Designs to Control Wind-Induced Oscillations of Launch Vehicles

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Summary

During the prelaunch time, launch vehicles will be exposed to prevailing ground winds. When circular cylindrical structures (such as launch vehicles) are exposed to winds, vortices are shed alternately from the sides of the structure which causes alternating lift forces to act upon the sides. Under certain conditions large oscillations can occur depending on the vehicle's structural damping and the characteristics of the wind forces. Wind tunnel investigations of launch vehicles\(^1\),\(^2\) indicate that launch vehicles do experience relatively large oscillation amplitudes.

This paper discusses the phenomenon of vortex shedding and techniques of calculating response of cylindrical structures subjected to wind. With this background, the paper moves to consider the two basic approaches to controlling the wind-induced oscillation amplitudes. The primary approach, Excitation Control Techniques, which consists of methods that either alter the nature or diminish the magnitude of the aerodynamic exciting force. The secondary approach, Response Control Techniques, includes methods that seek to reduce the systems admittance to these forces, counteract the force of the wind or dissipate the energy of the wind as the vehicle receives it. The control systems are discussed in the light of their advantages, limitations and methods of functioning; and the efficacy and economics of each of the systems is also pointed out. In the conclusions, the systems are compared, and the reasons for choosing some systems over others are discussed.

It is appropriate for the author to thank the Launch Support Equipment Engineering Division of the Kennedy Space Center who made this paper possible and the Brown Engineering Company associates who supplied background information.

Nomenclature

- \( A \): Projected area (D·L)
- \( C \): Damping
- \( C_L \): Coefficient of lift
- \( C_{CM} \): Command module
- \( D \): Diameter
- \( DB \): Damper brace
- \( f \): Force
- \( F \): Generalized force
- \( f_n \): Natural frequency (cps)
- \( h_i \): Height from vehicle base to the i-th degree-of-freedom
- \( i \): Degree-of-freedom index
- \( j \): Vibration mode index

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Vortex Shedding Phenomenon

When vortices are shed about cylindrical structures, it indicates the presence of the classical concept of circulation which generates a lift force in a direction that is perpendicular to the fluid stream flow. Since these vortices are shed alternately (and sometimes periodically) from the sides of the cylinder, the cylinder will oscillate laterally. These wind-induced oscillations are of serious concern to launch vehicle designers, who in their endeavors to produce a refined, light-weight structure almost inevitably find that their designs have very little internal damping. Consequently, these tall slender vehicles are susceptible to resonant-type buildup of oscillation amplitudes which can have adverse effects on the vehicle and launch operations.

Several factors must be considered to properly derive an analytical approach of the response of a launch vehicle to wind, but the length of the vortices (i.e. the spanwise correlation of the lift force) must be determined first. Recent investigators (Bohne, Schmidt, and Reed) probed this phenomenon to determine its characteristics. Figure 1 is an example of the variation of correlation coefficient with separation distance obtained from wind tunnel test. All of the aforementioned investigators agree that there is essentially no correlation at separation distances greater than 1.5D; however, it should be noted that tests have only been performed in the supercritical Reynolds number range ($2 \times 10^5 < \text{Re} < 3.5 \times 10^6$), and the degree of correlation is expected to be different at other Reynolds numbers. The spanwise correlation is important, because the periodicity of the lift force cannot be determined by observation of the amplitude of response without first knowing the degree of spanwise correlation.

There has been considerable disagreement and lack of information concerning the periodicity of the lift force; however, most agree that the periodicity depends on the Reynolds number (see Figure 2). The vortex shedding is essentially periodic
for Reynolds numbers less than $2 \times 10^5$. In the supercritical Reynolds number range, there is much disagreement. The dotted line in Figure 2 represents the results of investigators who have measured periodicity in this region. Fung$^6$, Bohne and Schmidt have found no periodicity in this region and have developed a power spectral density function as shown in Figure 3. There has been only one investigator (Roshko$^7$) who has tested at very high Reynolds number (i.e. $3.5 \times 10^6 < Re < 8.5 \times 10^6$) and he found that periodicity did exist at a Strouhal number of 0.27.

The periodicity and degree of correlation of the lift force may be a function of the oscillation amplitude. For example, a large oscillation may be started by purely random force, and once the oscillation is begun, the frequency of the forces "locks in" to the vehicles natural frequency, and the resultant larger oscillation causes the lift force to develop greater spanwise correlation. This may continue to build up or it may be deterred by a spurious wind gust. Perhaps the reason that many authors have not considered the periodic response analysis is due to the relationship between the dynamic model's natural frequency, the wind velocity and the forcing frequency. These may not have been of proper magnitude to trigger a large response. There were no direct considerations of gusts; however, gusts will effect the periodicity and spanwise correlation of the lift force, and these factors will be given some consideration in obtaining a response analysis.

**Vehicles Response Analysis to Wind**

A spring-mass system's steady state response may be obtained from

$$ x = \frac{fQ}{k} $$

and for a multiple degree-of-freedom system, the response for each mode, $j$, is

$$ q_j = \frac{FQ}{k} = \frac{\sum_i f_i \psi_{ij} Q_{ij}}{\omega_j^2 \sum_i m_i \psi_{ij}^2} $$

Now the lift force, $f$, is generally defined by the equation

$$ f_i = \frac{1}{2} \rho V^2 A_i C_{L_i} $$

To give $C_{L_i}$ complete flexibility, it will be defined in terms of a square matrix

$$ C_L = \left[ \Phi_{C_L} i, k (f) \right] $$

where the diagonal values represent the effective $C_{L_i}$ for the degree-of-freedom under consideration, and the off diagonal values represent the cross-correlation of $C_{L_i}$ at the other degrees-of-freedom (i.e. the interrelationship between a force at
one degree-of-freedom with all the other degrees-of-freedom). To obtain a mathematical model to sum these values correctly, we have

\[ q_j = \sqrt{\gamma_1 \left[ \Phi C_L i, k^{(f)} \right] \gamma_1 \left[ \omega_j^2 \sum m_i \psi_{ij}^2 \right]^2} \]

\[ \gamma_i = \frac{1}{2} \rho A_i \psi_{ij} V_i^2 \left[ \int_0^\infty \frac{d\omega}{\left( 1 - \frac{\omega^2}{\omega_j^2} \right)^2 + \left( 2 \xi_j \frac{\omega}{\omega_j} \right)^2} \right]^{\frac{1}{2}} \]

Equation (1) is sufficiently general to calculate a response with virtually any degree of correlation and any frequency distribution.

Let us consider the simplification of this equation in the light of recent investigations. Essentially no correlation was observed at more than 1.5D spacing; therefore, if the degrees-of-freedom are chosen to be approximately 1.5D in length, then the \( C_L \) matrix reduces to a diagonal matrix. For a random frequency distribution that is well behaved, all the significant response is at the natural frequency, \( \omega_j \); therefore, \( \gamma_i \) is reduced to (approximately)

\[ \gamma_i = \frac{1}{2} \rho A_i \psi_{ij} V_i^2 \sqrt{\frac{\omega_j^2}{8 \xi_j}} \]

For a discrete frequency, \( \gamma_i \) becomes

\[ \gamma_i = \rho A_i \psi_{ij} V_i^2 / 2 \left[ \left( 1 - \frac{\omega^2}{\omega_j^2} \right)^2 + \left( 2 \xi_j \frac{\omega}{\omega_j} \right)^2 \right]^{\frac{1}{2}} \]

Considering the random case which recent investigators have confirmed is the true case for supercritical Reynolds number, we find that equation (1) becomes

\[ q_j = \frac{n}{i} \frac{i}{\gamma_i \Phi C_L i(f)} \]

\[ \sigma_{x_i} = \frac{m_j q_j}{i} \psi_{ij} \]

\[ \sigma_{BMi} = \sigma_{x_i} \omega_j^2 \sum m_i \psi_{ij} \left( n - h_i \right) \]

which are simple hand calculations.
Fung found that $ C_L $ could be obtained using the equation:

$$ \Phi C_L (f) = \frac{D_i}{V_i} \Phi C_L (S) = \frac{D_i}{V_i} \left\{ \frac{0.08 \left[ 1 + 3 (4.8 \pi S)^2 \right]}{1 + (4.8 \pi S)^2} \right\} $$

When this is applied to the Saturn V, the analytical results are much less than the wind tunnel results. Wind tunnel tests need to be run and measurements need to be made to determine the power spectral density and cross-correlation coefficients which apply to the Saturn V before good analytical results can be obtained. It is interesting to note that assuming a periodic lift force and pure correlation on the 33 ft. diameter section of the Saturn V, produces a 65 inch amplitude at the Command Module. This is very close to the 70 inch amplitude obtained when the wind tunnel results of the Saturn V model were scaled up.

**Excitation Control Techniques**

The objective of these techniques is to either alter the nature or diminish the magnitude of the aerodynamic exciting force. These techniques are the primary approach, because they prevent the occurrence of the problem rather than curing the problem.

**Spoilers**

Spoilers are variations in the vehicle exterior shape to abate the aerodynamic effect. This can be done by designing nose shapes that will retard the formation of wind forces; however, for long slender vehicles these nose shapes are not very effective, and the vehicle should be designed for flight requirements and not for ground wind loads; therefore, nose configuration will not be discussed in this paper.

Figure 4 illustrates examples of tip spoilers. On vehicles with large fineness ratios (D/L), tip spoilers are effective, since they spoil the wind effect at the point of maximum leverage. On vehicles with small fineness ratios, they are less effective, because they affect only a small portion of the vehicle's length. The efficacy of all spoilers must be determined by experiments, since the phenomenon is not well defined and defies theoretical treatment, and experiments indicate that spoilers (a) and (c) of Figure 4 lack omnidirectional effectiveness which cannot be tolerated in natural wind applications. Also, none of these spoilers have been tested to any degree of completeness which would yield confidence in their application.

Protrusions from a cylinder in the form of wires or fins parallel to the cylinder's axis (see Figure 5) were investigated as vortex suppressors. These protrusions are designed to fix the stagnation and separation points, and consequently weaken the effect of the wind force on the cylinder. These spoilers, like those of Figure 4, lacked omnidirectional effectiveness and had insufficient tests to verify their efficacy.
The National Physical Laboratory in England performed many tests on helical strakes attached to cylinders and found that helical strakes were effective in reducing the wind force. Scruton and Walshe\textsuperscript{11}; Woodgate and Maybrey\textsuperscript{12}; and Cowdrey and Lowes\textsuperscript{13} found that the efficacy of helical strakes depended on the strake height, pitch of the windings, number of strakes, shape of the strake and the Reynolds number. Weaver\textsuperscript{14} and Scruton\textsuperscript{15} further optimized the characteristics of the strake to increase their efficacy.

A strake height of 0.09D was found to be more than adequate to serve the purpose. A pitch of 5D of three strakes at 120° apart were found to be the most effective. Strakes with circular cross-sections were found to be ineffective at high Reynolds numbers, but strakes with sharp edge rectangular cross-sections were found to be virtually independent of Reynolds numbers within the range tested ($10^4 < Re < 4 \times 10^6$). An example of the use of strakes on the Saturn V Vehicle is shown in Figure 6.

Environmental Systems

Environmental systems consist of shrouds or enclosures which would prevent the wind from approaching the vehicles or artificial flow fields which would disturb natural air currents. Very few of these techniques have been tested; consequently, most of these systems can only be justified from the theoretical viewpoint. Obviously, if the vehicles were completely enclosed, they could not experience ground wind loads; however, this would be entirely too expensive, so this idea will be considered impractical.

P. Price\textsuperscript{8} made wind tunnel tests of a perforated concentric shroud. An illustration of this shroud adapted to the Saturn V Vehicle is shown in Figure 7. The shroud has the effect of creating many small weak vortices about the cylinder, and these vortices are completely random and result in very little wind force. Figure 8 shows the difference in the wake behind a plain cylinder and a shrouded cylinder. Also note that the tip double amplitude was reduced from 0.8D to 0.04D (a reduction of 95% in amplitude). It should also be noted that the drag coefficient is reduced to 0.6 (based on the projected area of the shroud) which indicates no significant increase in drag. The problems with this system come from its size and weight. It would be difficult to manufacture and transport, and numerous interference problems would develop. It would also be difficult to retract for launch and to re-install in the event of an abort.

An artificial flow field consists of a system which generates air currents that disturb the natural air currents. One such system would be fans mounted at strategic areas and directed either vertically upward or downward. The fans would prevent the wind from flowing about the vehicle in the normal manner and consequently eliminate the von Karman Effect. This system would be economical and relatively simple; however, a wind tunnel test would be necessary to determine if this system would be effective for all wind directions and speeds.

Miscellaneous Systems

There are several other theoretically sound methods of suppressing wind force on vehicles, but for practical or other reasons they are poor solution. For
instance, a splitter plate or a cylinder fairing which could align itself with the wind, would prevent large wind forces from acting on the vehicles; however, the designing, manufacturing, transporting, installing and interfering problems would be tremendous. Some environmental techniques, such as a vehicle housing or a large wind screen about the vehicle, would solve the aerodynamic problems of the vehicle, but aerodynamic problems of these techniques themselves would be comparable to the ones of the vehicle.

Response Control Techniques

The response control techniques do not seek to alter the exciting force, but they alter the vehicle's response to this force. There are basically four methods of controlling response to the exciting force: (1) altering the vehicle's admittance to the force; (2) opposing the exciting force so as to neutralize the external force; (3) eliminating structural amplification; or (4) dissipating the energy that the vehicle receives from the wind. In this section, the forcing function is assumed to be completely correlated and periodic, because it facilitates the presentation of the efficacy of these systems.

Vehicle Natural Frequency Modulation

By varying the vehicle's natural frequency the amplitude of response may also be changed. The vehicle's natural frequency can be increased significantly beyond the wind's forcing frequency for the 99.9% wind thus preventing resonance, or the vehicle's natural frequency can be reduced so that resonant wind velocity is too slow to contain much energy. Both of these approaches would significantly reduce the amplitude of response.

The vehicle's natural frequency could be increased by either stiffening the vehicle's structure or reducing the mass of the vehicle; however, this could not be done without sacrificing some of the objectives of the Saturn V program (because stiffening the vehicle would mean a definite weight penalty, and reducing the mass would require elimination of vital components). Increasing the natural frequency also involves the possibility that the wind might exceed the design envelope, and if resonant vortex shedding should occur, the response amplitudes would surely be catastrophic. Also, the wind velocity which causes resonance vortex shedding on other vehicle stages, is increased, and the corresponding amplitudes may increase to dangerous levels. Raising the natural frequency could also be accomplished by bracing techniques which will be discussed later.

There are two primary methods of reducing the vehicle's natural frequency. The first is by adding mass (e.g. fuel) in such a manner that the vehicle is not proportionally stiffened, and the second is by decreasing the vehicle structural stiffness; however, other design parameters would undoubtedly require the stiffness to be kept at its present level and would eliminate this as a solution.

If CCl₃F (a clean liquid with a boiling point at 74.7°F and specific gravity of 1.57) were used to fill the tanks, a considerable reduction in the vehicle's natural frequency could be made with only a relatively small amount of the liquid. Let us consider the case of filling the S-IVB stage's tanks of the Saturn V with CCl₃F.
The natural frequency of the vehicle may be approximated by

\[ \omega = \sqrt{\frac{K}{\sum_{i=1}^{n} m_i \psi_i^2}} \]

and since the natural frequency of the empty vehicle is known \((\omega_n = 3.14 \text{ rad/sec})\), then using Table 1, the generalized spring constant may be obtained

\[ K = (3.14)^2 (274.6) = 2710 \text{ lb/in} \]

Using the generalized mass for the S-IVB tanks (see Table 2) filled with \( \text{C Cl}_3 \text{ F} \),

\[ \omega_n = \sqrt{\frac{2710}{1785}} = 1.23 \text{ rad/sec} \]

\[ f_n = 0.196 \text{ cps} \]

Based on the vehicle's largest diameter, the wind velocity which resonates the empty vehicle is 46.4 mph, and the vehicle with the S-IVB filled is 19.6 mph. Since the wind force is proportional to the square of the wind velocity, then for the S-IVB filled, the force will be reduced by a factor of 5.6, and the amplitude will also be reduced by a factor of 5.6 (i.e., at the Command Module, 65-inches amplitude will be reduced to 12-inches).

The vehicle structure would have to be investigated to determine if the 1.3-million lbs of \( \text{C Cl}_3 \text{ F} \) in the S-IVB tanks could be supported. It is apparent that for relatively small oscillations the vehicle would have relatively large bending moments. Also, the loading and unloading of the S-IVB tanks with fluid may cause some difficulty with the operation schedule for the launch sequences, and ground support equipment will need to be designed in order that the fluid can be stored at the launch site and pumped to and from the vehicle.

**Opposed Forcing Function**

A system of this nature would produce a force on the vehicle in the opposite direction of its motion, and the force would be of the same magnitude and same frequency, thereby neutralizing the resultant external force. One of the forms of an opposed forcing function is a dynamic absorber. A dynamic absorber is a spring-mass system which resonates at the frequency of the forcing function while the main body virtually remains at rest. The dynamic absorber is most useful when the forcing function frequency is constant, but in the case of wind induced oscillation many frequencies are present. This means that a vehicle could still resonate at a new frequency (caused by the addition of the spring-mass system). A system of this nature would be required to have a mass that was 10% of the vehicle generalized
mass, and it would be unlikely that the vehicle could support it; therefore, supporting structure would have to be added to the ground support equipment.

Another form of the opposed forcing function is an eccentric motor (i.e., a rotating motor with the frequency of rotation equal to that of the wind force). The force (which is caused by a mass off the center of rotation) could be varied to equal the wind force by varying the distance from the center of rotation to the mass, and the frequency of the opposing force could be aligned to the forcing frequency by varying the motor speed. One of the characteristics which makes the use of an eccentric motor difficult, is that the vehicle does not follow a smooth predictable motion; therefore, it is possible for the eccentric motor to get in phase with the wind force, and the motor would augment the vehicle's motion.

A servomechanism control system which senses the vehicle's motion, relays the information to a control devise and directs an opposing force to act, is another form of the opposed forcing function. The sensing device could be an accelerometer which senses the vehicle's movement. The control device can filter out all frequencies except the vehicle's natural frequencies, thereby giving resistance only to forces or motion at the vehicle's natural frequencies. The opposing force could be gas jets placed around the vehicle.

Elimination of Structural Amplification

Structural resonance can be eliminated by eliminating the fixity of the base of the vehicle; therefore, the elimination of structural amplification would infer that the force of the vortices would not result in the bending of the vehicle but would result in the lateral movement of the total vehicle. Two techniques for eliminating structural amplification (which is estimated to be about 30 for the Saturn V) are: making a pendulum of the vehicle by suspending it at the top or allowing the base of the vehicle to wobble; however, the vehicle pendulum will be the only technique developed in this paper. These ideas are presented for completeness, and they are not to be construed as necessarily good solutions to the problem.

The vehicle pendulum eliminated structural amplification, but a new mode of vibration which has its resonance is created. This new resonance, however, can be controlled by placing hydraulic dampers at the base of the vehicle. Even if this were not the case, the pendulum natural frequency of the vehicle (e.g., the Saturn V) when suspended by the umbilical tower crane is so much smaller than the cantilever frequency (i.e.,

\[
\frac{f}{n} = \frac{1}{2\pi} \sqrt{\frac{g}{L}} = \frac{1}{2\pi} \sqrt{\frac{32.2}{250}} = 0.057 \text{ CPS}
\]

where \( L \) is the distance from the crane to the vehicle center of gravity), that the force of the vortices at resonance is only a fraction of those for the cantilever case. The resonant pendulum wind velocity is

\[
V = \frac{f}{n} \frac{D}{S} = \frac{(0.057)(33)}{0.2} = 9.4 \text{ ft/sec} = 6.4 \text{ mph}
\]
as compared to 46.4 mph, and since the wind force is a function of the square of the wind velocity, the force of the wind at cantilever resonance is 52 times that of the pendulum resonance. In addition to this, the pendulum resonance can be easily controlled by hydraulic dampers at the base. Some of the obvious drawbacks to this technique would be the lack of structural strength in the tower and its crane.

**Damper Brace**

A launch vehicle damper brace system may be described as a brace to resist the vehicle's movements while some movement of the brace is allowed in order to reduce the load at the vehicle attach points. The resistive element is a damper which absorbs and dissipates energy as it tracks the vehicles oscillations.

Three basic configurations were investigated: guy-rope, buttress and cantilevered damper brace. The guy-rope and buttress configurations were ruled out, because they produced much larger loads on the vehicle than the cantilevered configuration due to the acuteness of the strut-to-vehicle angle. Also, they would incur problems in retraction, reconnection and interference. Figure 9 is an illustration of the cantilevered damper brace for the Saturn V.

To facilitate the presentation of the efficacy of the damper brace, the Saturn V and its Launcher-Umbilical Tower will be used as the dynamic model. Consider the case of the vehicle (V) and tower (T) vibrating with a rigid damper brace (DB) pin jointed at the vehicle and tower. The generalized force may be determined by (using data from Table 3)

\[ F = 2\zeta K_v x_{DB} = 2(0.015) (12700) (33.5) = 12,800 \text{ lbs} \]

and the amplitude of oscillation is

\[ x_{DB} = \frac{F}{2\zeta K} = \frac{12,800}{(0.03) 165,700} = 2.58 \text{ in.} \]

\[ x_{CM} = 1.94 \times x_{DB} = 5 \text{ in.} \]

Now, assume the damper brace is flexible with \( K = 10,000 \text{ lb/in} \) and \( C = 2300 \text{ lb sec/in} \) and the umbilical tower is rigid. The deflection of the damper brace is

\[ x_{DB} = \sqrt{\left(\frac{1}{C_{DB} \omega}\right)^2 + \left(\frac{1}{K_{DB}}\right)^2} \]

\[ x_{DB} = 12,800 \sqrt{\left(\frac{1}{(2300) (3.5)}\right)^2 + \left(\frac{1}{10000}\right)^2} = 2.04 \text{ in.} \]

\[ x_{CM} = 1.94 \times x_{DB} \approx 4 \text{ in.} \]
Since it is conservative to assume that the total deflection is the sum of the two, then the maximum amplitude of the command module (CM) for a 99.9% wind is

\[5 \text{ in} < x_{CM} < 9 \text{ in}\]

In summary, the damper brace can reduce the amplitude of oscillation for an empty vehicle from 65 inches to less than 9 inches while producing a load that is less than 12,800 lbs on the vehicle.

Conclusions and Recommendations

Since experimental evidence indicates that the amplitudes of various wind-induced oscillating structures could become excessive, and steps should be taken to insure that these vehicles will be protected from the wind-induced oscillations. Four systems which could possibly become solutions to the problem are (in order of their overall qualities):

a. Damper brace between the umbilical tower and the vehicle
b. Helical strakes
c. Opposed forcing function in the form of a servomechanism control system.
d. Vehicle natural frequency modulation by putting $C_1 F$ in some of the tanks.

Each of these systems appears to be an effective, economical solution, and with further study, they may be proven to be good solutions to the problem. The following paragraphs will summarize the qualities of these systems.

The investigation yielded results that the damper brace could reduce the ±65 inches vibration amplitude at the Command Module to less than ±9-inches for 99.9% winds. It should be pointed out, however, that the umbilical tower will also vibrate at a smaller amplitude than the vehicle at corresponding elevations. All the damper brace configurations will impose attachment loads on the vehicle, but the proposed configuration should require only a small degree of local reinforcement to diffuse the load. It offers the most flexible retraction and reconnection characteristics of the systems considered.

The helical strakes are a good solution from the standpoint of efficacy and economics. Wind tunnel tests have shown that the helical strakes not only prevent wind-induced oscillations from occurring, but they help damp out vibrations from other sources. The problem with them is replacing them on the vehicle in the event of an abort. It may be necessary to remove them before fueling; otherwise, they may become frozen to the hydrogen and oxygen tanks. Since the strakes could not easily be reattached to the vehicle, an abort would leave the vehicle unprotected when the vehicle is defueled.

The servomechanism control system is theoretically a good solution; however, there is not much experimental information to support such a system, and time has not been taken to analyze it thoroughly. This system needs further study to determine if an effective system could be designed and if it would be an economical and reliable system.
Vehicle natural frequency modulation by putting $C\, Cl\, F$ in some of its tanks is a relatively simple technique. It would reduce the vehicle's amplitude at the Command Module from ±65 inches to ±12 inches for the Saturn V. Possible problems with this system are interference with the scheduled operations of the launch sequences and excessive load for the vehicle structure.

Another system which could be a solution to the problem is the combination of the damper brace and the strakes. The strakes would alleviate the oscillatory wind force on the vehicle which could result in a decrease in required structural stiffening at the vehicle damper brace attach points. The strakes could be removed before fueling, and the damper brace could provide protection until the strakes could be reattached. This system would provide the reliability necessary for launch vehicles.

Care has been taken not to overlook any good ideas; however, some ideas were not studied, because of the lack of empirical evidence to verify their efficacy. It may be that systems not studied in this report will later prove to be best systems to use; however, it was the intent of this study to present the latest information and finding. Perhaps future wind tunnel tests will uncover many good solutions to the problem.

References


FIGURE 1. SPANWISE CORRELATION

\[ R_e = 0.75 \times 10^6 \]

\[ \Delta x/D \]

FIGURE 2. VORTEX SHEDDING FREQUENCY.

\[ S, \text{ STROUHAL NUMBER} \]

\[ \frac{FD}{V} \]

\[ R_e, \text{ REYNOLDS NUMBER, } \frac{VD}{D} \]

TWO DIMENSIONAL FLOW ABOUT A CIRCULAR CYLINDER

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Figure 3. Normalized power spectrum for lift force.

\[
P(S) = 2 \left( \frac{\ell}{d} \right) \frac{(1+3\eta^2)}{(1+\eta^2)}^2
\]

where \( \eta = 2nS \frac{d}{d} \) and \( \frac{\ell}{d} = 2.4 \). 

\[
P(S) = \int_{S_{\min}}^{S_{\max}} dS = 1
\]

Figure 4. Tip spoilers.

(a) (b) (c)
FIGURE 5. RADIAL FINS.
FIGURE 7. SHROUD
(a) WAKE OF OSCILLATING SHROUDED CYLINDER; DOUBLE AMPLITUDE OF TIP = 0.04 D.

(b) WAKE OF OSCILLATING PLAIN CYLINDER; DOUBLE AMPLITUDE OF TIP = 0.8D.

FIGURE 8. WAKE OBSERVATIONS IN WATER CHANNEL TESTS, Re = 4640 (SEE FIGURES C AND D, REF. 8).

FIGURE 9. CANTILEVERED DAMPER BRACE
## TABLE 1. SATURN V VEHICLE (UNFUELED.)

<table>
<thead>
<tr>
<th>STATION (SEE FIG. A-3)</th>
<th>NORMALIZED ELEVATION</th>
<th>NORMALIZED MODE SHAPE</th>
<th>MASS</th>
<th>GENERALIZED MASS $M = \sum m_i \Psi_i^2$</th>
<th>GENERALIZED BENDING MASS $G = \sum m_i \Psi_i h_i$</th>
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<td>$i$</td>
<td>$h_i$</td>
<td>$\Psi_i$</td>
<td>$m_i$</td>
<td>$m_i \Psi_i^2$</td>
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<td><strong>TOTAL</strong></td>
<td>274.8</td>
<td>299.9</td>
</tr>
</tbody>
</table>

$H_1 = 3703$ in, $\Psi_H = 1$, $G_u = 299.9$ lb/in/sec$^2$

$h_H = 1$, NORMALIZING STATION.

$M_u = 274.8$ lb/in/sec$^2$

$\omega_u = 3.14$ RADIANS / SEC

$k_u = 2710$ lb/in

## TABLE 2. SATURN V VEHICLE -"HEAVY-TOPE.

<table>
<thead>
<tr>
<th>STATION (SEE FIG. A-3)</th>
<th>NORMALIZED ELEVATION</th>
<th>NORMALIZED MODE SHAPE</th>
<th>MASS</th>
<th>GENERALIZED MASS $M = \sum m_i \Psi_i^2$</th>
<th>GENERALIZED BENDING MASS $G = \sum m_i \Psi_i h_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$</td>
<td>$h_i$</td>
<td>$\Psi_i$</td>
<td>$m_i$</td>
<td>$m_i \Psi_i^2$</td>
<td>$m_i \Psi_i h_i$</td>
</tr>
<tr>
<td>1</td>
<td>1.000</td>
<td>1.000</td>
<td>220</td>
<td>220.0</td>
<td>220.0</td>
</tr>
<tr>
<td>2</td>
<td>0.806</td>
<td>0.675</td>
<td>3385</td>
<td>1540.0</td>
<td>1840.5</td>
</tr>
<tr>
<td>3</td>
<td>0.612</td>
<td>0.400</td>
<td>104</td>
<td>16.6</td>
<td>25.5</td>
</tr>
<tr>
<td>4</td>
<td>0.417</td>
<td>0.200</td>
<td>194</td>
<td>7.8</td>
<td>16.2</td>
</tr>
<tr>
<td>5</td>
<td>0.222</td>
<td>0.065</td>
<td>194</td>
<td>0.8</td>
<td>2.8</td>
</tr>
<tr>
<td>6</td>
<td>0.028</td>
<td>0.0</td>
<td>725</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
<td>0.0</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>TOTAL</strong></td>
<td>1785</td>
<td>2105</td>
</tr>
</tbody>
</table>

$H_1 = 3703$ in, $\Psi_H = 1$, $G_T = 2105$ lb/in/sec$^2$

$h_H = 1$, NORMALIZING STATION.

$M_T = 1785$ lb/in/sec$^2$

$\omega_T = 1.232$ RADIANS / SEC

$k_T = 2710$ lb/in
TABLE 3. SATURN V (EMPTY) AND UMBILICAL TOWER DATA

<table>
<thead>
<tr>
<th>VEHICLE (V)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>STA.</td>
<td>NORMALIZED MODE SHAPE</td>
</tr>
<tr>
<td>i</td>
<td>( \psi )</td>
</tr>
<tr>
<td>1</td>
<td>1.940</td>
</tr>
<tr>
<td>2</td>
<td>1.310</td>
</tr>
<tr>
<td>DB</td>
<td>1.000</td>
</tr>
<tr>
<td>3</td>
<td>0.776</td>
</tr>
<tr>
<td>4</td>
<td>0.388</td>
</tr>
<tr>
<td>5</td>
<td>0.126</td>
</tr>
<tr>
<td>6</td>
<td>0.000</td>
</tr>
<tr>
<td>7</td>
<td>0.000</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1033.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOWER (T)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>STA.</td>
<td>NORMALIZED MODE SHAPE</td>
</tr>
<tr>
<td>8</td>
<td>( \psi )</td>
</tr>
<tr>
<td>9</td>
<td>1.39</td>
</tr>
<tr>
<td>DB</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>0.79</td>
</tr>
<tr>
<td>11</td>
<td>0.38</td>
</tr>
<tr>
<td>12</td>
<td>0.04</td>
</tr>
<tr>
<td>TOTAL</td>
<td>12047</td>
</tr>
</tbody>
</table>

\[
\omega_V = 2 \pi f_V = (2 \pi)(0.557) = 3.50 \text{ rad. sec.}^{-1}
\]

\[
K_V = \omega_V^2 \left( \sum m_i \psi_i^2 \right)_V = 12,700 \text{ lb. in.} \]

\[
\omega_T = 2 \pi f_T = (2 \pi)(0.567) = 3.56 \text{ rad. sec.}^{-1}
\]

\[
K_T = \omega_T^2 \left( \sum m_i \psi_i^2 \right)_T = 153,000 \text{ lb. in.} \]

\[
K = K_V + K_T = 165,700 \text{ lb. in.} \]

---

**BENDING DIRECTION FOR DATA**

![Diagram](attachment:image.png)