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A WIND PROFILE FOR GENERATING CONTROL REQUIREMENTS FOR ROCKET VEHICLES USING LIQUID-INJECTION CONTROL SYSTEMS

by Carl J. Daniele and Fred Teren

Lewis Research Center
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ABSTRACT

A synthetic wind profile with a plateau 5700 meters in width and which drops linearly from this plateau to zero wind velocity at zero altitude and to zero wind velocity at 20-km altitude was found to be the best fit of the type investigated to ten real winds with 90 to 95 percent peak wind velocities measured at the Eastern Test Range. Deflection-impulse requirements were obtained by using this new profile. These requirements were compared to those obtained for the ten real winds for five typical solid launch vehicles, and good agreement was obtained. To illustrate the use of the new synthetic profile, thrust-vector control (TVC) injectant requirements were then calculated for the five launch vehicles for 99 percent winds.

A WIND PROFILE FOR GENERATING CONTROL REQUIREMENTS FOR ROCKET VEHICLES USING LIQUID-INJECTION CONTROL SYSTEMS

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SUMMARY

A general synthetic wind profile was developed for the calculation of deflection-impulse requirements for rockets with liquid-injection thrust-vector control systems.

A general wind shape was assumed which had a wind velocity plateau of arbitrary width and which drops linearly from this plateau to zero velocity at altitudes of 0 and 20 kilometers. The width of the plateau was established by obtaining a best fit to ten real wind profiles with 90 to 95 percent peak wind velocities measured at the Eastern Test Range (ETR). The plateau altitude and wind velocity were varied for each real profile to obtain a best fit.

Deflection-impulse requirements obtained by using the synthetic profile were compared to requirements obtained for the ten real wind profiles for five typical solid-propellant launch vehicles. These requirements were found to be in good agreement.

To illustrate the use of the new synthetic profile, deflection-impulse requirements were calculated for the five vehicles for 99 percent winds. The required weight of liquid injectant for each vehicle was then calculated by assuming a nitrogen tetroxide liquid-injection system.

INTRODUCTION

Thrust-vector-control (TVC) requirements for space boosters depend on the nature of the wind profile that the vehicle must fly through. Typical wind profiles as represented by actual wind soundings can be used when generating TVC requirements. However, since many different wind profiles must be evaluated to provide a reasonable statistical sample, this approach is cumbersome and time-consuming.

A set of synthetic wind profiles that are statistically based on real wind soundings is presented in a work entitled, "Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development, 1966, Revision" by Glen E. Daniels, James R. Scoggins, and Orvel E. Smith of the Marshall Space Flight Center (MSFC). These wind profiles were designed with maximum shear, which results in minimum drift and maximum thrust-vector deflection angles. 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 liquid-injection TVC systems, an important consideration is the weight of the liquid injectants required. This is a function of the integrated deflection-time profile (deflection impulse) rather than the maximum deflection angle.

A preliminary investigation of the deflection-impulse requirements for five typical solid-propellant vehicles launched from ETR has shown that the above-mentioned procedure for generating synthetic wind profiles does not yield a good estimate of deflection-impulse requirements. Thus, the purpose of this report is to determine if a different treatment of real wind data would yield wind profiles more suitable to estimation of deflection angle.

The probability of occurrence for these synthetic winds has been established by using tables of peak wind velocity as a function of altitude, azimuth, and frequency of occurrence. These tables are presented in a work entitled, "Directional Wind Component Frequency Envelopes, Cape Kennedy, Florida, Atlantic Missile Range," by Orvel E. Smith and Glenn E. Daniels of MSFC.

The comparison of the synthetic and real deflection-impulse requirements was performed on five typical solid-propellant vehicles. The results include a comparison of deflection-impulse requirements obtained for the real and synthetic wind profiles for the launch vehicles studied. Also, the average and root-mean-square (rms) percentages of error are presented for the derived wind shapes. To illustrate the use of the new synthetic profile, deflection-impulse requirements were determined for 99 percent winds for each vehicle by using the new synthetic wind profiles selected along with the MSFC peak wind velocities. The deflection-impulse requirements for 99 percent winds (i.e., the peak wind velocities are not exceeded more than 1 percent of the time in the windiest month) were then related to injectant weight requirements for a liquid-injection TVC system.

ANALYSIS

Calculations of deflection-impulse requirements have revealed the need for a different synthetic wind model. For example, a 99 percent MSFC synthetic wind, as obtained from the previously mentioned works of Daniels and Smith, gave a deflection impulse much smaller than that resulting from a real wind with a lower peak wind velocity. A representative MSFC synthetic wind profile is shown in figure 1. Specifically, a typical high-velocity real wind from a work entitled, "FPS-16 Radar/Jimsphere Wind Data Measured at the Eastern Test Range," by J. R. Scoggins and M. Susko (March 9,

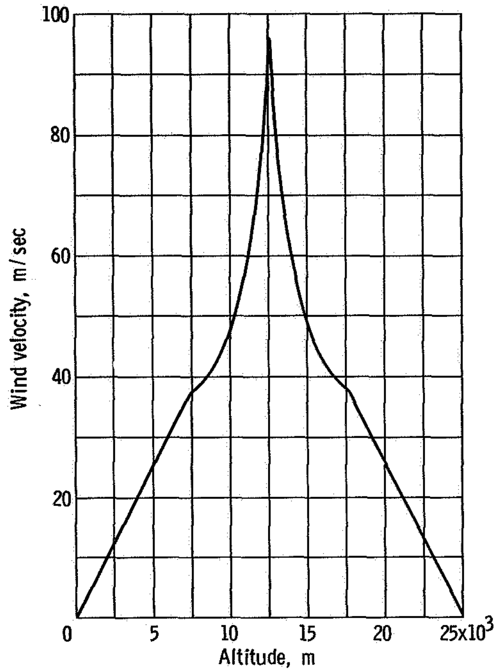


Figure 1. - Synthetic wind velocity profile for 99 percent wind.

1965, No. 1639) gave a deflection-impulse requirement of 41.22 degree-seconds for a typical solid propellant vehicle. This wind had only a 95 percent peak wind velocity, based on data from the work by Smith. However, a 99 percent synthetic wind derived from the works of Daniels and Smith with the same vehicle launch azimuth and a wind azimuth which was an average of the real wind azimuth profile gave a deflection impulse of 34.13 degree-seconds for the same vehicle. Thus, the need for a different approximation is evident.

These results and all other results presented in this report were obtained by using a simplified approximate procedure for calculating deflection requirements. This procedure is presented in detail in appendix B, along with a comparison of the approximate results with detailed 6-degree-of-freedom calculations.

In developing the new method, ten real winds with the greatest magnitude and duration of peak wind velocity were selected from the work of Scoggins. A simplified wind shape was then developed which best fit these ten wind profiles. Three variations of the simplified wind shape were studied, and the resulting deflection-impulse requirements for each were compared with the real wind requirements. The best of the three approximations was chosen from this comparison.

The comparison of the synthetic and real deflection-impulse requirements was performed on five typical solid-propellant vehicles. The first two vehicles consisted of a single 260-inch solid motor for the first stage and the SIVB second stage (ref. 1) with two different payloads, the Apollo payload (command module, service module, and Lunar Excursion Module (LEM) adapter) and the Extended Voyager. The third vehicle studied, referred to as the SSOPM, consists of a booster stage with seven 260-inch (6.61-m) solid motors and a solid-propellant second stage. This vehicle also includes an orbital propulsion module (OPM) plus the payload. The final two vehicles consisted of one 300-inch (7.61-m) solid motor with a cryogenic (hydrogen-oxygen) second stage, and a clustered version of this vehicle with six motors in both first and second stages. The clustered vehicle and the SSOPM are designed to deliver 450 000 kilograms of payload to a 185-kilometer circular orbit. The five vehicles are shown in figure 2.

The wind profile developed is not a 99 percent wind profile, but rather a typical wind shape for real winds ranging from 90 to 95 percent. This wind shape was used in conjunction with MSFC peak wind velocities from the work by Smith. The final form of the profile was determined by how well it agreed with the real winds used in given deflection-impulse requirements for the five launch vehicles.

In order to determine the proper form for the new synthetic wind profile, the ten most severe winds from the standpoint of duration and magnitude of peak velocity were selected from the work of Scoggins. The corresponding wind numbers are 1639, 1801, 1654, 1655, 1657, 1662, 1721, 1735, 1706, and 1272-5. For these winds, the maximum

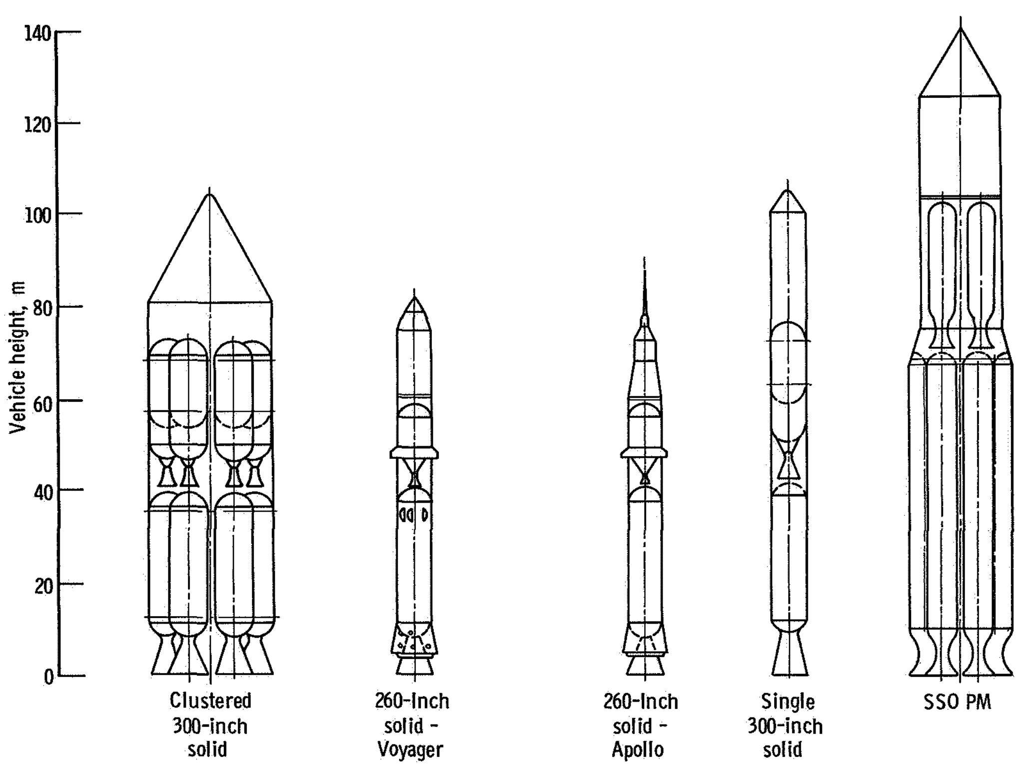


Figure 2. - Launch vehicles used in determining synthetic wind profile.

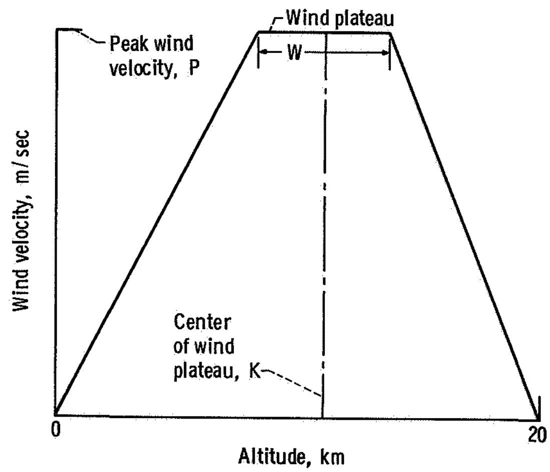


Figure 3. - Synthetic wind profile.

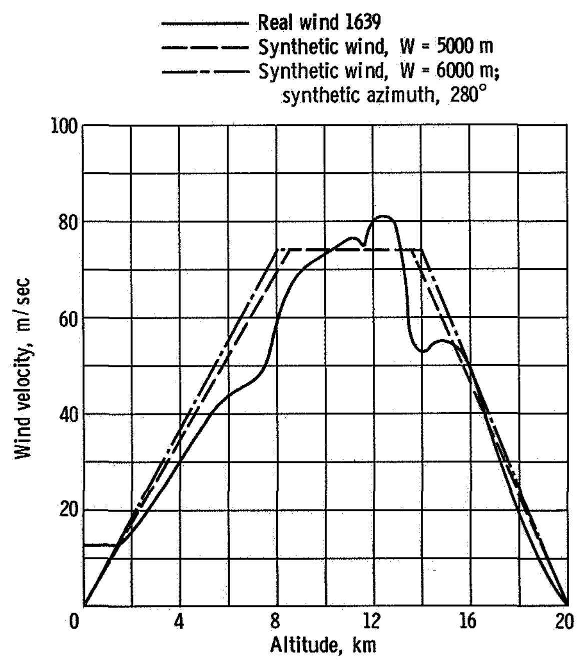


Figure 4. - Comparison of synthetic and real wind profiles.

wind velocity persisted over a range of altitudes of 5 to 6 kilometers. Also, the wind profiles generally start with low velocity at low altitude, then rise to some velocity plateau and subsequently decrease to low velocity at an altitude of about 20 kilometers. Figure 3 shows the general synthetic wind profile derived. Based on these data, two synthetic profiles were tested; the first having a wind plateau of 5 kilometers (W = 5 km on fig. 3), and the second having a wind plateau of 6 kilometers (W = 6 km on fig. 3). The wind velocity then drops linearly from this plateau to zero velocity at altitudes of 0 and 20 kilometers. The final considerations for these profiles were the positioning of the peaks and the wind azimuths. The ten real winds were examined individually for average maximum wind velocity (P in fig. 3), for the center of the average maximum wind (K in fig. 3), for the center of the average maximum wind (K in fig. 3), and for an average wind azimuth for all altitudes.

Two synthetic wind profiles were constructed for each real wind in this manner. For example, the two synthetic profiles are shown in figure 4 superimposed on the real profile for wind 1639. Both synthetic profiles gave close agreement with the real value of the deflection-impulse requirements as shown in tables I(a) to (e). The rms percentage of deviation was 8.49 percent over the 50 cases tried; and the average percentage of error was 2.39 percent for the profile with the 5-kilometer wind plateau; while for the 6-kilometer wind plateau, the rms percentage of deviation was 8.61 percent, and the average percentage of error was -1.50 percent. The rms percentage of deviation was calculated by using the formula:

$$\text{rms percentage of deviation} = \left[\frac{1}{N}\sum_{j=1}^{N}\left(\frac{\text{Real - Synthetic}}{\text{Real}}\right)^2\right]^{1/2}$$

while the average percentage of error was calculated by using the formula:

$$\text{Average percentage of error} = \frac{1}{N}\sum_{j=1}^{N}\left(\frac{\text{Real - Synthetic}}{\text{Real}}\right)$$

The rms percentage of deviation should be interpreted as a measure of the "variance" between the synthetic wind profiles and typical real winds; that is, deflection-impulse requirements resulting from typical real winds and synthetic winds of the same peak wind velocity should agree to about the rms percentage of deviation, on the average.

The average percentage of error is a measure of the average bias between real and synthetic deflection-impulse requirements. In order to reduce the average percentage of error, another plateau width was attempted. The wind plateau was changed to 5.7 kilometers (W = 5.7 km in fig. 3). The values of P, K, and wind azimuth used for this profile are the same as those used for the previous profiles. The 5.7-kilometer wind plateau synthetic profile superimposed on real wind 1639 is shown in figure 5(a). This profile resulted in an average percentage of error of -0.31 percent, and the rms percentage of deviation was reduced to 8.38 percent as shown in table I.

Thus, the synthetic profile with the 5.7-kilometer wind plateau was selected as the best in giving deflection-impulse requirements. The other nine real winds, along with the synthetic profile for each, are shown in figures 5(b) to (j).

TABLE I. - COMPARISON OF DEFLECTION IMPULSE FOR REAL WINDS AND THEIR CORRESPONDING SYNTHETIC WIND

(a) 260-Inch solid - Apollo vehicle

Wind	Deflection impulse, deg-sec			
	Real wind	Width of synthetic wind plateau, m		
		5000	6000	5700
1639	24.91	27.94	29.02	28.71
1801	15.47	17.07	17.67	17.48
1654	24.48	24.92	25.90	25.62
1655	24.14	23.40	24.33	24.06
1657	24.36	21.93	22.67	22.44
1662	23.02	21.80	22.66	22.41
1721	22.97	22.31	23.06	22.82
1735	24.94	21.89	22.75	22.50
1706	21.86	21.89	22.75	22.50
1272-5	16.23	15.51	16.01	15.86
Average percentage of error		1.34	-2.31	-1.23
rms percentage of deviation		7.57	8.09	7.76

(b) 260-Inch solid - Voyager vehicle

Wind	Deflection impulse, deg-sec			
	Real wind	Width of synthetic wind plateau, m		
		5000	6000	5700
1639	41.22	46.17	47.96	47.45
1801	25.63	28.20	29.16	28.86
1654	40.45	41.17	42.78	42.32
1655	39.86	38.65	40.17	39.74
1657	40.16	36.25	37.45	37.08
1662	38.07	35.99	37.40	37.00
1721	37.98	36.89	38.10	37.72
1735	41.15	36.14	37.55	37.15
1706	36.00	36.14	37.55	37.15
1272-5	26.77	25.48	26.30	26.04
Average percentage of error		1.39	-2.23	-1.16
rms percentage of deviation		7.49	7.99	7.67

(c) SSOPM vehicle

Wind	Deflection impulse, deg-sec			
	Real wind	Width of synthetic wind plateau, m		
		5000	6000	5700
1639	31.20	34.74	36.38	35.86
1801	18.32	20.84	21.71	21.45
1654	30.90	30.84	32.72	31.82
1655	31.00	28.92	30.24	29.83
1657	31.07	26.79	27.91	27.57
1662	28.26	26.75	27.97	27.59
1721	29.17	27.16	28.29	27.95
1735	31.40	26.99	28.23	27.84
1706	28.06	26.99	28.23	27.84
1272-5	20.80	19.07	19.86	19.62
Average percentage of error		3.40	-1.03	0.44
rms percentage of deviation		9.54	9.46	9.22

(d) Single 300-inch vehicle

Wind	Deflection impulse, deg-sec			
	Real wind	Width of synthetic wind plateau, m		
		5000	6000	5700
1639	59.91	65.95	68.62	67.78
1801	34.18	38.81	40.46	39.98
1654	57.92	58.24	60.59	59.85
1655	59.28	54.41	56.61	55.92
1657	58.46	50.29	52.47	51.83
1662	52.34	50.19	52.23	51.58
1721	53.43	50.96	53.21	52.55
1735	57.56	50.62	52.66	52.02
1706	52.26	50.62	52.66	52.02
1272-5	40.09	36.68	38.19	37.76
Average percentage of error		3.04	-0.97	0.25
rms percentage of deviation		9.02	8.89	8.74

(e) Clustered 300-inch solid vehicle

Wind	Deflection impulse, deg-sec			
	Real wind	Width of synthetic wind plateau, m		
		5000	6000	5700
1639	66.77	73.01	75.79	74.92
1801	38.79	44.12	45.83	45.34
1654	64.55	64.97	67.42	66.65
1655	65.14	60.96	63.26	62.53
1657	65.23	56.46	58.68	58.04
1662	58.52	56.18	58.30	57.63
1721	59.67	56.83	59.07	58.43
1735	63.88	56.95	59.10	58.43
1706	58.50	56.95	59.10	58.43
1272-5	45.46	41.31	42.89	42.44
Average percentage of error		2.75	-0.97	0.16
rms percentage of deviation		8.63	8.54	8.40

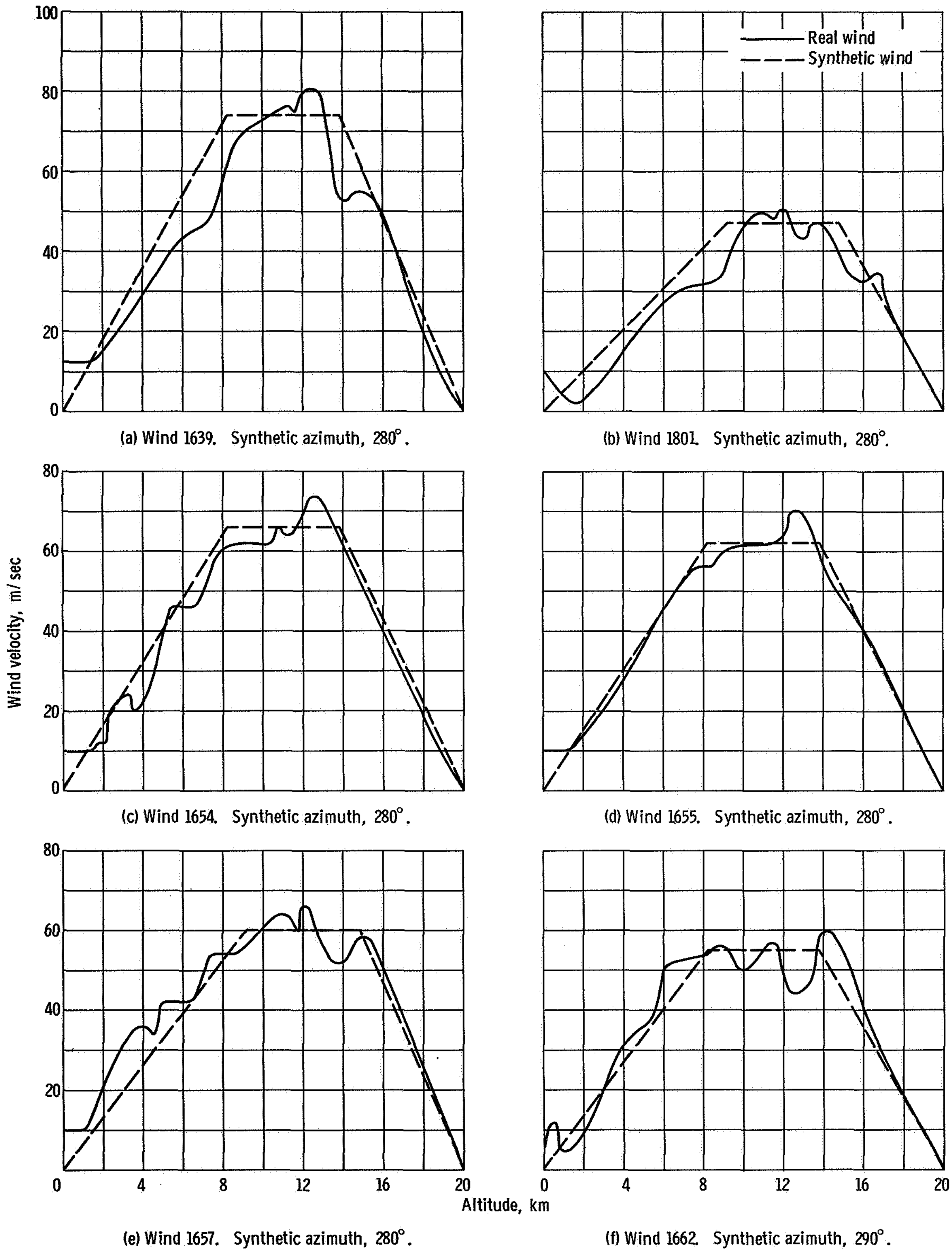


Figure 5. - Comparison of synthetic and real wind profiles for 5700-meter wind plateau.

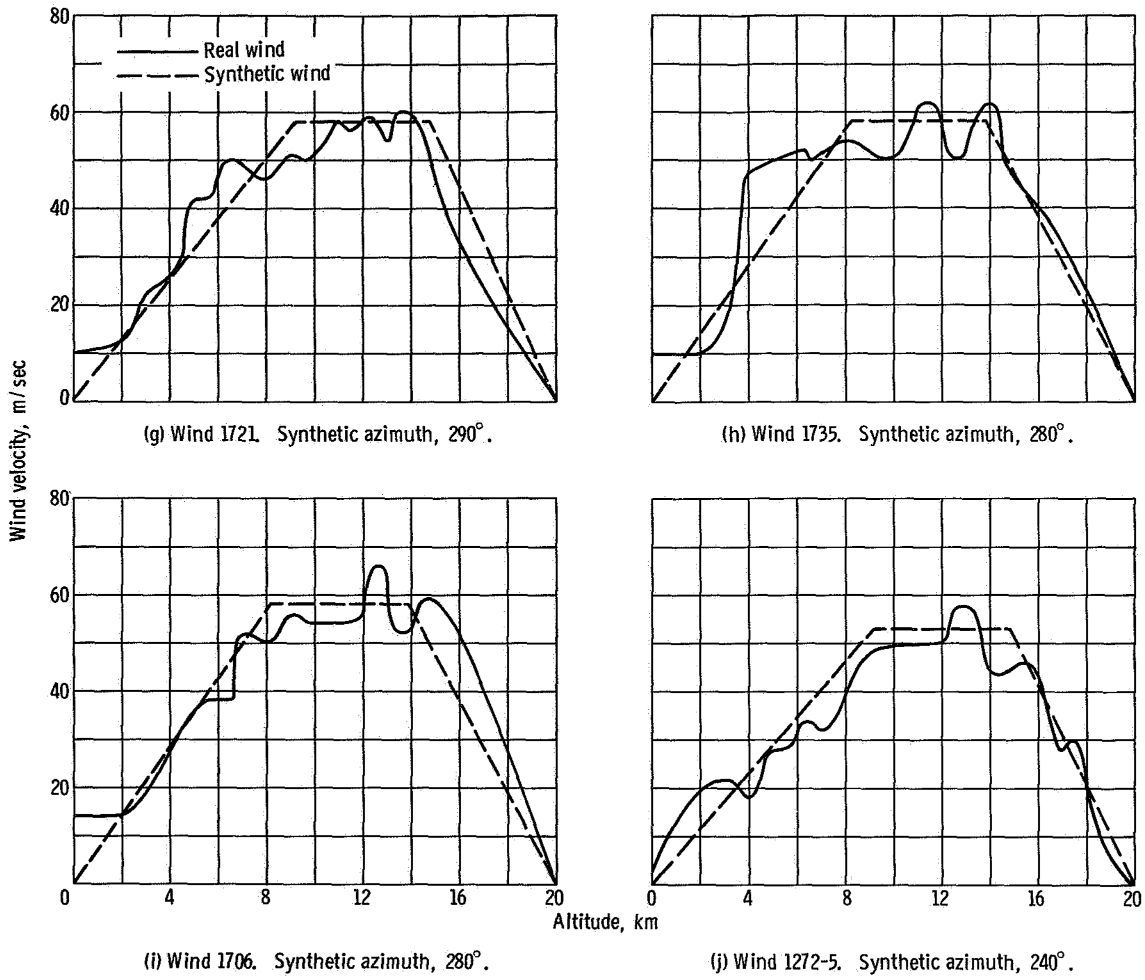


Figure 5. - Concluded.

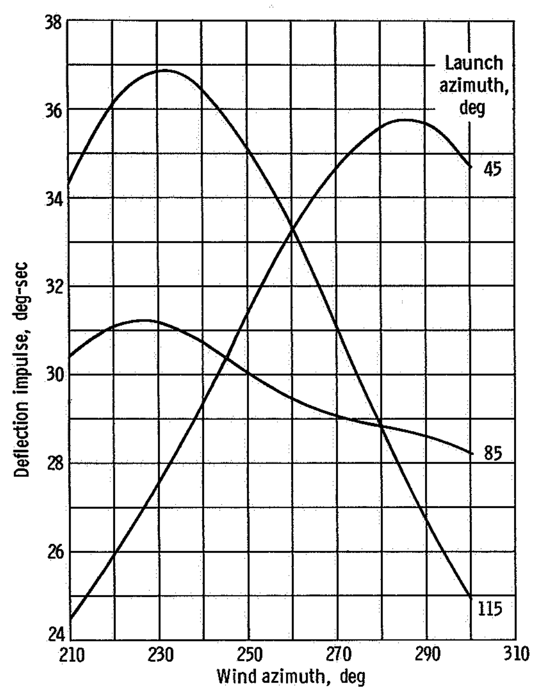
CALCULATION OF DEFLECTION-IMPULSE REQUIREMENTS

Several assumptions were made in order to calculate deflection-impulse requirements for 99 percent winds. These assumptions are listed below:

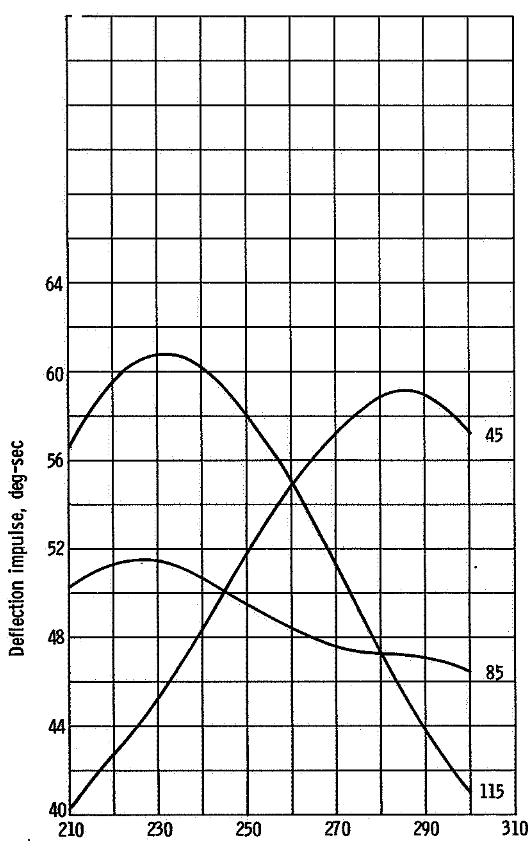
(1) An Eastern Test Range (ETR) launch is assumed.

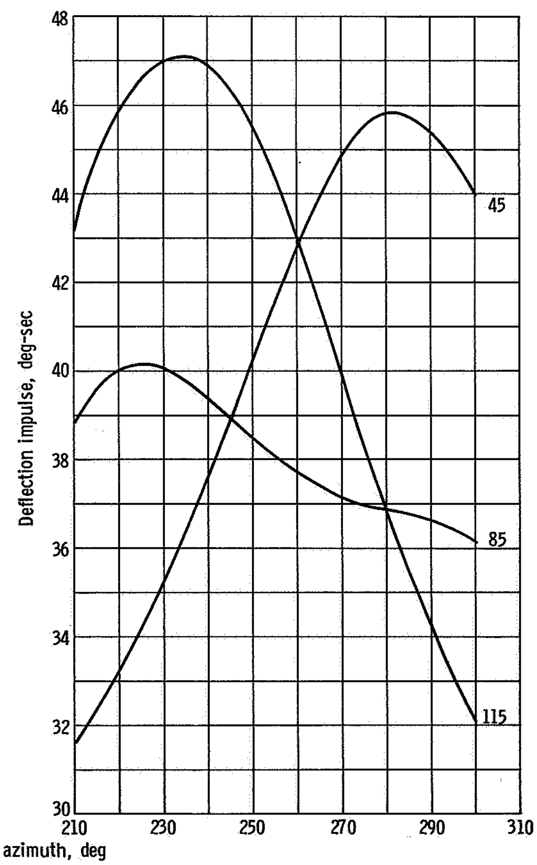
(2) The allowable launch azimuth sector is limited from 45° to 115° because of range safety restrictions.

In order to illustrate the use of the synthetic wind profile, the deflection-impulse requirements for 99 percent winds were calculated for the five vehicles. The 99 percent peak wind velocities are defined in the work by Smith such that the probability of the wind velocity exceeding the 99 percent wind velocity is less than 1 percent in the worst monthly period. It should be noted here that this synthetic wind profile is not a 99 percent profile but rather a representation of the general shape of high-velocity real winds.



(a) 260-Inch solid - Apollo vehicle.

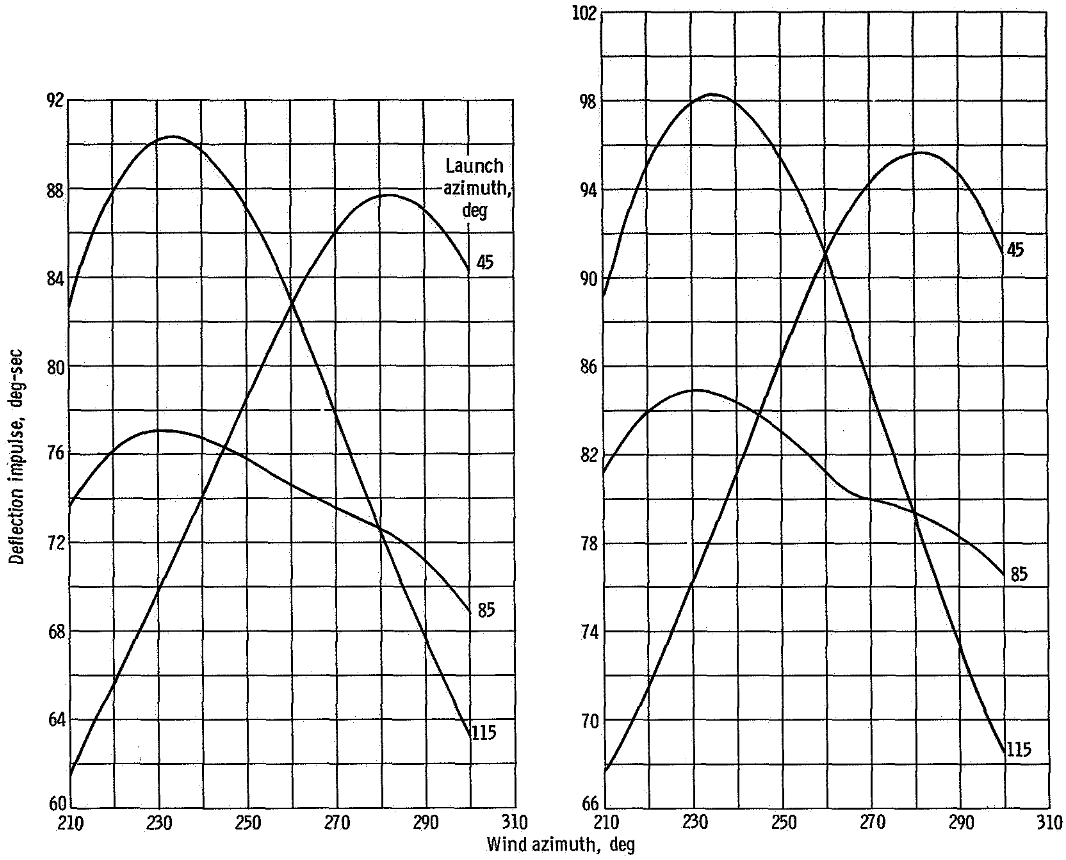




(b) 260-Inch solid - Voyager vehicle.

(c) SSO PM

Figure 6. - Deflection impulse as function of wind azimuth. Center of wind plateau, 10.4 kilometers; 99 percent winds.



(d) Single 300-inch solid vehicle.

(e) Clustered 300-inch solid vehicle.

Figure 6. - Concluded.

The 99 percent wind velocities from the work of Smith were used with this new wind profile. The range of altitudes of peak wind was chosen by referring to the sample of ten real winds, which showed that the maximum wind velocity occurred at about 10 kilometers on the average. In order to determine the maximum deflection-impulse requirements for 99 percent winds, the launch azimuth was varied from 45° to 115°, the wind azimuth from 210° to 300°, and the center of the 5.7-kilometer wind plateau (which will be referred to as peak wind altitude) from 7 to 13 kilometers. It was assumed herein that although the real winds studied had a velocity plateau of 5 to 6 kilometers at an altitude of 10 kilometers, the same plateau width could be assumed to be valid for wind peaks ranging from 7 to 13 kilometers altitude. The peak wind velocity in each case was determined from the work by Smith.

Graphs were plotted for each vehicle by holding peak wind altitude constant and plotting deflection impulse as a function of wind azimuth for all launch azimuths. One of these graphs is presented for each vehicle in figures 6(a) to (e) for three different launch azimuths. It is evident from these figures that the launch azimuth of 115° gave the greatest deflection impulse. However, wind azimuth is also important, and as the wind azimuth increased, the greatest deflection impulse was obtained from the 45° launch azimuth.

Figure 7 was obtained by selecting the peak deflection impulse from figures 6 and other figures of the same type for other peak wind altitudes. This figure shows that the maximum deflection-impulse requirement for all five vehicles was obtained for a peak wind altitude of about 10.4 kilometers, a launch azimuth of 115°, and a wind azimuth between 230° and 235°. For example, from figure 7, the largest deflection impulse for the 260-inch solid - Voyager vehicle resulted from a launch azimuth of 115°, a wind azimuth of 230°, and the center of the 5.7-kilometer plateau at about 10.4 kilometers.

Since the five vehicles studied are all symmetrical about the longitudinal axis and all have about the same nominal trajectory, the values of peak altitude, launch azimuth, and wind azimuth which determined the largest deflection impulse are all about the same. However, if an unsymmetrical vehicle, such as the Titan IIIC, or a different nominal trajectory or launch azimuth sector is used, the launch azimuth, wind azimuth, and peak altitude must be varied as done herein to obtain the maximum deflection impulse.

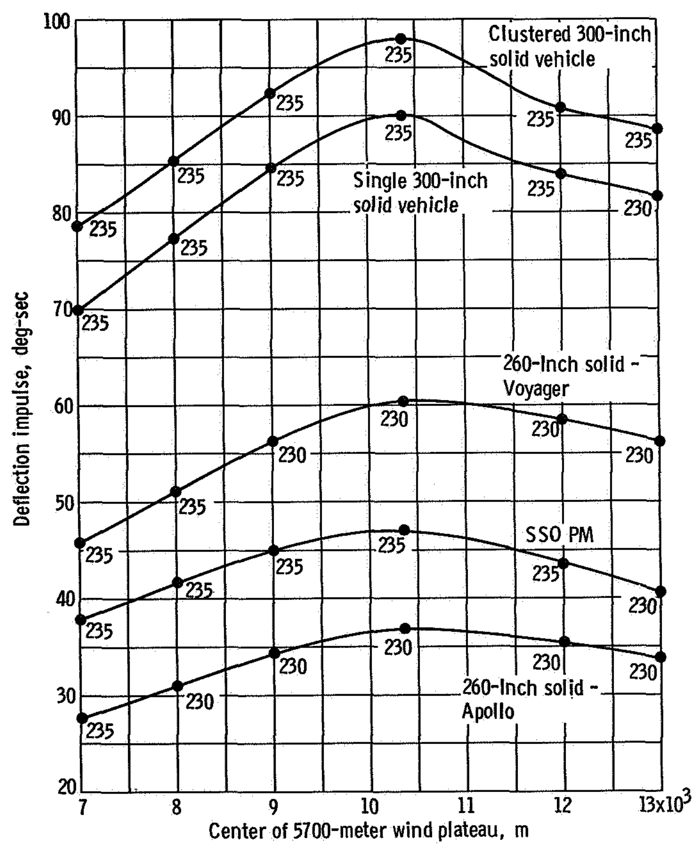


Figure 7. - Deflection impulse as function of center of 5700-meter wind plateau. Launch azimuth, 115°, 99 percent winds. Numbers at data points indicate wind azimuth.

It must be noted here that the real winds used to determine the new synthetic profile are 90 to 95 percent winds as determined from the work by Smith. Data from the work by Daniels show that more severe winds tend to have shorter duration. Therefore, the use of the new synthetic wind profile to determine deflection-impulse requirements for the higher-percentage winds would tend to give slightly conservative results. Also, lower-velocity winds tend to have broader peaks, and thus the use of the new synthetic profile would result in a lower value of deflection-impulse requirements than the true value for these cases. The synthetic wind profile selected should give reasonable results for peak wind velocities from 90 to 99 percent.

HIGH-ALTITUDE CONSIDERATIONS

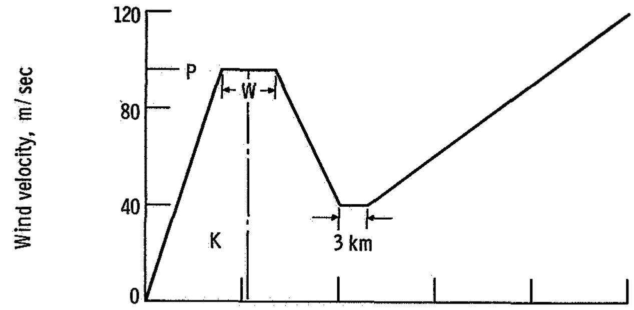
The deflection-impulse requirements calculated thus far are lower than the actual required values because of high-altitude requirements which have been omitted. These requirements, high-altitude drift and winds, were not considered for the following reasons:

(1) Because of the lack of high-altitude wind data from the work by Scoggins, all the ten real winds simulated were given zero velocity at altitudes greater than 20 kilometers.

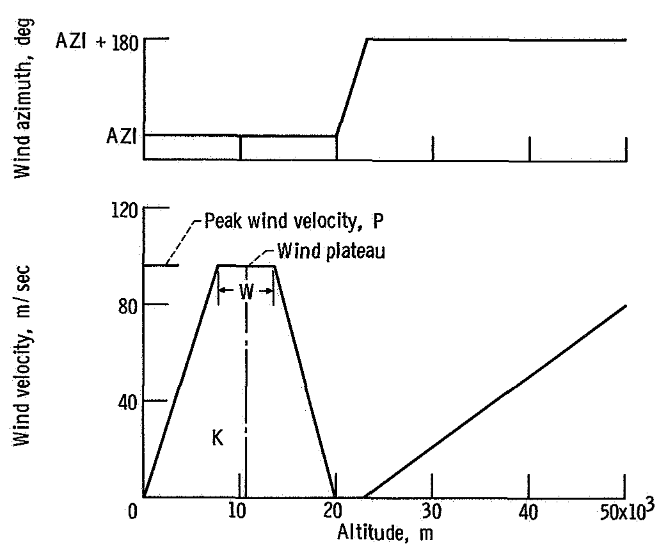
(2) Due to the lack of wind data above 20 kilometers altitude, the calculation of deflection impulse was terminated at an altitude of about 23 kilometers. This resulted in flight times of 90 seconds for all vehicles except the SSOPM, which requires 105 seconds to reach this altitude.

The deflection impulse required for altitudes greater than 20 kilometers is not zero, even if the wind velocity is zero. This is because the trajectory drifts from the nominal during the wind disturbance so that the angle of attack (and consequently the deflection angle) is not zero after the wind subsides. This effect can be observed by referring to the equations in appendix B. In order to estimate the added deflection impulse for this effect, some of the trajectories obtained earlier were continued to a flight time of 120 seconds. Although all the vehicles had a first-stage duration greater than 120 seconds, the deflection impulse required for winds is negligible after this time because of the low dynamic pressure and high relative velocity. It was found that the added flight time increased the deflection impulse by a maximum of about 4 percent.

The work by Daniels presents peak wind velocity data for altitudes greater than 20 kilometers for various probabilities of occurrence. These data were used to determine two variations on the synthetic wind profile derived earlier. These variations are illustrated in figures 8(a) and (b). In variation 1, the wind velocity drops to 40 meters per second at 20 kilometers, remains at this value up to 23 kilometers, and then in-



(a) Variation 1.



(b) Variation 2.

Figure 8. - Variations of synthetic wind profile. Wind plateau width, 5700 meters.

creases. The wind azimuth is held constant. Variation 2 is similar, except that the wind velocity is held at zero between 20 and 23 kilometers, and the wind direction is reversed at an altitude of 23 kilometers when the wind velocity increases.

Several typical pitch, yaw, and total deflection profiles are illustrated in figures 9(a) to (f) for the two synthetic wind profile variations. Corresponding deflection profiles for the original synthetic wind profile are also shown for comparison. Total deflection angle is calculated from

$$\delta_T = \sqrt{\delta_p^2 + \delta_y^2}$$

The effects of these variations on deflection impulse are a function of wind and launch azimuths and, in some cases, result in decreased deflection impulse. However, it was

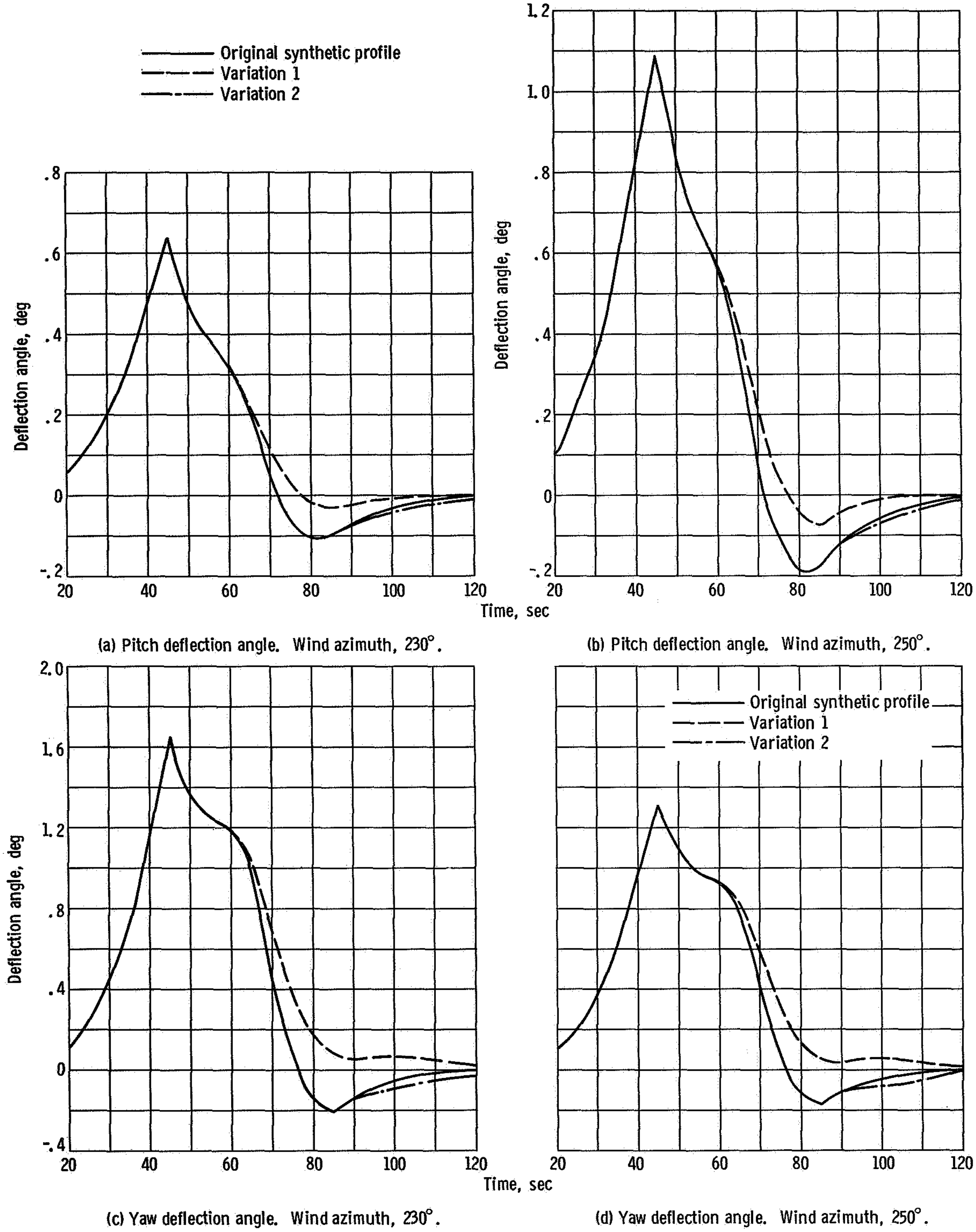
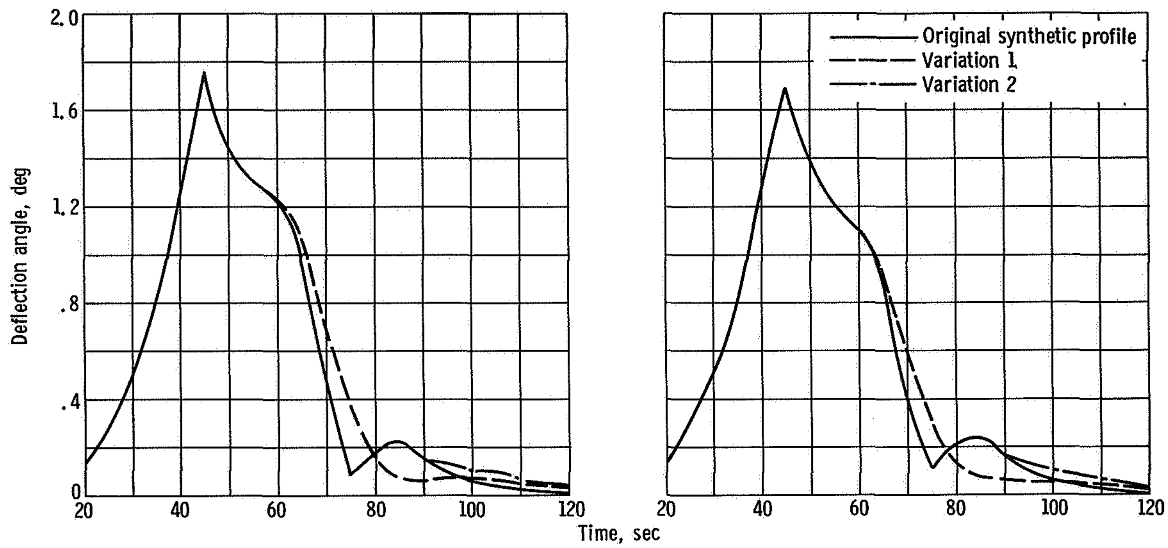


Figure 9. - Comparison of deflection profiles for 260-inch solid - Voyager vehicle. Altitude of peak wind, 8.4 kilometers; launch azimuth, 115°.



(e) Total deflection angle. Wind azimuth, 230°.

(f) Total deflection angle. Wind azimuth, 250°.

Figure 9. - Concluded.

found that the two wind profile variations resulted in a maximum of 4 percent increase over the values calculated for the flight time of 120 seconds with the original synthetic wind profile. Therefore, high-altitude winds and drift can add a maximum of about 8 percent to the deflection impulse shown in figure 7. It seems reasonable that this value would also apply to other vehicles.

CALCULATION OF WEIGHT OF LIQUID INJECTANTS

The deflection-impulse requirements for 99 percent winds were related to the required weight of TVC injectant for each vehicle. Reference 2 presents injectant flow rate against deflection angle for the 260-inch solid vehicle. The injectant was nitrogen tetroxide and was introduced at a nozzle expansion ratio of 4. To relate the data in reference 2 to other vehicles, it was assumed that the injectant flow rate required for a given deflection angle is proportional to the vehicle thrust level. For example, the maximum thrust for the 260-inch solid - Voyager vehicle is 3.13×10^{7} newtons while the SSOPM develops a maximum thrust of 3.32×10^{8} newtons. Thus, the flow rates obtained from the graph in reference 2 were multiplied by $3.32\times10^{8}/3.13\times10^{7}$ or 10.6. The TVC conversion factor (injectant flow rate divided by maximum deflection angle) for each vehicle is presented in table II. Finally, the TVC constants were used in conjunction with figure 7 to find the weight of liquid injectants needed to control the vehicle during 99 percent wind disturbances. For example, from figure 7, the maximum deflection impulse for 99 percent winds for the 260-inch solid - Apollo vehicle is 36.84 degree-seconds.

TABLE II. - THRUST-VECTOR CONTROL

CONVERSION FACTORS

Vehicle	Conversion factor, (kg/sec)/deg
260-Inch solid - Apollo	178
260-Inch solid - Voyager	214
SSOPM	1790
Single 300-inch solid	241
Clustered 300-inch solid	1690

This value must be increased by 8 percent to account for high-altitude effects. The resulting value does not include thrust vector misalinement, which is estimated to be about 0.25° (ref. 3). Since the flight time for the 260-inch solid - Apollo vehicle is 150 seconds, the deflection impulse for thrust-vector misalinement is 150×0.25 or 37.5 degree-seconds. Other effects, such as pitchover and vehicle dispersions, do not contribute measurably to deflection-impulse requirements. The total deflection impulse for this vehicle is then $36.84 + 36.84 \times 0.08 + 37.5$ or 77.54 degree-seconds, and the corresponding TVC liquid weight is

$$\text{TVC weight} = 77.54 \text{ deg-sec} \times 178 \text{ (kg/sec)/deg}$$

$$= 13\ 800 \text{ kg (260-in. solid - Apollo vehicle)}$$

The flight time for each of the five vehicles studied is shown in table III, while the TVC injectant weight required for each vehicle is shown in table IV.

TABLE III. - VEHICLE FLIGHT TIMES

Vehicle	Flight time, sec
260-Inch solid - Apollo	150
260-Inch solid - Voyager	150
SSOPM	150
Single 300-inch solid	125
Clustered 300-inch solid	125

TABLE IV. - REQUIRED THRUST-VECTOR

CONTROL INJECTANT WEIGHT

FOR 99 PERCENT WINDS

Vehicle	Injectant weight, kg
260-Inch solid - Apollo	13 800
260-Inch solid - Voyager	22 100
SSOPM	158 000
Single 300-inch solid	31 000
Clustered 300-inch solid	232 000

CONCLUDING REMARKS

Calculations of deflection-impulse requirements have shown that the MSFC synthetic wind profiles do not give a good estimate of deflection-impulse requirements for launch vehicles using liquid-injection thrust-vector control systems. Therefore, a new synthetic wind profile was developed. The shape of this profile was established by obtaining a best fit to ten real wind profiles with 90 to 95 percent peak wind velocities measured at ETR. The synthetic wind profile generated deflection impulses with an average percentage of error of -0.31 percent and an rms percentage of deviation of 8.38 percent relative to the deflection impulse obtained with the ten real winds and five typical solid-propellant launch vehicles.

The new profile is generated by picking a wind azimuth and an altitude of peak wind velocity, and then using the MSFC wind tables for the appropriate peak wind velocity at the percentage wind level needed. The plateau of the profile is 5.7 kilometers wide and is centered about the altitude of peak wind velocity. The profile is then dropped linearly to zero velocity at zero altitude and zero velocity at an altitude of 20 kilometers.

In order to illustrate the use of the synthetic wind profile, deflection-impulse requirements were calculated for 99 percent peak wind velocities for each of the five launch vehicles. An ETR launch was assumed. It was found that about 8 percent should be added to this requirement in order to allow for high-altitude effects which were not considered in the development of the synthetic wind profile. Also, the deflection impulse required for thrust-vector misalinement should be added to the original requirement. The total deflection-impulse requirements were then related to the required weight of liquid injectants by assuming a nitrogen tetroxide liquid-injection system.

For the five launch vehicles studied, the largest deflection-impulse requirements resulted from a peak wind altitude of about 10.4 kilometers and launch and wind azimuths of 115° and about 230°, respectively. However, for other launch vehicles, the complete range of peak altitude, wind azimuth, and launch azimuth may have to be investigated in order to determine the maximum deflection-impulse requirements. An additional 8 percent should be added to this value for higher-altitude effects, and requirements due to thrust-vector misalinement should be considered.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 3, 1968,
125-19-04-02-22.

APPENDIX A

SYMBOLS

AZI	starting wind azimuth, deg
a, b	constants defined in appendix B, sec^{-1}
CG	distance from center of gravity to gimbal station, m
CP	distance from center of pressure to center of gravity, m
$C_{N,\alpha}$	normal force coefficient per angle of attack, rad^{-1}
d	constant defined in appendix B, sec^{-2}
F_A	axial force, N
g	gravitational constant, m/sec^2
I	moment of inertia, $N\text{-}m\text{-}sec^2$
K	center of synthetic wind plateau, km
k	wind angle slope, rad/sec
m	mass, kg
N	normal force per angle of attack, N/rad
P	peak wind velocity, m/sec
Q	dynamic pressure, N/m^2
Q*	modified dynamic pressure, N/m^2
S_{ref}	vehicle reference area, m^2
s	Laplace operator, sec^{-1}
T	thrust, N
TVC constant	injectant flow rate per maximum deflection angle, (kg/sec)/deg
t	time, sec
V	velocity, m/sec
W	width of synthetic wind plateau, m
α	angle of attack, rad
γ	flightpath angle, rad
δ	deflection angle, rad

θ vehicle pitch attitude, rad

μ_c vehicle control parameter, sec^{-2}

μ_α vehicle aerodynamic parameter, sec^{-2}

Subscripts:

n nominal

o initial condition

p pitch plane

rel relative

T total

w wind

y yaw plane

APPENDIX B

EQUATIONS USED IN CALCULATING DEFLECTION IMPULSE

A simplified approximate procedure was derived for the calculation of thrust-vector deflection requirements for vehicle control during wind disturbances. This procedure was programmed on a digital computer and is several orders of magnitude faster than a 6-degree-of-freedom computer program in calculating deflection requirements. The saving in computer time in obtaining the results presented is substantial because of the large number of cases that were considered.

The simplified procedure is based on the assumption that the trajectory altitude and velocity magnitude are unchanged from the nominal due to the wind disturbance. The change in flightpath angle as a result of the wind was determined by integrating the linearized equations presented herein.

The nominal trajectory for each vehicle was obtained by using a 6-degree-of-freedom computer program. The first stage was flown at 0^{o} angle of attack, with the amount of lofting adjusted to maximize payload capability into a 185-kilometer circular orbit. The vehicle equations of motion in the pitch plane are

$$\left.\begin{aligned}
\ddot{\theta} &= -\mu_c \sin\delta + \mu_\alpha \alpha \\
\alpha &= \theta - \gamma - \alpha_w \\
\dot{\gamma} &= \frac{1}{mV}\left[T\sin(\theta - \gamma + \delta) - F_A \sin(\theta - \gamma) + N\alpha\cos(\theta - \gamma) - mg\cos\gamma\right] \\
\dot{V} &= \frac{1}{m}\left[T\cos(\theta - \gamma + \delta) - F_A \cos(\theta - \gamma) - N\alpha\sin(\theta - \gamma) - mg\sin\gamma\right] \\
\sin\alpha_w &= \frac{V_w}{V_{rel}}\sin\gamma
\end{aligned}\right\} \tag{B1}$$

where

$$\left.\begin{aligned} N &= Q^* S_{ref} C_{N,\alpha} \\ \mu_c &= T \frac{CG}{I} \\ \mu_\alpha &= \frac{N}{1} CP \end{aligned}\right\} \tag{B2}$$

All symbols are defined in appendix A, and some are illustrated in figure 10. Equations (B1) may be applied to the yaw plane by setting $g = 0$. If equations (B1) are linearized about the nominal values, and a 0^o angle of attack, zero wind nominal trajectory is assumed so that

$$\theta_n = \gamma_n$$

$$\alpha_n = \alpha_{w,n} = 0$$

$$\delta_n = 0$$

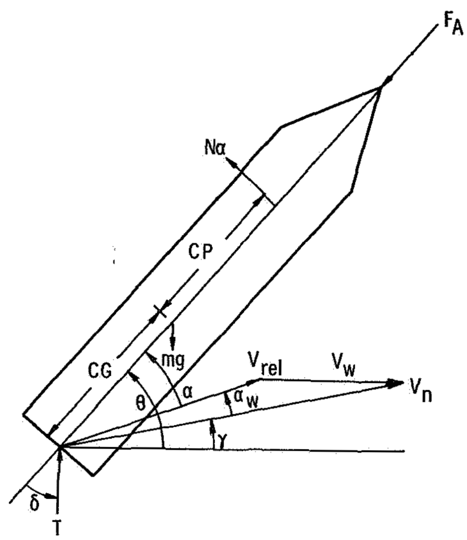


Figure 10. - Definition of trajectory and control variables, pitch plane.

and

$$\gamma_n = \theta_n = 90^o \qquad \text{for the yaw plane}$$

The following equations are obtained:

$$\left.\begin{aligned}
\ddot{\theta} &= -\mu_c\delta + \mu_\alpha\alpha \\
\alpha &= \theta - \gamma - \alpha_w \\
\dot{\gamma} &= \frac{1}{mV_n}\left[N\alpha + mg\sin\gamma_n\gamma + T(\theta - \gamma + \delta) - F_A(\theta - \gamma)\right] + \frac{g\cos\gamma_n V}{V_n^2} \\
\dot{V} &= -g\cos\gamma_n\gamma \\
\sin\alpha_w &= \frac{V_w}{V_{rel}}\sin\gamma_n
\end{aligned}\right\} \tag{B3}$$

In equations (B3) and in the equations that follow, the unsubscripted state variables refer to the linearized variables.

The linearized trajectory is assumed to be trimmed through the wind disturbance so that

$$\left.\begin{aligned}
\theta &= 0 \\
\delta &= \frac{\mu_\alpha}{\mu_c}\alpha
\end{aligned}\right\} \tag{B4}$$

Combining equations (B3) and (B4), switching to LaPlace notation, and solving for α in terms of α_w result in

$$\alpha = -\left(\frac{s^2 + as + d}{s^2 + bs + d}\right)\alpha_w \tag{B5}$$

where

$$a = \frac{T - F_A - mg \sin \gamma_n}{mV_n}$$

$$b = \frac{T\left(1 + \frac{\mu_\alpha}{\mu_c}\right) + N - F_A - mg \sin \gamma_n}{mV_n}$$

$$d = \frac{g^2 \cos^2 \gamma_n}{V_n^2}$$

The constants a, b, and d are vehicle and trajectory dependent. Constants a and b are nearly equal early in flight (because N is small), and both become small as V_n increases. Constant d is always small since γ_n is nearly 90^o early in flight and V_n increases later. Therefore, assume that $d = 0$. Then

$$\alpha(s) = -\left(\frac{s + a}{s + b}\right)\alpha_w(s)$$

Assuming initial conditions,

$$\alpha(s) = -\left[\left(\frac{s + a}{s + b}\right)\alpha_w(s) + \frac{\alpha_o - \alpha_{w,o}}{s + b}\right] \tag{B6}$$

Let $\alpha_w(t)$ be a ramp

$$\alpha_w(t) = \alpha_{w,o} + kt$$

$$\alpha_w(s) = \frac{\alpha_{w,o}}{s} + \frac{k}{s^2} \tag{B7}$$

where k is assumed to be constant for a time interval Δt.

$$k = \frac{\alpha_w(t_o + \Delta t) - \alpha_w(t_o)}{\Delta t}$$

The time interval Δt was assumed to be 5 seconds, and parameters a and b were averaged over this interval.

Substituting equation (B7) into equation (B6) results in

$$\alpha(s) = -\left[\frac{k}{s^2}\left(\frac{s + a}{s + b}\right) + \frac{s\alpha_o + a\alpha_{w,o}}{s(s + b)}\right]$$

The solution is

$$\alpha(t) = -\left[\alpha_o e^{-bt} + \frac{ka}{b} t + \frac{(kb - ka + ab\alpha_{w,o})(1 - e^{-bt})}{b^2}\right] \tag{B8}$$

Where, given α_w at t_o and at $t_o + \Delta t$

$$\alpha_{w,o} = \alpha_w(t_o)$$

The variables T, F_A, m, and $\sin\theta_n$ are input to the program from a nominal trajectory. The other variables are calculated from

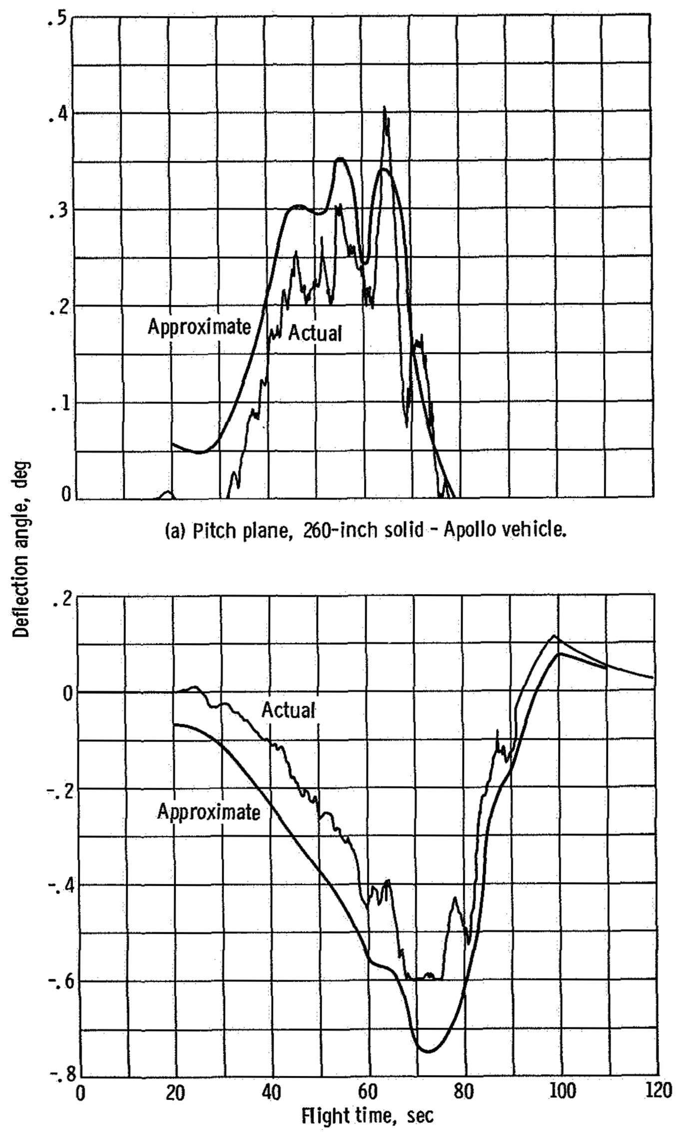
$$V_{rel} = \sqrt{V_n^2 + V_{w,p}^2 - 2V_n V_{w,p} \cos\theta_n + V_{w,y}^2}$$

$$\alpha_{w,p} = \sin^{-1}\left(\frac{V_{w,p} \sin\theta_n}{V_{rel}}\right)$$

$$\alpha_{w,y} = \sin^{-1}\left(\frac{V_{w,y}}{V_{rel}}\right)$$

$$Q^* = Q\left(\frac{V_{rel}}{V_n}\right)^2$$

Figure 11 presents a comparison of deflection profiles obtained with the simplified procedure and a 6-degree-of-freedom computer program. By using this procedure, the results differ from the 6-degree-of-freedom results by about 10 percent.



(a) Pitch plane, 260-inch solid - Apollo vehicle.

(b) Yaw plane, SSO PM vehicle.

Figure 11. - Deflection requirements for real wind.

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