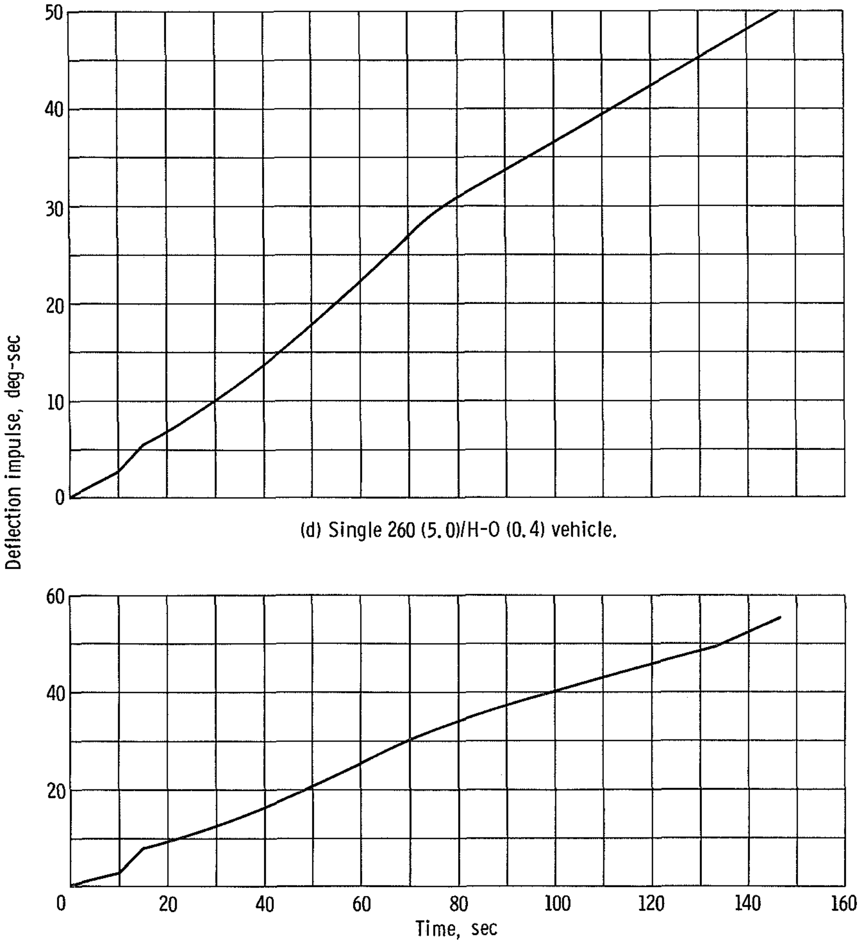
(e) Clustered 260 (30.0)/H-O (2.4) vehicle.

Figure 11. - Concluded.



(c) 260 (5.0)/MS-IVB vehicle.

Figure 12. - Deflection impulse as function of time (usage schedule for LITVC system). 90-percent winds; biased pitch program; ratio of fin area to vehicle reference area, 0.5.



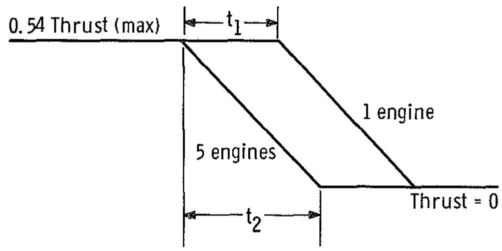
(d) Single 260 (5.0)/H-O (0.4) vehicle.

(e) Clustered 260 (30.0)/H-O (2.4) vehicle.

Figure 12. - Concluded.

TAIL-OFF ANALYSIS

The effect of thrust unbalance during tail-off was also considered for the clustered 260-inch (6.61-m) solid launch vehicle. Tail-off dispersions can result from two sources: (1) a deviation in the web action time and (2) a change in tail-off shape. In this analysis, it was assumed that five motors followed the nominal decay curve while the sixth motor began to decay either 3σ early or late. It was also assumed that all motors have the same tail-off shape. The worst case for this tail-off dispersion mode was found to be when five motors follow the nominal decay curve and the sixth motor begins decay 3σ later. In figure 13, t_1 is the variation in web action time, and t_2 is the tail-off duration. Also, it is assumed that tail-off begins when the thrust level has decreased to 54 percent of its maximum value and then decreases linearly to zero. The value of 54 percent was selected from the thrust profile derived in reference 6. At this time, hard tail-off (referred to as tail-off in this report) begins.



Sketch b

Figure 13. - Thrust tail-off profile for clustered 260 (30.0)/H-O (2.4) vehicle.

Tail-off requirements for a gimbaled nozzle and for a liquid injection TVC system were investigated. The gimbaled nozzle control system will be discussed first. It was decided to assume the peak deflection capability to be that required for effects other than tail-off. Therefore, a value of 1.4° was assumed. Although there is no deflection requirement due to winds during tail-off, it is still necessary to provide for misalinement errors. Since the thrust unbalance and misalinement errors are both assumed to be normally distributed, their root sum square must be equal to the peak deflection capability. Therefore, the maximum thrust vector deflection angle allowed for control of thrust unbalance is about 1.3°.

The deflection angle required to trim the vehicle during tail-off increases with time and can exceed the allowable value for the latter part of tail-off. Therefore, the vehicle is maintained trimmed up to the time the maximum deflection angle is reached. After this time, the maximum deflection angle is used and the vehicle rotates from the nominal attitude. Attitude rate and attitude errors at first stage burnout are plotted against tail-off duration in figure 14. The variation of web action time t_1 ranged from 1 to 3 seconds. In figure 14(a), it is illustrated that attitude rate error decreases as tail-off duration t_2 increases. However, increasing the tail-off duration results in a payload loss. Also, as variation of web action time increases, there is a corresponding increase in attitude rate error. For this study, an attitude rate error limit of 1 degree per second is assumed. This limit is imposed so that large attitude errors do not accumulate during the time between first stage burnout and second stage ignition (5 to 8 sec for typical H-O stages). Observe that for a t_1 of 2.5 seconds or larger, t_2 can be increased to 15 seconds and the attitude rate error is still unacceptable. For a t_1 of 2 seconds, a t_2 of 11 seconds or larger is required for acceptable errors. Similarly, a t_2 of 6 seconds or larger is required for t_1 equal to 1.5 seconds.

Figure 14(b) is the corresponding plot of attitude error at first stage burnout against tail-off duration. Notice that for those t_1, t_2 combinations which result in acceptable attitude rate error, the attitude error is quite small. For example, for t_1 equal to 2 seconds and t_2 equal to 11 seconds, the attitude error is about 2°. Therefore, attitude

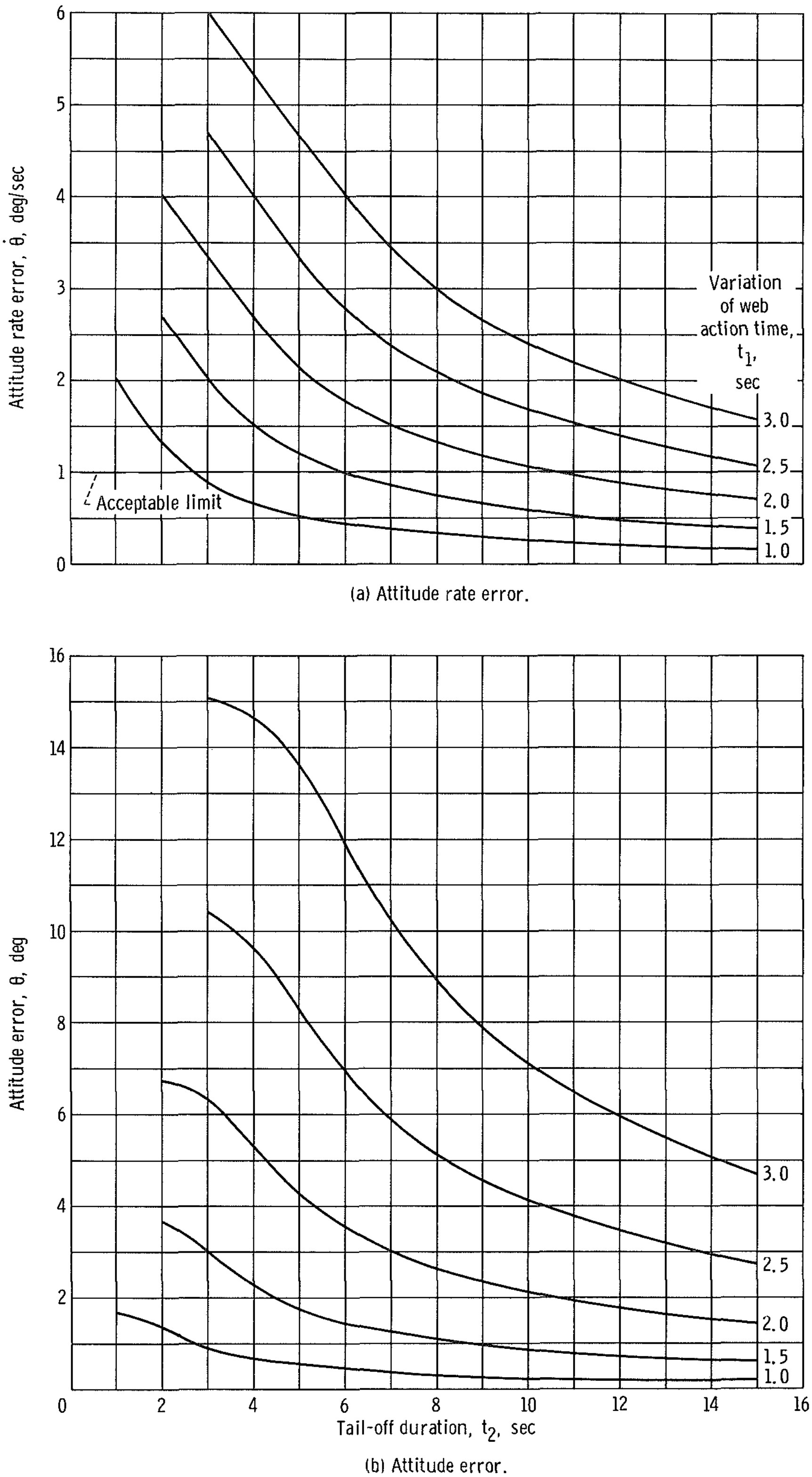


Figure 14. - Effect of unequal solid rocket motor tail-off for clustered 260 (30.0)/H-O (2.4) vehicle. Effect of web action time variation.

rate errors are the constraining quantities for the tail-off analysis.

The variation in web action time is given in reference 7 to be about 2.5 seconds (3σ). Also, tail-off durations are generally designed to be 10 to 15 seconds (ref. 6). Figure 14(a) demonstrated that for these values of t_1 and t_2, tail-off will introduce attitude rate errors which are unacceptable. Therefore, two methods were investigated for reducing these errors.

A convenient method of reducing attitude rate and attitude errors is to cant the nozzles. Figures 15 are plots of attitude rate and attitude errors as a function of t_2 for various cant angles. The variation of web action time was assumed to be 2.5 seconds. Cant angles ranging from 0° to 6° were investigated. Figure 15(a) demonstrates that a cant angle of 2° gives an acceptable attitude rate error for t_2 greater than or equal to 11 seconds. In figure 15(b), it is again illustrated that attitude errors are reasonable for these values of t_1 and t_2.

When nozzle canting is used, a payload loss results because of the reduction in axial thrust. Figure 16 illustrates that payload loss increases as the square of the cant angle. According to figure 15(a), a cant angle of about 2° is required to reduce attitude rate error to an acceptable value. Therefore, a payload penalty of about 320 kilograms results. This should be compared with the nominal payload capability of 410 000 kilograms.

An alternate method investigated for reducing attitude rate and attitude errors was to increase the allowable maximum deflection angle. Figure 17(a) is a plot of attitude rate error, and figure 17(b) is a plot of the corresponding attitude error. The maximum deflection angle was increased from its nominal value of about 1.3° to 2° and 3°. From figure 17(a), it is seen that a deflection angle of about 2.5° is required for acceptable attitude rate errors for a t_2 of 10 seconds. If the t_2 is increased to 15 seconds, the required deflection angle is reduced to about 1.4°. However, a payload loss results from increased values of t_2. Figure 17(b) demonstrates that the corresponding attitude error is acceptable.

Tail-off errors were also investigated for the liquid injection TVC system described earlier. The maximum thrust vector deflection angle available for tail-off is 1.16° (at maximum thrust) as determined from total 3 in table III, using a biased pitch program and allowing for misalinement. However, the deflection angle available during tail-off is larger because of the reduced thrust level. Using this deflection angle, it was found that the liquid injection system can maintain trimmed flight during tail-off for all t_1 and t_2 values of interest. However, the deflection impulse required during tail-off must be added to the total deflection impulse requirement. To compute the tail-off requirement, the minimum deflection angle required to maintain trimmed flight was calculated. For a t_1 of 2.5 seconds and a t_2 of 10 seconds, the deflection impulse requirement was calculated to be 2 degree-seconds.

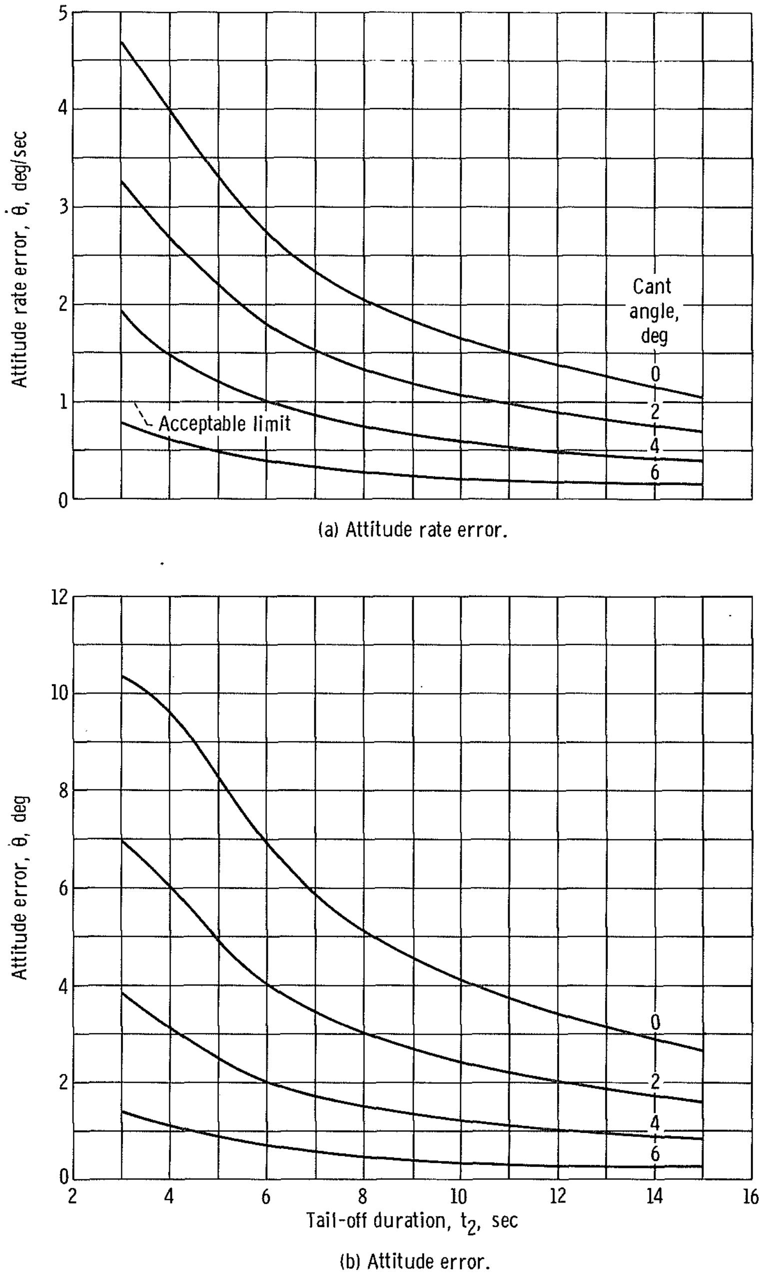


Figure 15. - Effect of unequal solid rocket motor tail-off for clustered 260 (30.0)/H-O (2.4) vehicle. Effect of cant angle. Web action time, 2.5 seconds.

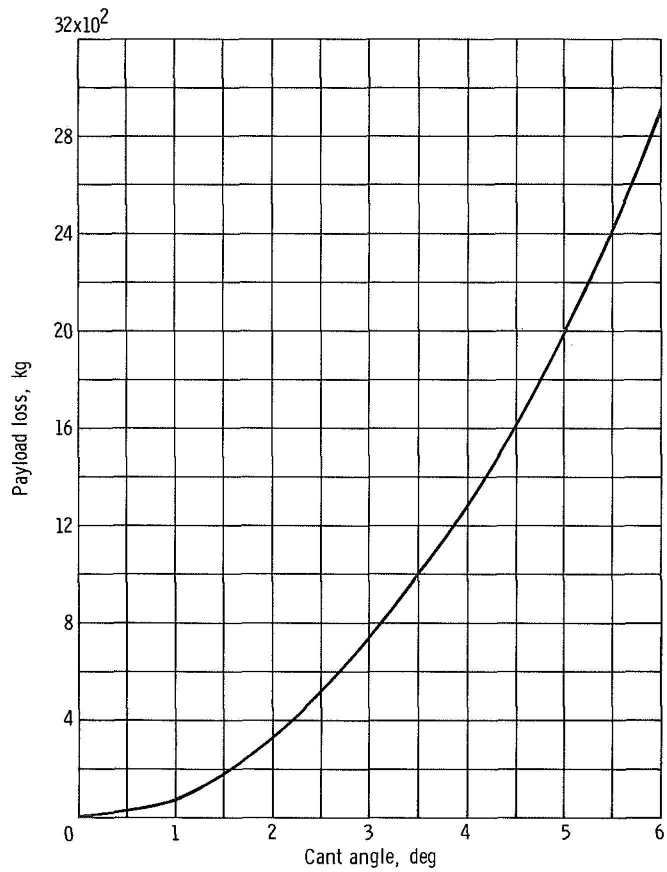
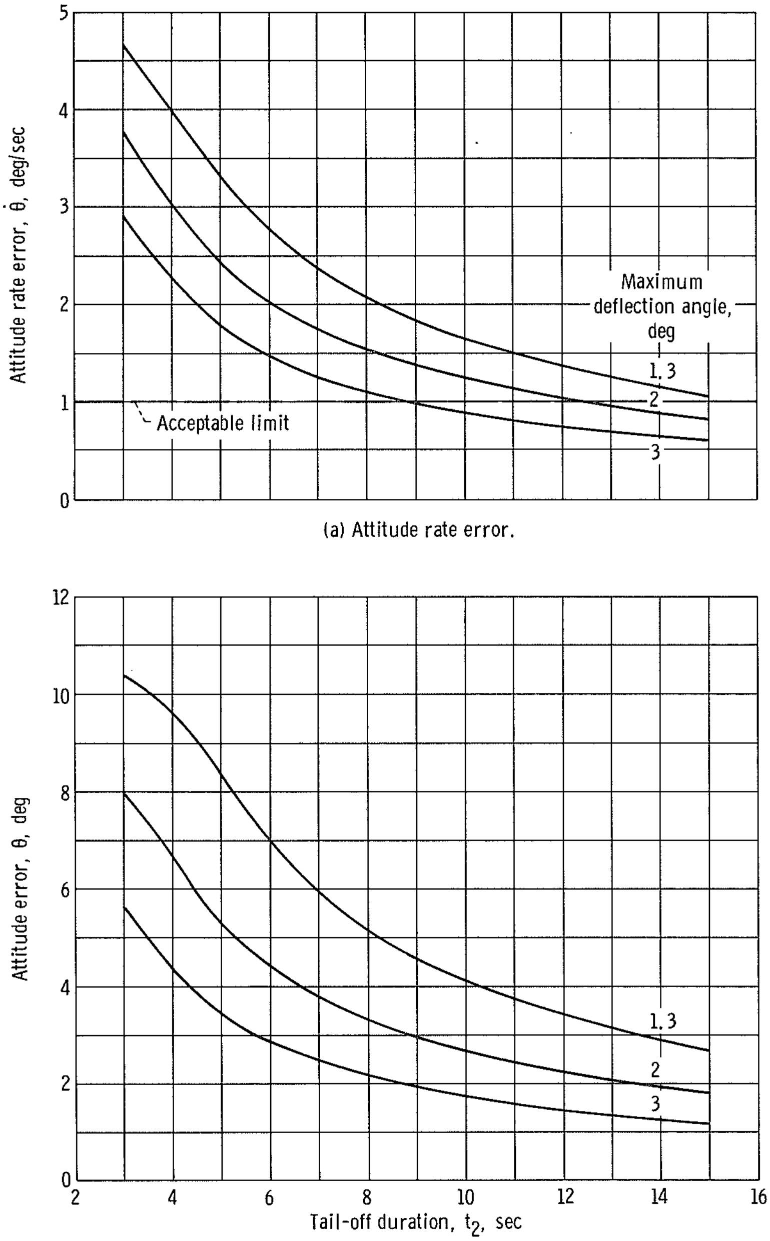


Figure 16. - Payload penalty resulting from solid motor canting for clustered 260 (30.0)/H-O (2.4) vehicle.



(a) Attitude rate error.

(b) Attitude error.

Figure 17. - Effect of unequal solid rocket motor tail-off for clustered 260 (30.0)/H-O (2.4) vehicle. Effect of deflection capability. Web action time, 2.5 seconds.

COMPARISON OF LITVC SYSTEM PERFORMANCE

Finally, the LITVC system alone and the LITVC system used in conjunction with base fins (LITVC system with fins) were compared on the basis of payload loss for 90 percent launch availability. The comparison was made with a vehicle having no TVC system. It was assumed that the fixed weight of the liquid system (fixed weight is weight carried to first stage separation) is proportional to the weight of liquid injectant needed. The constant of proportionality was obtained from the data presented in reference 1 where for the Phase II LITVC system it is 0.285. The payload influence coefficients, as shown in table V, are 1 kilogram of payload lost for every 6.9 kilograms of fixed weight and 1 kilogram of payload lost for every 64.3 kilograms of injectant dumped along the flight for the reference vehicle. In determining these coefficients, a linear dump schedule and a 100-second axial specific impulse were assumed. Also in table V, constants to determine fin weight for the single engine and clustered vehicles are shown. A fin weight of 39 kilograms per square meter was assumed. Table VI shows the LITVC system trade-offs, and payload losses for vehicles both with and without fins for 90 percent winds. The payload loss for the reference vehicle is 698 kilograms for the LITVC system without fins. The effect of the fins (with an area ratio of 0.5) is to save 15 kilograms of payload over the liquid injection only case. However, this number is slightly optimistic since the payload loss due to aerodynamic drag has been neglected. Thus, the addition of fins to a vehicle having a LITVC system and BPP does not seem warranted when 90 percent winds are used.

TABLE V. - PAYLOAD INFLUENCE COEFFICIENTS

AND OTHER CONSTANTS

Vehicle	Dumped weight coefficient, kg/kg	Fixed weight coefficient, kg/kg
260 (3.4)/MS-IVB	-64.3	-6.9
260 (1.7)/MS-IVB	-67.6	-7.8
260 (5.0)/MS-IVB	-65.3	-7.3
Single 260 (5.0)/H-O (0.4)	-61.0	-6.95
Clustered 260 (30.0)/H-O (2.4)	-61.0	-6.95

Vehicle	Fixed weight of fins	
	Area ratio × S_{ref} × Fin density	Total
Single engine	$0.5 \times 34.2\ m^2 \times 39\ kg/m^2$	669 kg
Clustered	$0.5 \times 384\ m^2 \times 39\ kg/m^2$	7500 kg

TABLE VI. - LIQUID INJECTANT THRUST VECTOR CONTROL TRADEOFFS

Vehicle	Fins	Parameter, kg				Payload penalty, kg, due to -				Total payload penalty, kg
		Injectant	Injection	Excess injectant	Fin weight (0.5 S_{ref})	Injectant	Injection system	Excess injectant	Fin weight	
						Dumped	Fixed	Fixed	Fixed	
260 (3.4)/MS-IVB	Without	9 000	2 850	1000	----	140	413	145	----	698
	With	7 535	2 386	837	669	117	348	121	97	683
260 (1.7)/MS-IVB	Without	5 985	1 895	665	----	89	243	85	----	417
	With	4 630	1 470	514	669	69	188	66	86	409
260 (5.0)/MS-IVB	Without	11 970	3 800	1330	----	183	520	183	----	886
	With	10 260	3 250	1140	669	158	446	156	92	852
Single 260 (5.0)/H-O (0.4)	Without	12 330	3 905	1370	----	202	562	197	----	961
	With	10 800	3 420	1200	669	178	493	173	97	941
Clustered 260 (30.0)/H-O (2.4)	Without	88 200	28 000	9800	----	1450	4025	1410	----	6885
	With	71 280	22 600	7920	7500	1170	3250	1140	1080	6640

REQUIREMENTS FOR 95 AND 99 PERCENT WINDS

Since design criteria may show a need for greater launch availability, requirements for 95 and 99 percent winds are presented.

Gimbaled Nozzle System

Total deflection angle. - Table VII shows a comparison of total deflection angle requirements for three wind probabilities. The requirements for the 95 and 99 percent wind probabilities were derived in the same manner as described for the 90 percent winds. As was discussed previously, both pitchover and high wind requirements must be compared. For all the vehicles, both pitchover and high wind requirements increase with peak wind velocity; however, the high wind requirement increases faster causing the design requirement to shift from the pitchover to the high wind region.

Use of base fins. - Table VII can be used to determine if fins would be worthwhile in decreasing deflection requirements for the gimbaled nozzle TVC system for higher wind probabilities. In all cases presented, except for the 260(1.7)/MS-IVB vehicle, the pitchover and high wind requirements, totals (2) and (3), are nearly the same as long as the use of BPP is assumed. Thus, the use of fins to reduce deflection requirements seems worthwhile only for the 260(1.7)/MS-IVB vehicle where the wind requirement is much greater than the pitchover requirement for all wind probabilities.

LITVC System

Total deflection angle. - Table VIII shows the total deflection angle required for 90, 95, and 99 percent winds for the LITVC system. The deflection requirements are lower than for the gimbaled nozzle TVC system because of the assumed increase in control moment arm. Here also, the deflection requirements for both pitchover and high wind regions must be compared to determine the design total deflection angle.

Total deflection impulse. - The total deflection impulse for the three wind probabilities is presented in table IX. The method used to determine the totals for the 95 and 99 percent winds was the same as discussed for the 90 percent wind case previously. The conditions resulting in the maximum deflection impulse requirement for winds were the same for the 90 and 95 percent winds (altitude of peak wind of 10.4 km, wind azimuth of about 290°, and launch azimuth of 45°). However for the 99 percent winds there was a shift in the conditions to a wind azimuth of about 230° and a launch azimuth of 115° while the altitude of peak wind remained the same. From table IX it is evident that the

TABLE VII. - COMPARISON OF THRUST VECTOR DEFLECTION REQUIREMENTS FOR GIMBALED NOZZLE TVC SYSTEM FOR THREE DIFFERENT WIND PROBABILITIES OF OCCURRENCE

Wind, percent		Vehicle									
		260(3.4)/MS-IVB		260(1.7)/MS-IVB		260(5.0)/MS-IVB		Single 260(5.0)/H-O(0.4)		Clustered 260(30.0)/H-O(2.4)	
		Total deflection angle, deg									
		Region									
		Pitchover	Maximum Q	Pitchover	Maximum Q	Pitchover	Maximum Q	Pitchover	Maximum Q	Pitchover	Maximum Q
90	Without BPP	1.31	1.78	1.44	3.44	1.50	1.36	1.34	1.45	1.47	1.82
	With BPP		1.25		2.30		0.98		1.04		1.28
95	Without BPP	1.35	2.05	1.54	4.07	1.52	1.57	1.38	1.69	1.52	2.08
	With BPP		1.42		2.71		1.12		1.20		1.44
99	Without BPP	1.45	2.56	1.77	5.18	1.59	1.93	1.47	2.11	1.62	2.56
	With BPP		1.74		3.43		1.34		1.46		1.74

TABLE VIII. - COMPARISON OF THRUST VECTOR DEFLECTION REQUIREMENTS FOR LITVC SYSTEM FOR THREE DIFFERENT WIND PROBABILITIES OF OCCURRENCE

Wind, percent		Vehicle									
		260(3.4)/MS-IVB		260(1.7)/MS-IVB		260(5.0)/MS-IVB		Single 260(5.0)/H-O(0.4)		Clustered 260(30.0)/H-O(2.4)	
		Total deflection angle, deg									
		Region									
		Pitchover	Maximum Q	Pitchover	Maximum Q	Pitchover	Maximum Q	Pitchover	Maximum Q	Pitchover	Maximum Q
90	Without BPP	1.04	1.44	1.10	2.69	1.19	1.07	1.07	1.18	1.19	1.52
	With BPP		0.99		1.79		0.75		0.82		1.04
95	Without BPP	1.06	1.68	1.13	3.22	1.20	1.25	1.10	1.40	1.23	1.76
	With BPP		1.14		2.14		0.87		0.96		1.19
99	Without BPP	1.14	2.13	1.31	4.10	1.26	1.57	1.17	1.76	1.31	2.19
	With BPP		1.43		2.70		1.07		1.19		1.47

TABLE IX. - COMPARISON OF DEFLECTION IMPULSE REQUIREMENTS FOR LITVC SYSTEM FOR THREE DIFFERENT WIND PROBABILITIES OF OCCURRENCE

Wind, percent		Vehicle				
		260(3.4)/MS-IVB	260(1.7)/MS-IVB	260(5.0)/MS-IVB	Single 260(5.0)/H-O(0.4)	Clustered 260(30.0)/H-O(2.4)
		Total deflection impulse, deg-sec				
90	Without BPP	78	103	70	73	92
	With BPP	59	71	56	57	68
95	Without BPP	84	111	74	78	97
	With BPP	62	75	58	59.5	70.5
99	Without BPP	96	131	84	90	112
	With BPP	68	85	63	65.5	78

greater the peak wind velocity, the greater the deflection impulse required. The use of BPP reduces the wind requirement by 50 percent.

Use of base fins. - It was found that the use of fins to reduce deflection impulse for 90 percent winds would not be worthwhile. However, since the higher peak wind velocities increase the angle of attack, the fins are more effective. Thus, for a fixed fin weight, the reduction in injectant (and the payload saving achieved by using fins) increases with peak wind velocity. The increased payload saving, however, was found to be small.

Tail-Off

Since the winds do not have a first order effect in determining tail-off requirements, an increase in peak wind velocity has a negligible effect on the requirements. However, the increased peak winds necessitate greater deflection angles for the gimbaled nozzle TVC system, which results in more deflection capability available during tail-off. For the LITVC system, the tail-off requirement was assumed to be 2 degree-seconds for the 95 and 99 percent winds also.

CONCLUDING REMARKS

An investigation was made of a family of 260-inch (6.61-m) solid launch vehicles to determine requirements for gimbaled nozzle and liquid injection TVC systems. Both biased and unbiased pitch programs were assumed in all calculations; but BPP's were given prime consideration since they reduce the maximum deflection angle by 40 percent and the deflection impulse for winds by 50 percent for 90 percent launch availability. Representative values of thrust misalinement were assumed in calculating the requirements.

For the reference vehicle, the maximum deflection angle required for 90 percent winds for the gimbaled nozzle system is 1.31° which is the pitchover requirement. If fins are added with an area ratio of 1.0, the peak deflection angle during the high wind region is reduced to 0.72°. However, the pitchover requirement is not reduced appreciably. Therefore, fins do not improve the gimbaled nozzle system requirements appreciably when BPP's are used unless the deflection angle for winds is quite high as for the 260(1.7)/MS-IVB vehicle.

The rate and acceleration requirements for the gimbaled nozzle system were also determined; for the reference vehicle, the rate was 1.3 degrees per second and the acceleration was 4.0 degrees per second squared.

The investigation of a LITVC system showed that a deflection impulse of 59 degree-seconds for 90 percent winds is required for the reference vehicle. If fins are added with an area ratio of 0.5, the requirement drops to 49 degree-seconds. The reduction in deflection impulse is small since thrust misalinement is not affected by the use of fins. Also, the reduction in deflection impulse and, thus injectant weight, is offset by the weight of the fins. The results show therefore that the addition of fins to a vehicle having a liquid injection system and BPP is probably not warranted.

The effect of thrust unbalance during tail-off was also considered for the clustered 260-inch (6.61-m) solid vehicle, for both the gimbaled nozzle and LITVC systems. For the gimbaled nozzle system, attitude rate and attitude errors were found to be unacceptable as a result of thrust unbalance when the peak deflection capability, as required for effects other than tail-off, was assumed. It was shown that a cant angle of about 2° results in acceptable attitude rate and attitude errors. Also, it was demonstrated that by increasing the maximum deflection angle to 2.5°, acceptable errors result for a tail-off duration of 10 seconds.

An investigation of the LITVC system demonstrated that the vehicle can be maintained trimmed during tail-off and the additional deflection impulse required was 2 degree-seconds.

An analysis was also made of TVC requirements for both 95 and 99 percent winds. It was found that as the peak wind velocity increased, both pitchover and high wind deflection requirements increased; however, the high wind requirement increased more quickly than the pitchover requirement and hence became the design requirement. The use of fins to reduce the higher total deflection angle requirements for the gimbaled nozzle system does not seem warranted. Although the fins are more effective at the higher wind velocities, the use of fins to reduce deflection impulse for the LITVC system does not seem worthwhile. Also, tail-off problems are not affected by changing the peak wind velocity. However, due to the higher winds, the deflection requirements for the gimbaled nozzle system are increased, giving more deflection capability at tail-off. For the LITVC system, tail-off requirements remained well within the system capability.

Finally, all the values presented in the report are calculated values without any margin. For an actual design analysis, some design margin should be provided over the calculated values.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 9, 1969,
128-31.

APPENDIX A

SYMBOLS

CG — distance from center of gravity to gimbal station, m

CP — distance from center of pressure to center of gravity, m

C_{N_α} — normal force coefficient per angle of attack, rad^{-1}

D — system characteristic equation

I — moment of inertia, $N\text{-}m\text{-}sec^2$

K — undamped natural frequency of TVC loop, rad/sec

K_I — integral gain constant, sec^{-1}

K_R — attitude rate gain constant, sec

K_θ — attitude gain constant

Q — dynamic pressure, N/m^2

S_{ref} — vehicle reference area, m^2

s — Laplace operator, sec^{-1}

T — thrust, N

t_1 — variation of web action time, sec

t_2 — tail-off duration, sec

α — vehicle angle of attack, rad

αQ — angle of attack times dynamic pressure, $(N\text{-}deg)/m^2$

α_W — wind shear, rad/sec

β — pole which results from the use of integral gain, sec^{-1}

δ — thrust vector deflection angle, rad

$\dot{\delta}$ — thrust vector deflection rate, rad/sec

$\ddot{\delta}$ — thrust vector deflection acceleration, rad/sec^2

θ — vehicle attitude, rad

$\dot{\theta}$ — vehicle attitude rate, rad/sec

θ_p — commanded vehicle pitch attitude, rad/sec

μ_c — vehicle control parameter, sec^{-2}

μ_α — vehicle aerodynamic parameter, sec^{-2}

φ — damping ratio of control loop

ψ — damping ratio of TVC loop

ω_n — undamped natural frequency of control loop, rad/sec

APPENDIX B

USE OF BIASED PITCH PROGRAMS

Statistical analyses of wind soundings indicate that the winds tend to have a preferred direction and speed depending on the particular season and geographic location. These studies also show that the wind velocity against altitude profiles tend to have similar overall shapes. Because of these effects, it is advantageous to use a nominal pitch program designed to give zero angle of attack for the average expected wind sounding. Such a pitch program is called a biased pitch program. Similar programs can be derived for the yaw plane (biased yaw program).

A further reduction in aerodynamic loads can be obtained if a family of biased pitch and yaw programs are derived. Each of these programs is designed to minimize the expected aerodynamic loads for part of the wind sample. Then the user can measure the flight wind prior to the launch and select the pitch and yaw programs which minimize the aerodynamic loads for the wind.

The purpose of this appendix is to derive biased pitch and yaw programs and to determine the possbile reduction in aerodynamic loading, thrust vector deflection requirements, and deflection impulse. The analysis was done for the reference vehicle as defined earlier, and a launch azimuth of 105° was assumed for the study. The BPP's were derived for the month of March.

The results are based on a trimmed vehicle (aerodynamic moments are assumed to be instantaneously canceled by engine gimbaling). The results are presented in the pitch plane; however, similar results of launch availability against alpha times dynamic pressure (αQ) were obtained in the yaw plane.

A simplified analytic procedure was derived for computing BPP, which is based on the analysis in reference 4. This procedure, due to its simplicity, makes it feasible to evaluate large samples of actual wind soundings. The analytic equations also allow the calculations of an optimal biased pitch program (i.e., the one that minimizes aerodynamic loads). In addition, this pitch program is designed to give the nominal burnout altitude and flight path angle.

The BPP's were derived based on a sample of 100 March Rawinsonde wind measurements taken in 1956, 1957, 1958, and 1959. To show the improvement obtained by using a set of three BPP's compared to a single BPP, the winds were grouped according to peak wind velocity, and separate BPP's were derived for winds with peak velocity less than 40.5 meters per second, greater than 40.5 meters per second, but less than 57 meters per second, and greater than 57 meters per second. The single BPP was designed for the complete sample of 100 winds. Figure 18 shows the four different biases derived in the analysis. The nominal pitch program was designed to optimize

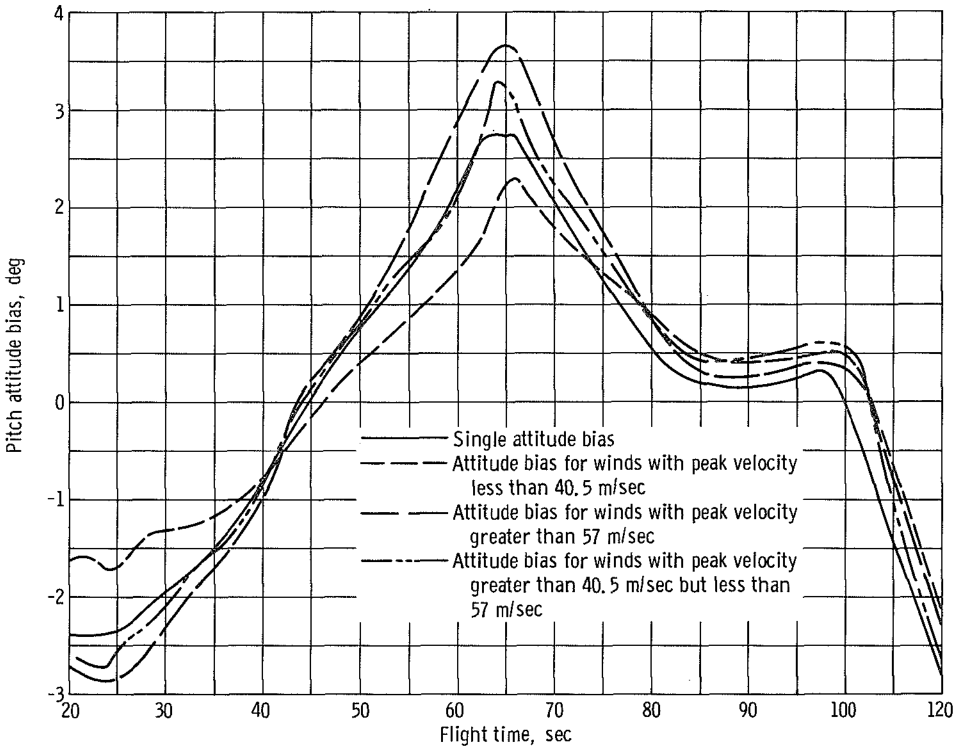


Figure 18. - Optimum attitude bias for month of March.

payload capability for a zero wind, zero angle of attack trajectory.

Figure 19 gives the results obtained by using the bias for maximum wind velocities smaller than 40.5 meters per second. Figure 19(a) gives the launch availability in terms of maximum αQ, which is proportional to compressive aerodynamic loads. Figure 19(b) gives launch availability in terms of maximum thrust vector deflection angle for winds, and figure 19(c) in terms of deflection impulse requirements for winds. Figures 20 and 21 give the same results as above for the biased pitch program with peak wind velocities greater than 40.5 meters per second but less than 57 meters per second and greater than 57 meters per second, respectively. Figure 22 gives a comparison between a single biased and three BPP's.

To illustrate the use of the curves, consider the following case: First, assume that 90 percent launch availability is desired for the month of March. Then from figure 22(a), the maximum αQ is reduced from 224 000 to 124 000 newtons-degree per square meter by using a single BPP, a reduction of 44.7 percent. Using the three BPP's, an additional 4.5 percent can be obtained or a total improvement of 49.2 percent. From figure 22(b), the maximum thrust vector deflection requirement for winds is reduced from 0.78° to 0.46° and 0.45° using one or three BPP's, respectively. The improvement is 41 percent for the single BPP and 42.4 percent for the three BPP's. From figure 22(c), the deflection impulse for winds is reduced by 46.6 percent for a single BPP and by 55.4 percent for three BPP's.

From figure 22, it is evident that this vehicle configuration, and launch availability between 90 and 99 percent, an overall maximum αQ, deflection angle, and deflection impulse for winds reduction of 40 to 60 percent may be obtained by using BPP.

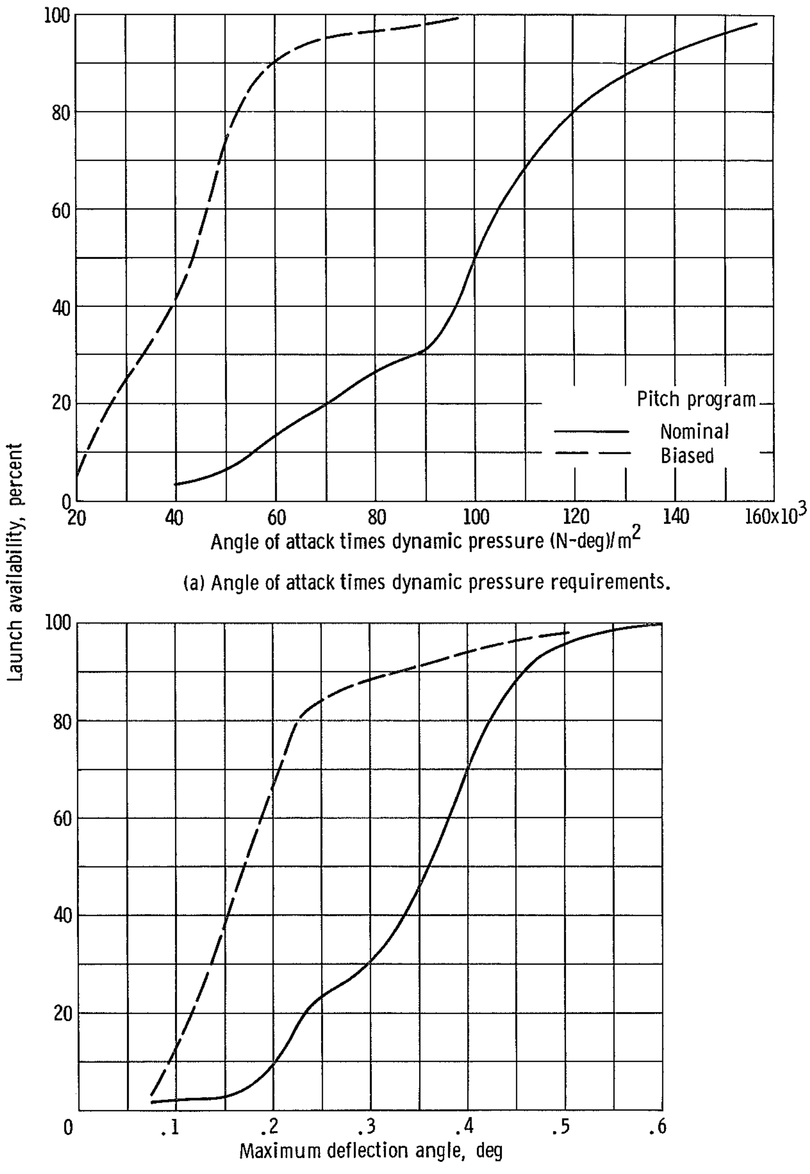
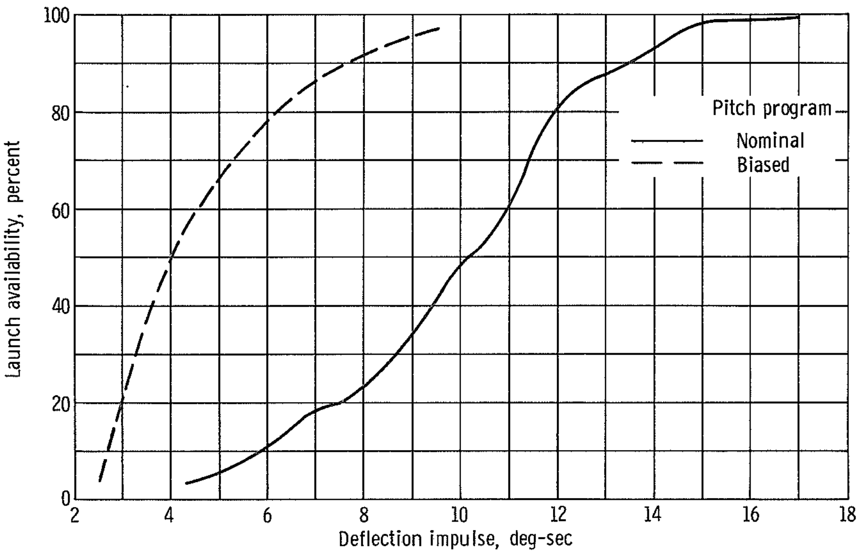
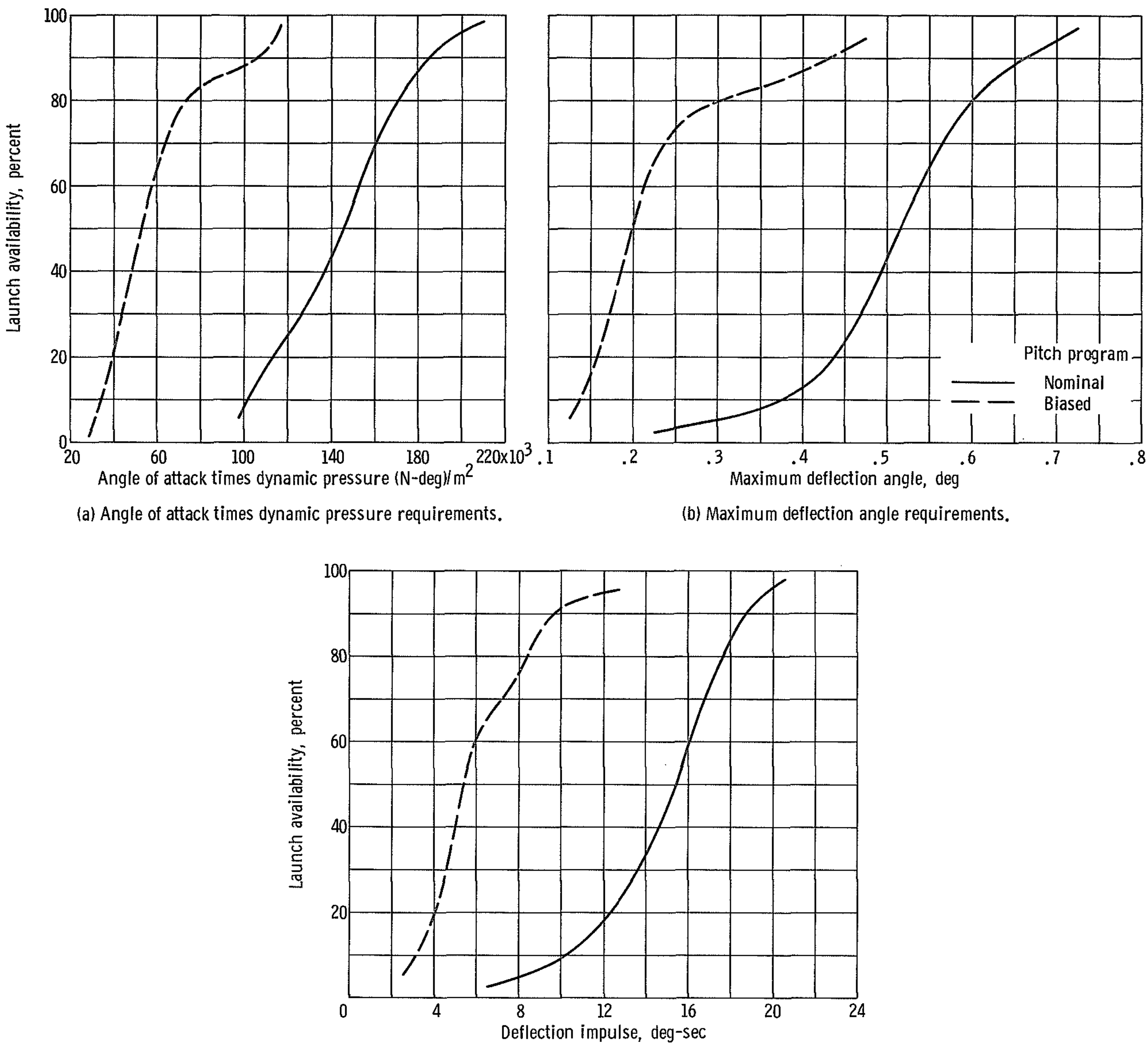


Figure 19. - Launch availability for month of March. Maximum wind speed less than 40.5 meters per second.



(c) Deflection impulse requirements.

Figure 19. - Concluded.



(a) Angle of attack times dynamic pressure requirements.

(b) Maximum deflection angle requirements.

(c) Deflection impulse requirements.

Figure 20. - Launch availability for the month of March. Maximum wind speed less than 57 meters per second, but greater than 40.5 meters per second.

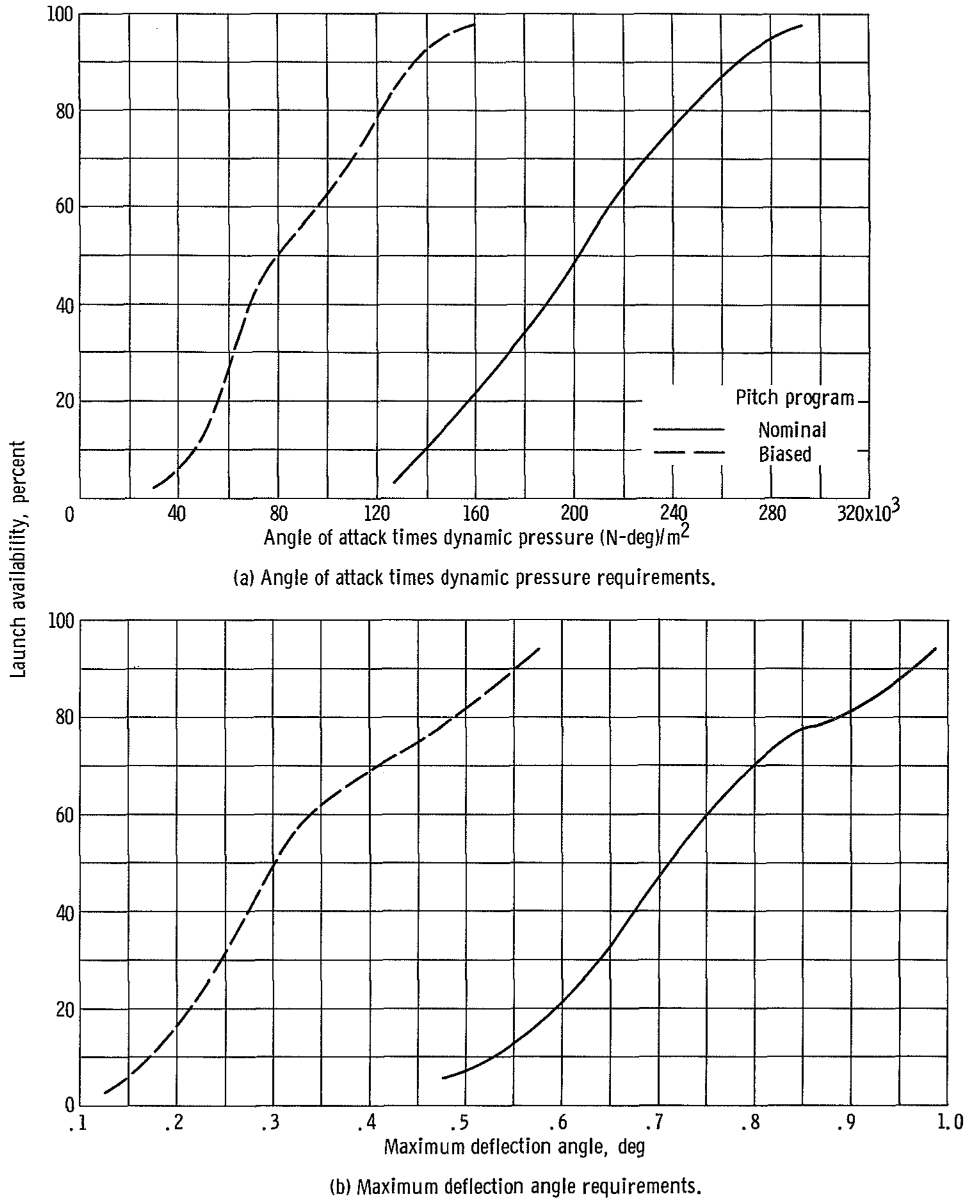
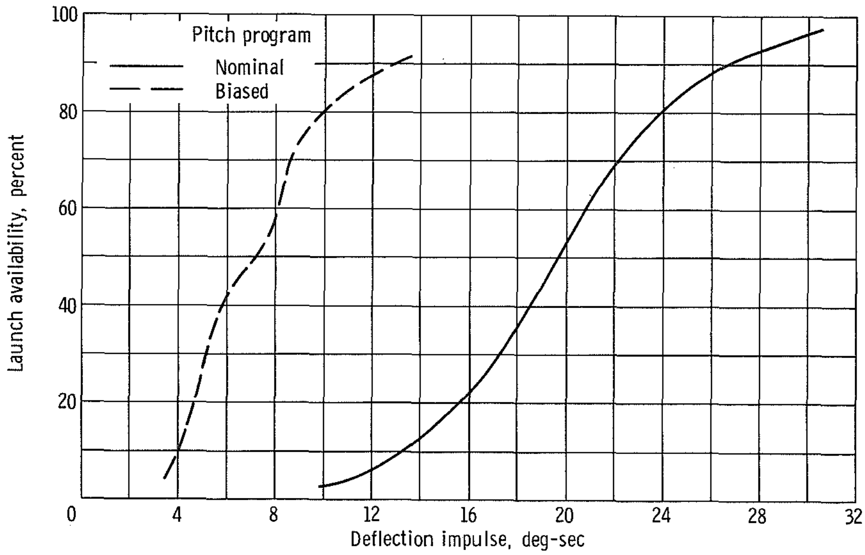
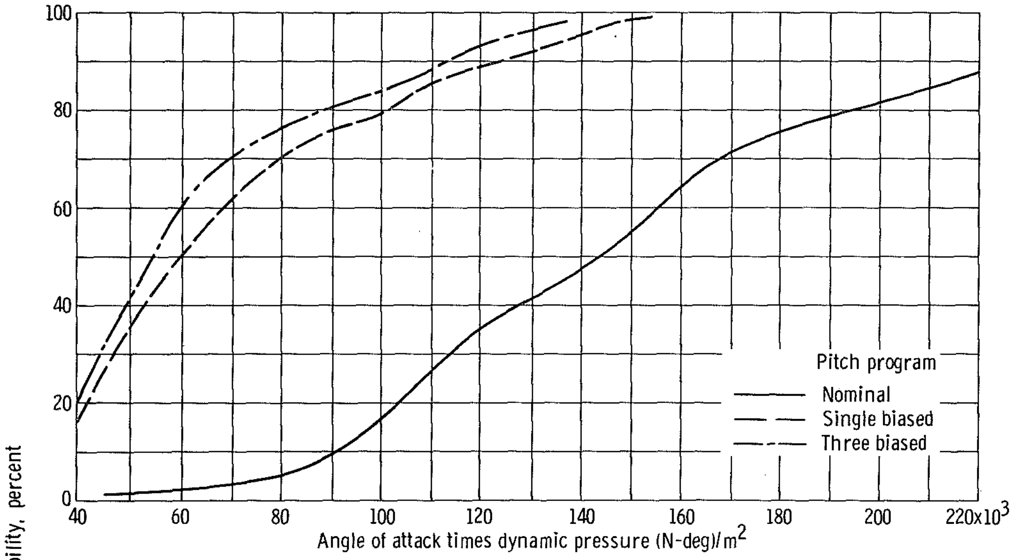


Figure 21. - Launch availability for month of March. Maximum wind speed, greater than 57 meters per second.

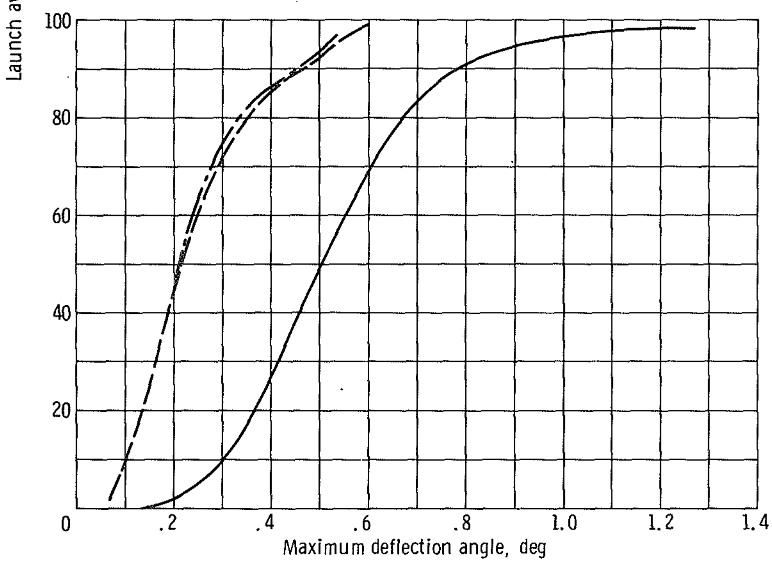


(c) Deflection impulse requirements.

Figure 21. - Concluded.

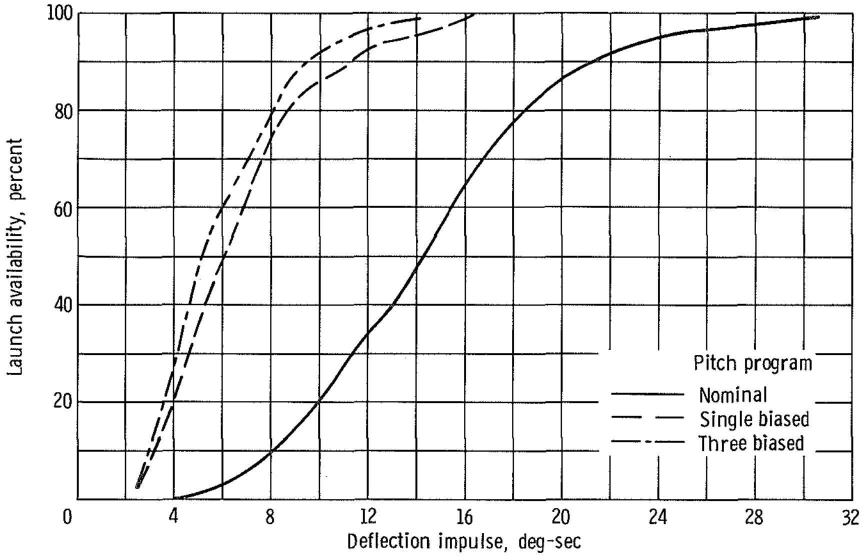


(a) Angle of attack times dynamic pressure requirements.



(b) Maximum deflection requirement.

Figure 22. - Launch availability for month of March, using single or three biased pitch programs.



(c) Deflection impulse requirements.

Figure 22. - Concluded.

APPENDIX C

CALCULATION OF RATE AND ACCELERATION REQUIREMENTS FOR GIMBALED NOZZLE TVC SYSTEM

In order to determine the rate and acceleration requirements for a gimbaled nozzle TVC system, a control system, as shown in figure 23, using integral gain with attitude

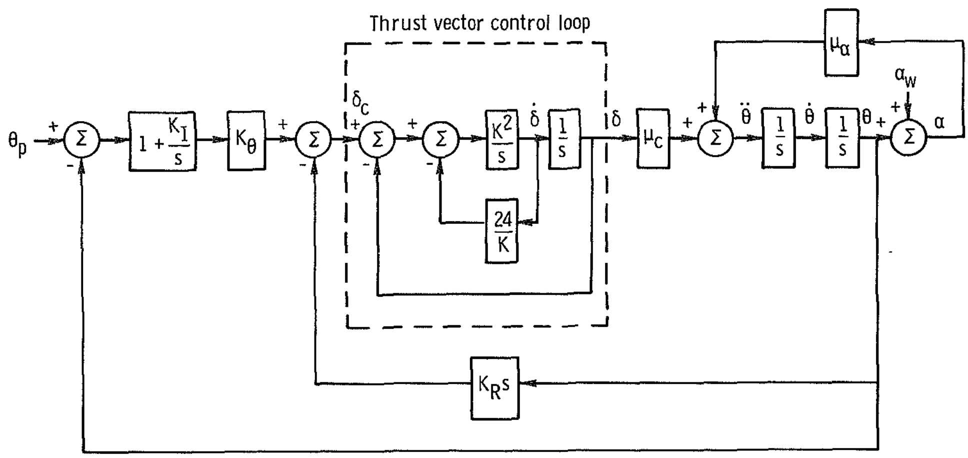


Figure 23. - Third order and fifth order (with thrust vector control loop) control systems for determining rate and acceleration requirements for gimbal nozzle control system.

and attitude rate feedback was used. The control system without the TVC loop has a third order characteristic equation, and the system equations are

$$\ddot{\theta} = \mu_c \delta + \mu_\alpha \alpha \tag{C1}$$

$$\alpha = \theta + \alpha_W \tag{C2}$$

$$\delta = \left(1 + \frac{K_I}{s}\right) K_\theta (\theta_p - \theta) - K_R s \theta \tag{C3}$$

Rewriting (C1) in Laplace notation and substituting the value of α from (C2) results in

$$s^2 \theta = \mu_c \delta + \mu_\alpha \theta + \mu_\alpha \alpha_W \tag{C4}$$

Rewriting equations (C3) and (C4) results in

$$\delta + \left(\frac{\mu_\alpha}{\mu_c} - \frac{s^2}{\mu_c}\right)\theta = \frac{\mu_\alpha}{\mu_c}\,\alpha_W \tag{C5}$$

$$\delta + \left(\frac{K_R s^2 + K_\theta s + K_\theta K_I}{s}\right)\theta = \left(1 + \frac{K_I}{s}\right)K_\theta \theta_p$$

In matrix form, these equations are

$$\begin{pmatrix} 1 & \dfrac{\mu_\alpha}{\mu_c} - \dfrac{s^2}{\mu_c} \\ 1 & \dfrac{K_R s^2 + K_\theta s + K_\theta K_I}{s} \end{pmatrix} \begin{pmatrix} \delta \\ \theta \end{pmatrix} = \begin{pmatrix} \dfrac{\mu_\alpha}{\mu_c}\,\alpha_W \\ \left(1 + \dfrac{K_I}{s}\right)K_\theta \theta_p \end{pmatrix} \tag{C6}$$

Solving for the characteristic equation results in

$$D(s) = \left(\frac{K_R s^2 + K_\theta s + K_\theta K_I}{s}\right) + \frac{s^2}{\mu_c} - \frac{\mu_\alpha}{\mu_c}$$

or

$$\mu_c s D(s) = s^3 + \mu_c K_R s^2 + (\mu_c K_\theta - \mu_\alpha)s + \mu_c K_\theta K_I \tag{C7}$$

However, the characteristic equation must also satisfy

$$\mu_c s D(s) = \left(s^2 + 2\varphi\omega_n s + \omega_n^2\right)(s + \beta)$$

or

$$\mu_c s D(s) = s^3 + (2\varphi\omega_n + \beta)s^2 + \left(2\varphi\omega_n\beta + \omega_n^2\right)s + \beta\omega_n^2 \tag{C8}$$

Equating coefficients in (C7) and (C8) yields

$$\left.\begin{aligned} K_R &= \frac{2\theta\omega_n + \beta}{\mu_c} \\[2ex] K_\theta &= \frac{2\theta\omega_n\beta + \omega_n^2 + \mu_\alpha}{\mu_c} \\[2ex] K_I &= \frac{\beta\omega_n^2}{\mu_c K_\theta} \end{aligned}\right\} \tag{C9}$$

The values of φ and ω_n were determined from reference 1 and were equal to 0.707 and 1 radian per second, respectively. The β was picked to be 1.5 so that overshoot and response time could be optimized. The other constants were calculated by

$$\left.\begin{aligned} \mu_c &= \frac{T \times CG}{I} \\[2ex] \mu_\alpha &= \frac{Q \times S_{ref} \times (CP - CG) \times C_{N_\alpha}}{I} \end{aligned}\right\} \tag{C10}$$

Next, the control system in figure 23 was programmed on the analog computer. The value of the TVC loop damping ratio ψ was set at 0.707 while the natural frequency K was varied from 5 to 20 radians per second.

The results were

(1) The acceleration $\ddot{\delta}$ increased with K.

(2) Coupling between the control and TVC loops decreased as K increased.

(3) The peak deflection angle δ decreased with K, while the rate remained relatively insensitive.

(4) K was chosen at 5 radians per second as a compromise of these considerations.

This procedure was performed at pitchover using the pitch rate defined on the vehicle reference trajectory and at the maximum dynamic pressure region using a wind shear determined in reference 1. Results for both regions are shown in figures 24 and 25 for the reference vehicle and tabulated in table II for all the vehicles. The design value for $\dot{\delta}$ and $\ddot{\delta}$ is the larger of the two values.

Several attempts were made to limit the δ, $\dot{\delta}$, and $\ddot{\delta}$ maximum values. The results are shown in table X. These results show the δ response could be limited without causing the commanded δ, $\dot{\delta}$, and $\ddot{\delta}$ to increase appreciably. However, limiting of the $\dot{\delta}$ and $\ddot{\delta}$ responses caused the commanded values to increase greatly; and, eventually, the system became unstable.

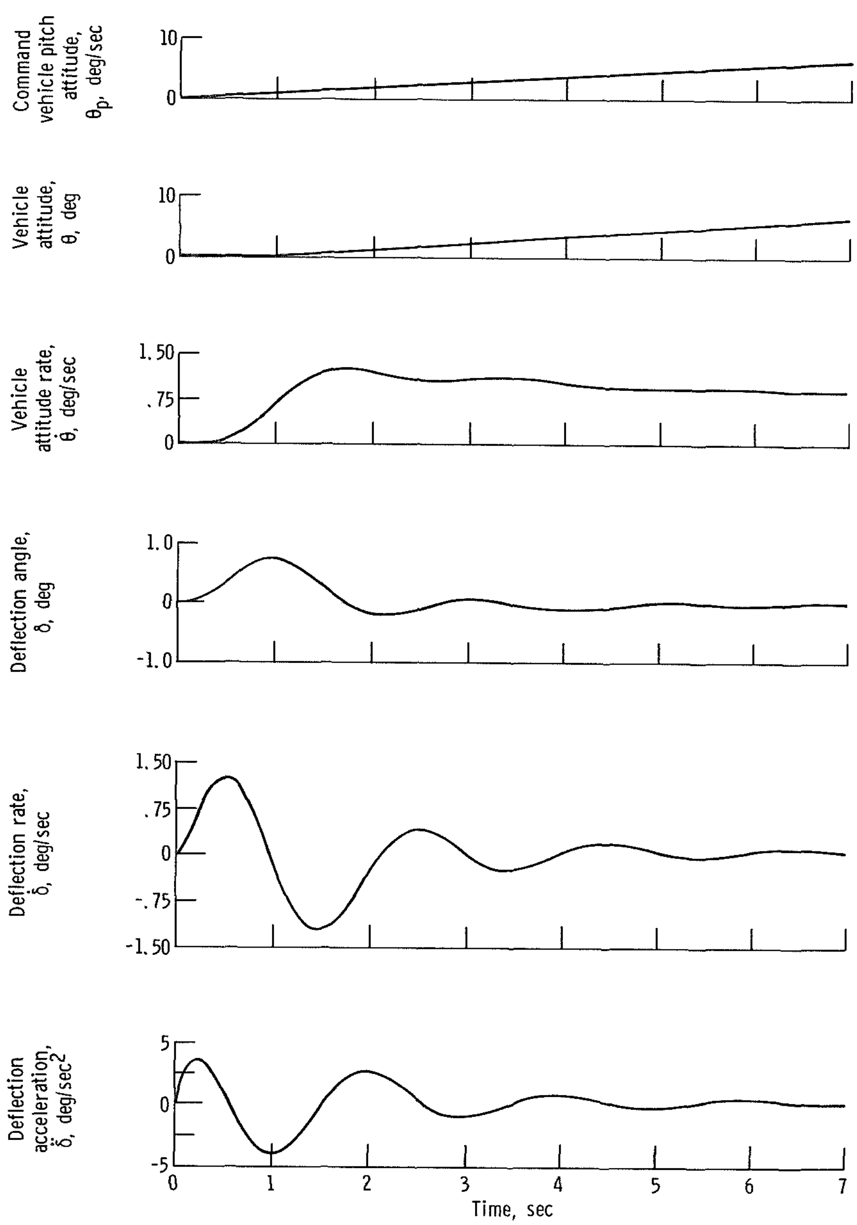


Figure 24. - Control system response for pitchover region for 260 (3.4)/MS-IVB vehicle.

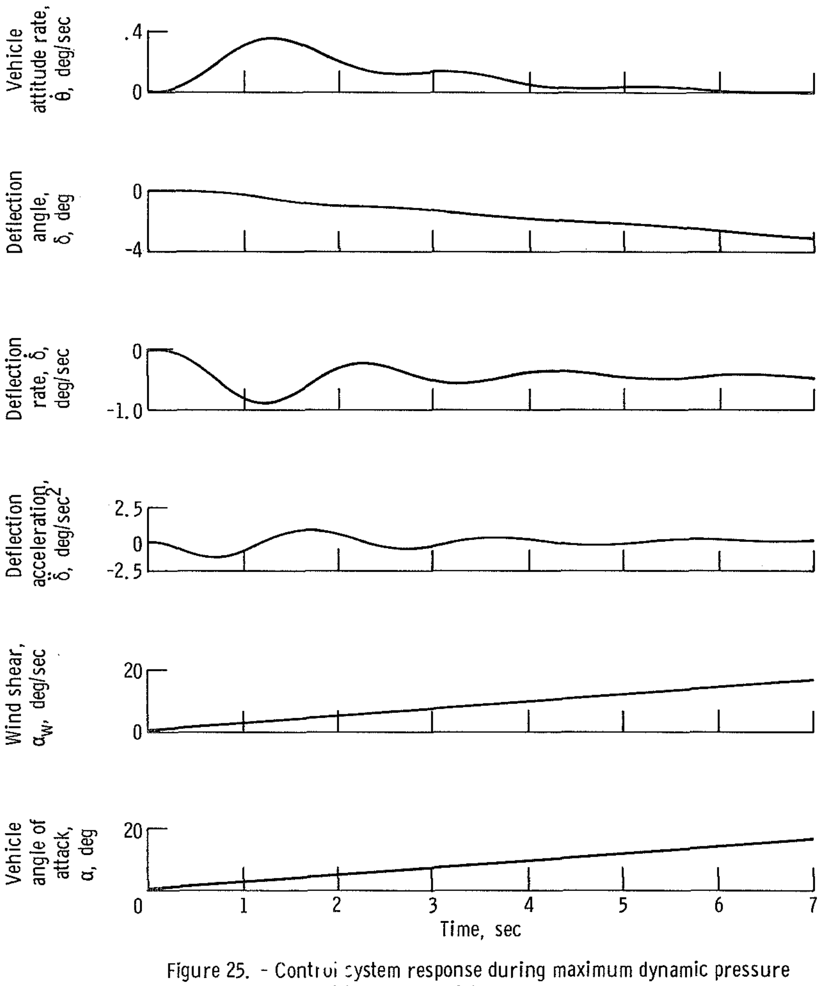


Figure 25. - Control system response during maximum dynamic pressure region for 260 (3.4)/MS-IVB vehicle.

TABLE X. - RATE AND ACCELERATION REQUIREMENTS FOR 260 (3.4)/MS-IVB VEHICLE

Case	Response description	Natural frequency, K, rad/sec	Commanded thrust vector deflection			Limited thrust vector deflection		
			Acceleration, $\ddot{\delta}$, deg/sec^2	Rate, $\dot{\delta}$, deg/sec	Angle, δ, deg	Acceleration, $\ddot{\delta}$, deg/sec^2	Rate, $\dot{\delta}$, deg/sec	Angle, δ, deg
1	θ_p	5	4.0	1.3	0.73	----	---	---
2	α_W	5	1.4	.9	----	----	---	---
3	θ_p	10	7.0	1.4	.56	----	---	---
4		20	13.0	1.5	.46	----	---	---
5		5	7.5	3.2	1.5	----	---	0.5
6		5	5.3	1.8	.75	----	1.2	1.0
7		5	----	(a)	----	----	1.1	
8		20	30.0	2.6	.46	----	1.2	
9			85.0	9	.64	----	1.0	
10			20	1.7	.48	10	1.5	
11			50	2	.6	7.5	1.5	
12			----	(a)	----	5.0	1.5	

[a]Unstable.

Constants	Pitchover	Maximum dynamic pressure region
Damping ratio of thrust vector control loop, ψ	0.707	0.707
Vehicle control parameter, μ_c, sec^{-2}	1.77739	2.41718
Vehicle aerodynamic parameter, μ_α, sec^{-2}	0	0.44045
Integral gain constant, K_I, sec^{-1}	0.4860	0.4212
Attitude gain constant, K_θ	1.756	1.473
Attitude rate gain constant, K_R, sec	1.63949	1.20554
Commanded vehicle pitch attitude, θ_p, deg/sec	0.86	0
Wind shear, α_W, deg/sec	0	2.4

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