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# NASA LeRC's Acoustic Fill Effect Test Program and Results

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# NASA LeRC's Acoustic Fill Effect Test Program and Results

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## Summary

NASA Lewis Research Center, in conjunction with General Dynamics Space Systems Division, has performed a test program to investigate the acoustic fill effect for an unblanketed payload fairing for a variety of payload simulators. This paper will discuss this test program and fill factor test data, and make comparisons with theoretical predictions. This paper will also address the NASA acoustic fill effect standard which was verified from the test data analysis.

## Introduction

The understanding of acoustic fill effects for specifying an acoustic environment is critical for payload hardware design and testing. The fill effect is the term used to describe the changes in the interior sound pressure levels (SPL) of an expendable launch vehicle's (ELV) payload fairing (PLF) or the Space Shuttle's cargo bay caused by the presence of the payload.

Often, the acoustic environment defined for ELVs or the Space Shuttle is representative of the unfilled or empty environment. It then becomes necessary to account for the presence of the payload fill and its effects on the interior SPL. Historically, fill effects were determined from one of three different fill factor curves available within the aerospace community [1-3]. In order to reduce disputes between multiple organizations involved with a NASA program, while maintaining the proper acoustic environments, it was important for NASA to develop a fill effect standard.

NASA Lewis Research Center (LeRC), in conjunction with General Dynamics Space Systems Division (GDSSD), has recently completed a test program to investigate the acoustic fill effect for an unblanketed payload fairing for four different payload simulators. The fill effect is the difference in the interior SPL between the filled PLF test data arid the empty PLF test data. The analysis of the data obtained enabled NASA LeRC to define a NASA fill effect standard. This standard has been incorporated into the "NASA Standard for Vibroacoustic Test Criteria."

## Test Program's Objectives

Since data to support the understanding of the acoustic fill effect is limited, and often proprietary, NASA LeRC in coordination with GDSSD developed a test program whose primary purpose was to investigate the fill effect for a number of simplified payload fills. In addition to measuring the fill effect in the interior of the PLF, the test program's objectives were to investigate how the fill effect varied with radial fill, volume fill and payload shape. The analysis of the test data would result in advancing the aerospace community's understanding of the fill effect and the establishment of a NASA fill effect standard.

## Payload Fairing Test Structure

GDSSD's 14-ft diameter Atlas/Centaur PLF was used for the testing. The basic fairing structure consists of a thin aluminum skin with longeron stringers, and ring frames at intervals. The PLF test hardware was full scale and of flight quality. The PLF test structure consisted of the nose cone section without cork on the exterior surface, the fairing cylindrical section, the boattail and the stub adapter.

In the boattail region's interior was an equipment module (EM) and payload adapter (PLA). The avionics components on the EM were mass simulated. The forward bulkhead of the Centaur tank, underneath the EM, was represented with a foam filled volumetric simulator. The PLF had no acoustical blankets. All openings in the PLF, such as vents and port holes, were sealed to prevent acoustic leakage. Figure 1 illustrates the test article stackup.

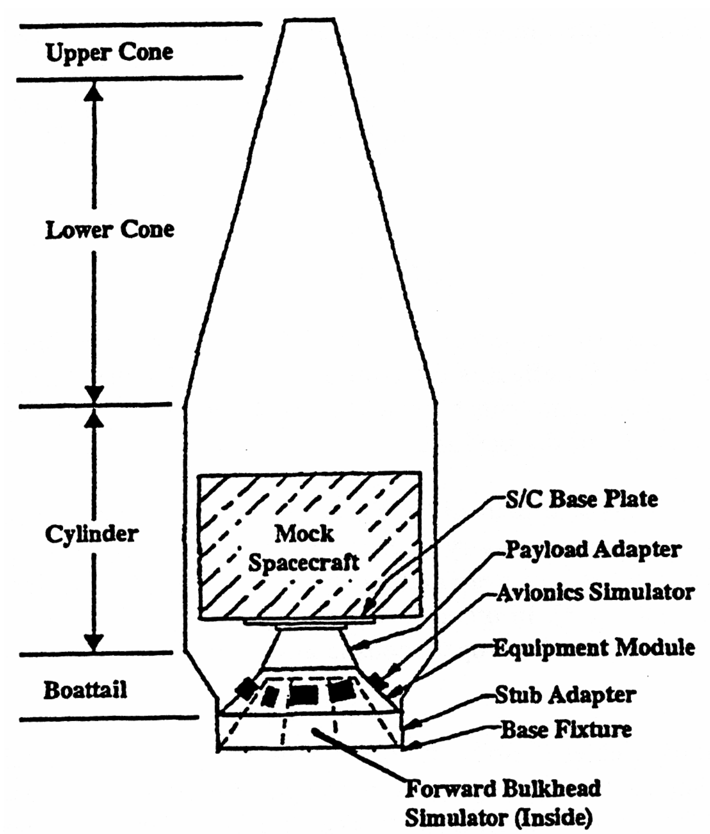



Figure 1.—Test article stackup.

## Spacecraft Mockup Test Units

The mock spacecraft units were designed to acoustically perform similar to a real payload. The design goals were to make the spacecraft impedance much greater than the impedance of the air in the gap between the fairing skin and the mock spacecraft and to prevent radiation of acoustic energy from the interior of the mock spacecraft.

To accomplish these goals the top, bottom and side walls were constructed of 1-in, thick particle board wood with an approximate surface weight of 4 lb/ft$^2$. The units had interior wood framing. The interior volume was completely filled with 2.0 lb/ft$^3$ polyurethane foam. The exterior surfaces of the mockup units were painted with a commercial grade high gloss paint to minimize absorption by the spacecraft mockup. All mock spacecraft units were of similar construction.

The mock spacecraft units were designed to yield representative fill factors and interior SPL by simulating the geometry of current and future actual payloads. The mockups also needed to be simple enough in geometry to aid the interpretation of the test data. The four different mockup spacecraft units that were tested are shown in figure 2.

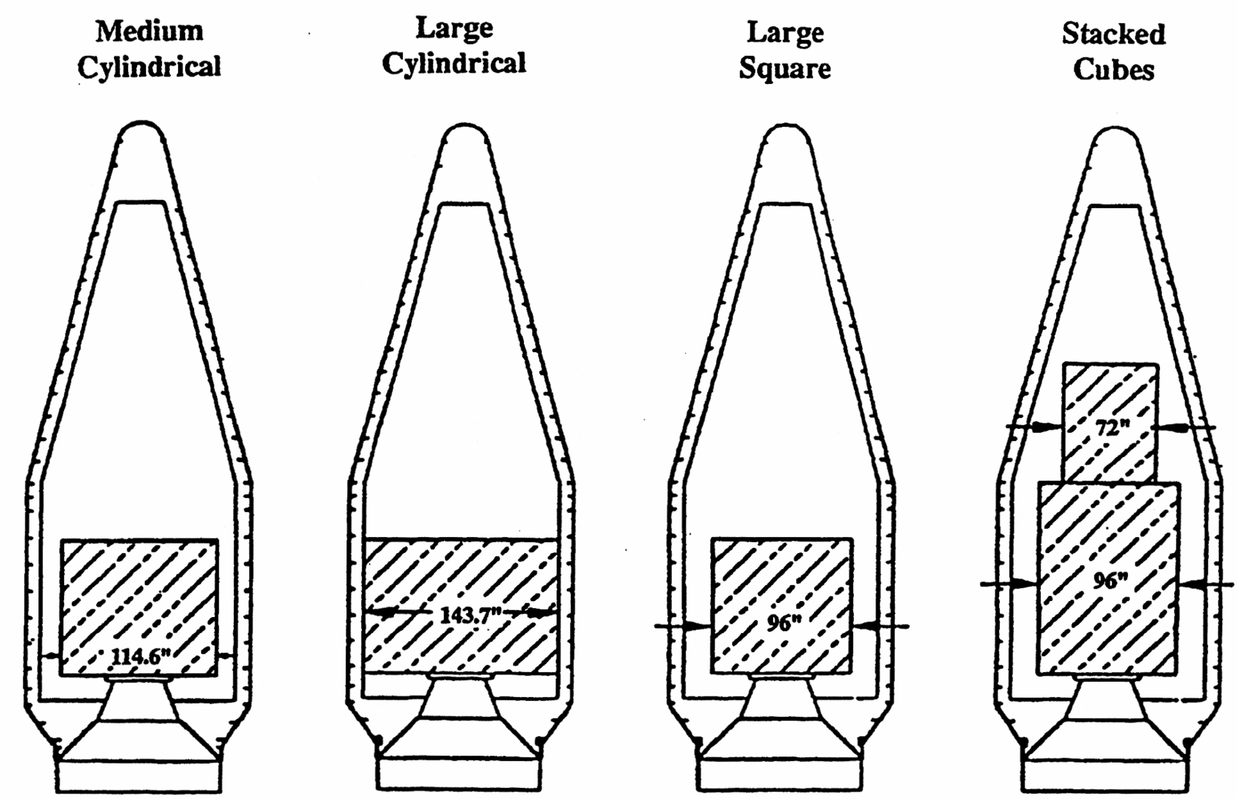



Figure 2.—Mock spacecraft configurations.

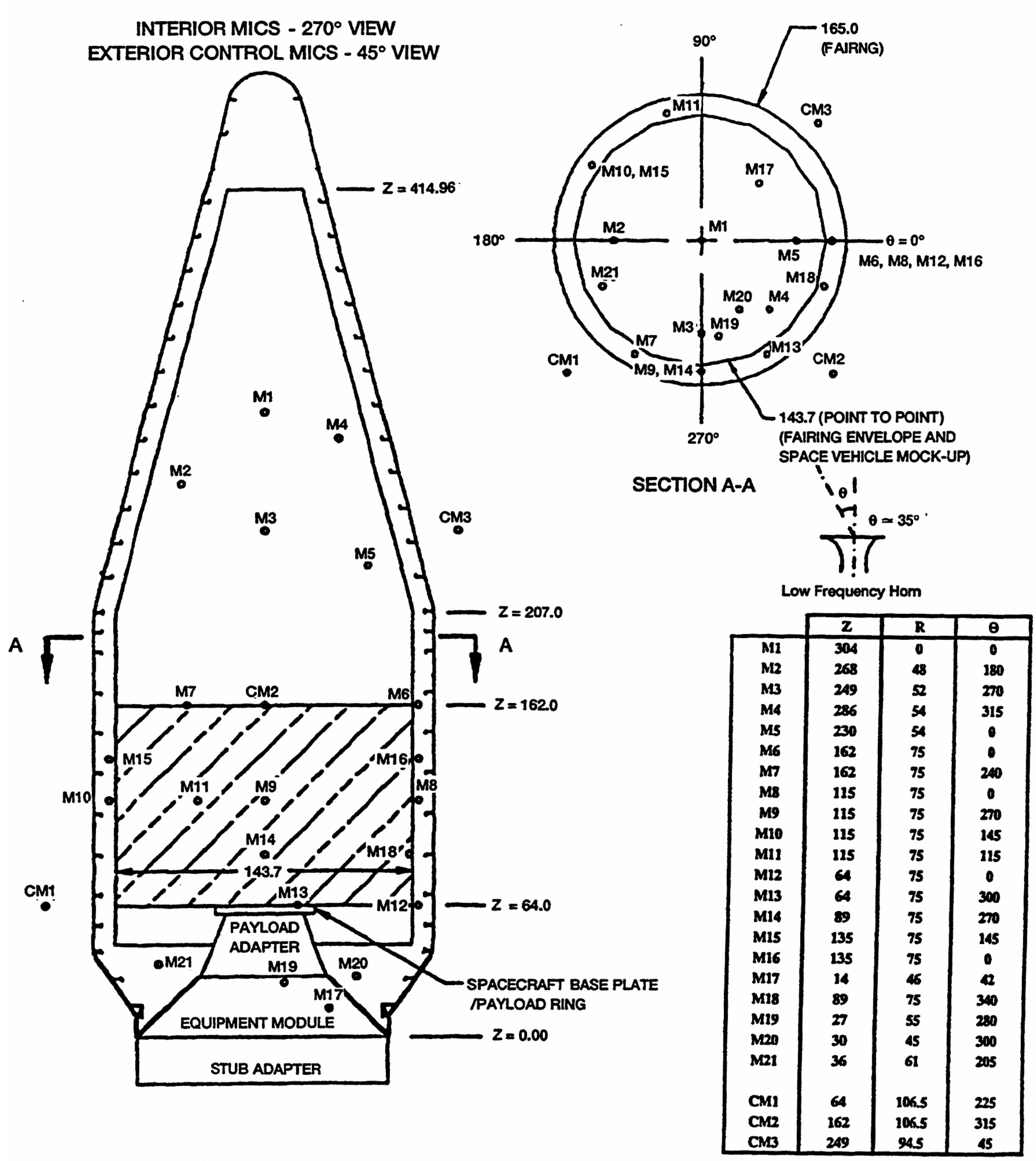
The first mockup denoted as "medium cylindrical" is a 16 sided polygon, with a diameter of 114.6 in. resulting in an average distance of 25.8 in. between the mock spacecraft and the PLF inner skin. The mockup has a height of 98.0 in. (3/4 of the height of the fairing cylindrical section) and weighed 2900 lb.

The second mockup or "large cylindrical" unit is a 16 sided polygon, with a diameter of 143.7 in. resulting in an avenge distance of 11.4 in. between the mock spacecraft and PLF inner skin. The mockup has a height of 98.0 in. and weighed 4400 lb.

The third mockup is a "large square" whose width is 96.0 in. The distance of the mockup to the PLF inner skin varied from 14.6 to 34.5 in. The mockup has a height of 98.0 in. and weighed 3120 lb. The payload volume fills of the medium cylindrical unit and the large square unit are approximately the same (within 8%).

The fourth mockup consisted of “stacked cubes” resulting in significant nose cone fill. An extension was added to the large square unit to form a larger lower unit (96.0 by 96.0 by 148.0 in.). A smaller cube (72.0 by 72.0 by 74.0 in. was placed on top of the lower unit and extended into the nose cone of the PLF. The distance between the “stacked cubes” and the PLF inner skin varied from 11.2 to 45.2 in. The unit weighed 6380 lb.

The goal of identifying small fill effects requires well controlled test to test repeatability of the external SPL, along with a sufficient number of test measurements. A total of 24 microphones and 14 accelerometers were utilized for each test. The microphone locations are illustrated in figure 3.




| | Z | R | θ |
|---|---|---|---|
| M1 | 304 | 0 | 0 |
| M2 | 268 | 48 | 180 |
| M3 | 249 | 52 | 270 |
| M4 | 286 | 54 | 315 |
| M5 | 230 | 54 | 0 |
| M6 | 162 | 75 | 0 |
| M7 | 162 | 75 | 240 |
| M8 | 115 | 75 | 0 |
| M9 | 115 | 75 | 270 |
| M10 | 115 | 75 | 145 |
| M11 | 115 | 75 | 115 |
| M12 | 64 | 75 | 0 |
| M13 | 64 | 75 | 300 |
| M14 | 89 | 75 | 270 |
| M15 | 135 | 75 | 145 |
| M16 | 135 | 75 | 0 |
| M17 | 14 | 46 | 42 |
| M18 | 89 | 75 | 340 |
| M19 | 27 | 55 | 280 |
| M20 | 30 | 45 | 300 |
| M21 | 36 | 61 | 205 |
| CM1 | 64 | 106.5 | 225 |
| CM2 | 162 | 106.5 | 315 |
| CM3 | 249 | 94.5 | 45 |

Figure 3.—Microphone locations.

Three control microphones (CM1-CM3) were used to measure the PLF exterior SPL. The placement of these control microphones was similar to past GDSSD fairing tests.

The remaining 21 microphones were distributed throughout the PLF's interior. The interior microphones were suspended on bungy cords between convenient fairing structures (vibration isolated) and remained fixed to the PLF during test chaugeouts. Careful planning minimized the movement of microphones. Only microphone2 M14 needed relocating for a single test. All other microphones were in the exact same locations for all five tests (empty PLF and four filled tests).

The region of high fill (PLF cylinder) was of particular interest and therefore was monitored by 12 microphones (M6-M16, M18). Five different station levels were measured in the area of mock spacecraft fill.

The nose cone region was measured by five microphones (M1-M5). The boattail and EM region was measured by four microphones (M17, M19-M21).

The microphones in all regions, were irregularly distributed to give a good circumferential sampling.

The accelerometers were used to monitor the mock spacecraft vibration and verified that the spacecraft mockup units were not responding unusually. Other accelerometers were used to monitor the fairing's skin and frames and to measure the response of the EM and PLA. Further details of the test accelerometers are not relevant to the objectives of this paper.

## Test Order

To aid in the understanding of results, testing was performed in a specific order. Test #1 was the empty PLF test, which provided the baseline levels for assessing the fill effect. Test #2 had the medium cylindrical mockup, which was expected to give the smallest fill effect. Test #3 had the large cylindrical mockup, expected to give a larger fill effect but otherwise similar to Test #2 in geometry. Test #4 had the large square mockup, which had a more complicated geometry than the cylinder units but roughly the same volume fill as Test #2. Finally, Test #5 had the stacked cubes mockup which was similar to Test #4 with extension into the nose cone. Further details of the test program are found in reference 4.

## Test Results

The testing was performed from March 4-24, 1994 at GDSSD's Acoustic/Thermal Test Facility in San Diego, California. During the tests the external microphones were controlled to simulate the Atlas I external launch environment (146.7 dB OASPL).

The acoustic microphone data obtained was of excellent quality for all the tests. Typical acoustic test plans require controlling the PLF exterior SPL to ±3 dB in each one-third octave band, but for this test the GDSSD test personnel were asked to control to ±1 dB in each one-third octave band. Figure 4 illustrates that they were successful. This resulted in excellent test to test repeatability, which is crucial when looking for small fill effect differences between Test #1 and Tests #2-5.

To aid in the interpretation of results, the microphones were grouped into seven zones. Zone 1 was the PLF exterior region made up of microphones CM1-CM3. Zone 2 was the cone region defined as microphones M2-M5. Zone 3 was the cylinder region consisting of M8-M 11, M 14-M 16 and M18. Zone 4 was the equipment module region defined as M17, M19-M21. Zone 5 was the cylinder's upper transition region consisting of M6-M7. Zone 6 was the cylinder's lower transition region defined as M12-M13. Zone 7 was the only centerline measurement, Ml.

To compute the zonal averages, an arithmetic average of the decibel levels was calculated on the appropriate microphone set. The zonal averages are then used to compute the zone fill effect. For example, to compute the fill effect for the cylindrical region, Zone 3, the empty Zone 3 average is subtracted from the filled Zone 3 average.

Corrections for slight external differences between tests have been done. However, in the interest of simplicity and clarity, the data will be shown uncorrected for external differences. As figure 4 illustrates, correcting the data for external differences results in little change in the final conclusions.

Figure 5 illustrates how each of the zones vary for the medium cylindrical fill (Test #2). The other tests show similar characteristics. First note that the SPL for some zones exceeds the external control average SPL (Zone 1). This occurs at strong individual acoustic modes of the PLF's interior volume. Various payload fills can shift the number and frequencies of these peaks, but this phenomena occurs even for the empty PLF test data.

Next note that Zone 7, corresponding to a single microphone Ml, is significantly lower than the rest of the test data, below 160 Hz. This was also consistent throughout all the tests. The low SPL seen for this centerline microphone is due to its being on an acoustic node and is consistent with previous centerline test data.

As a final note for figure 5, the high frequency (500 Hz and above) test data converges for Zones 2-7. This was also noted in all five tests. This is due to the fact that at high frequencies there are many acoustic modes which create a diffuse field and thus little spatial variation exists within the fairing's interior.

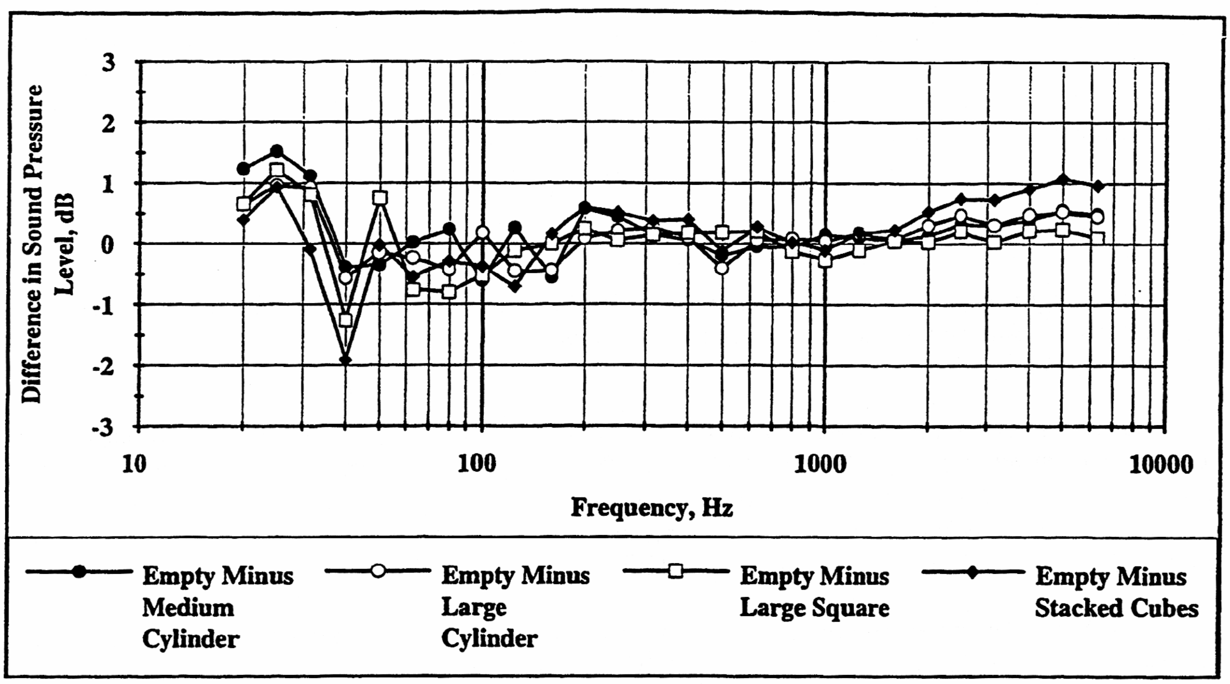



Figure 4.—Differences in external levels (zone 1 average) between filled and empty test configurations.

The fill effect is the difference between the filled test data and the empty test data in the filled zone of interest (Zone 3). Figures 6 to 9 show the average SPL for the cylindrical region (Zone 3) and the PLF exterior region (Zone 1) for the empty and the four spacecraft mockup tests, respectively. The Zone 1 curves are provided to show that the external levels did not vary significantly.

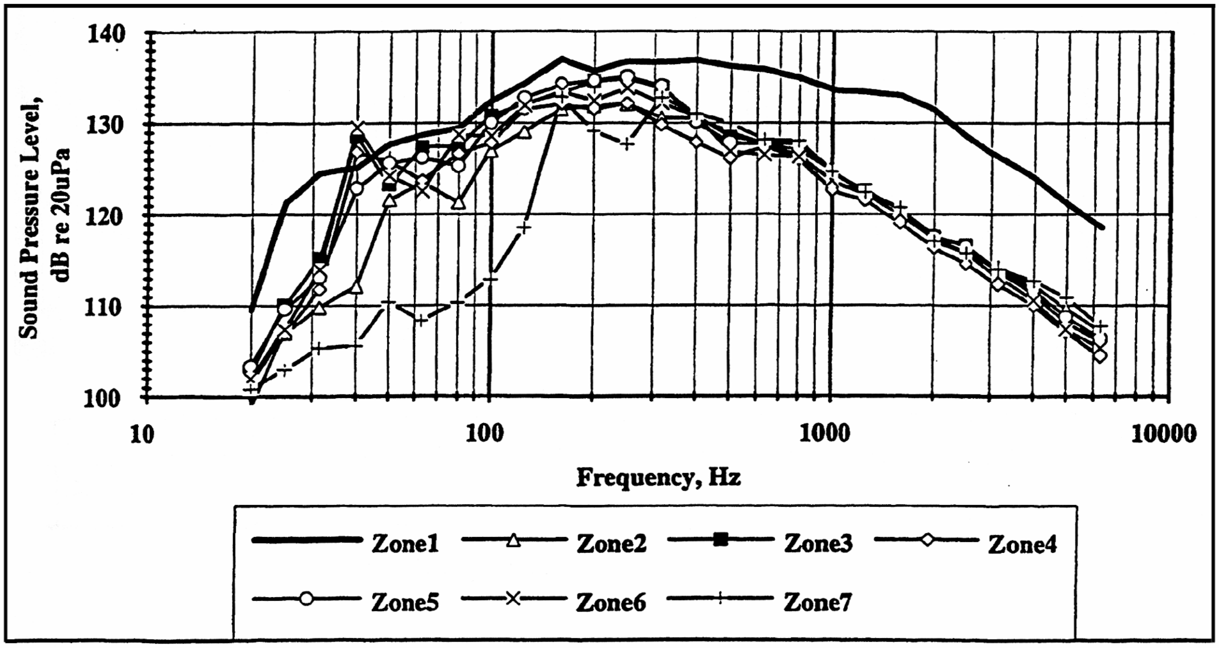



Figure 5.—Medium cylindrical fill (test #2) zonal averages (dB).

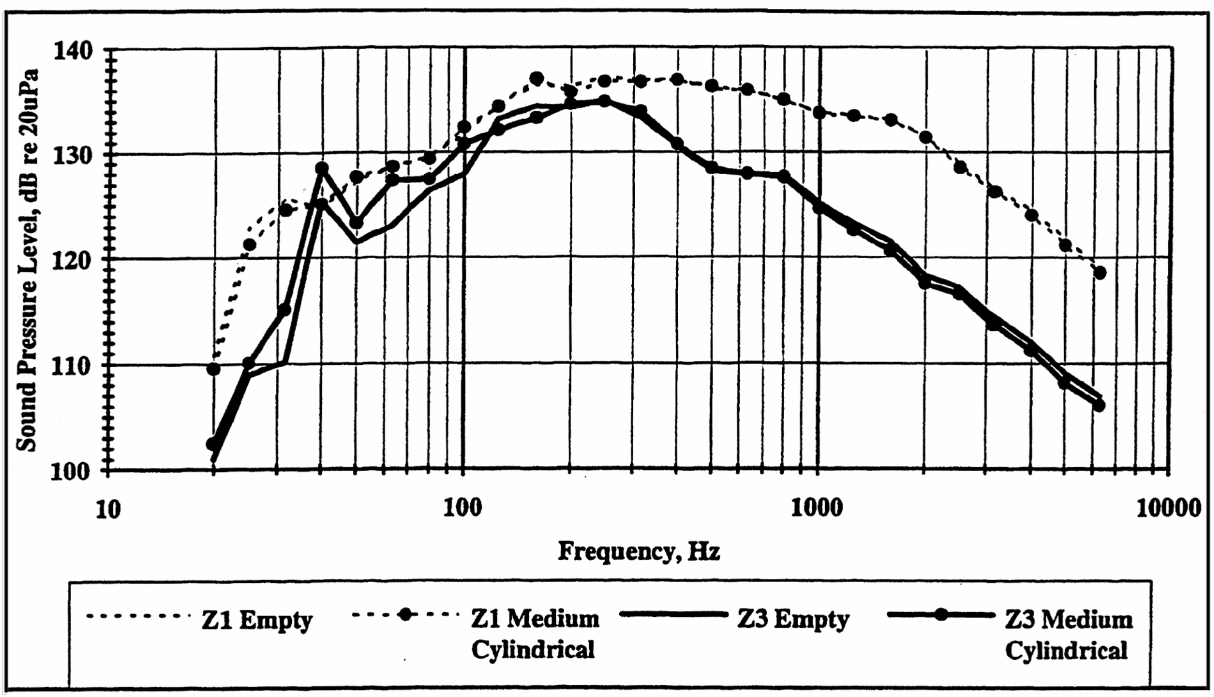



Figure 6.—Zonal averages (Z1,Z3) for the empty and medium cylindrical tests.

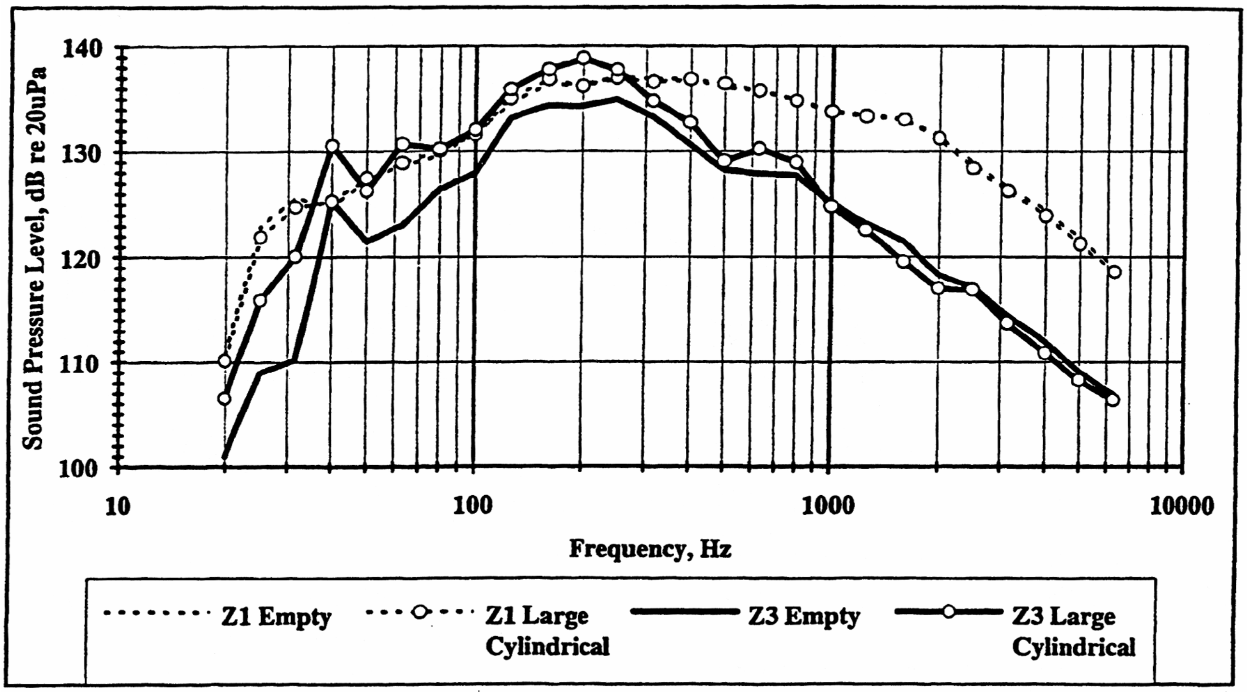



Figure 7.—Zonal averages (Z1,Z3) for the empty and large cylindrical tests.

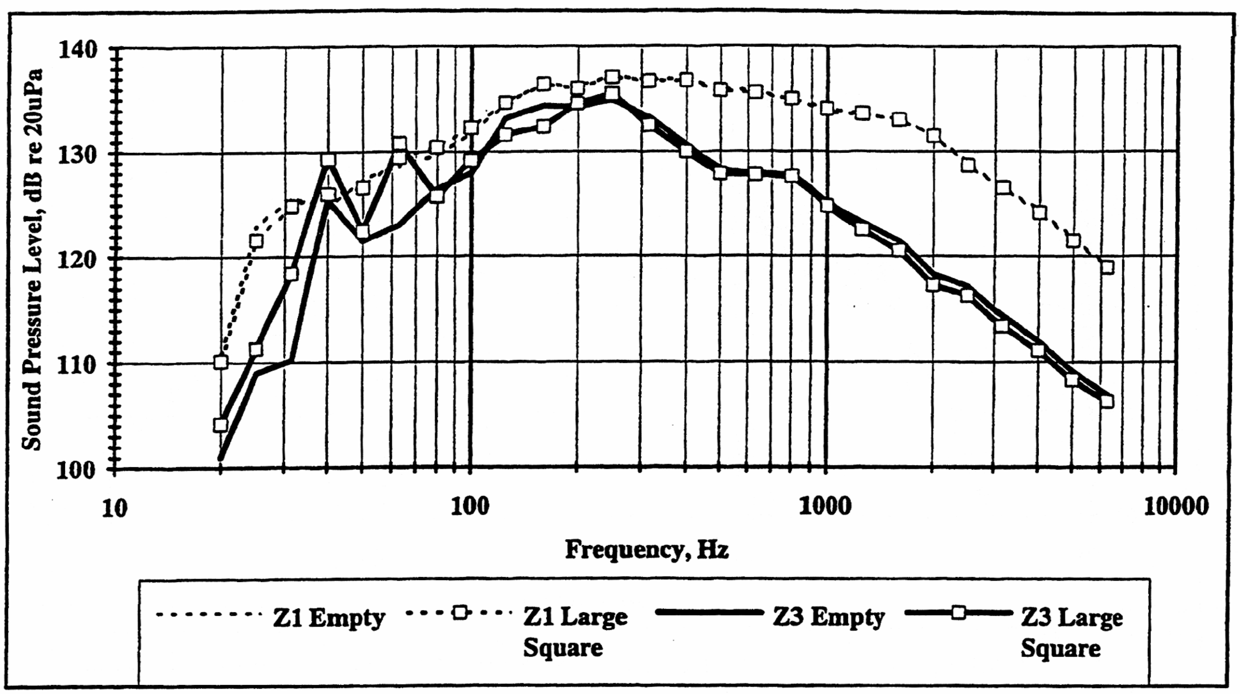



Figure 8.—Zonal averages (Z1,Z3) for the empty and large square tests.

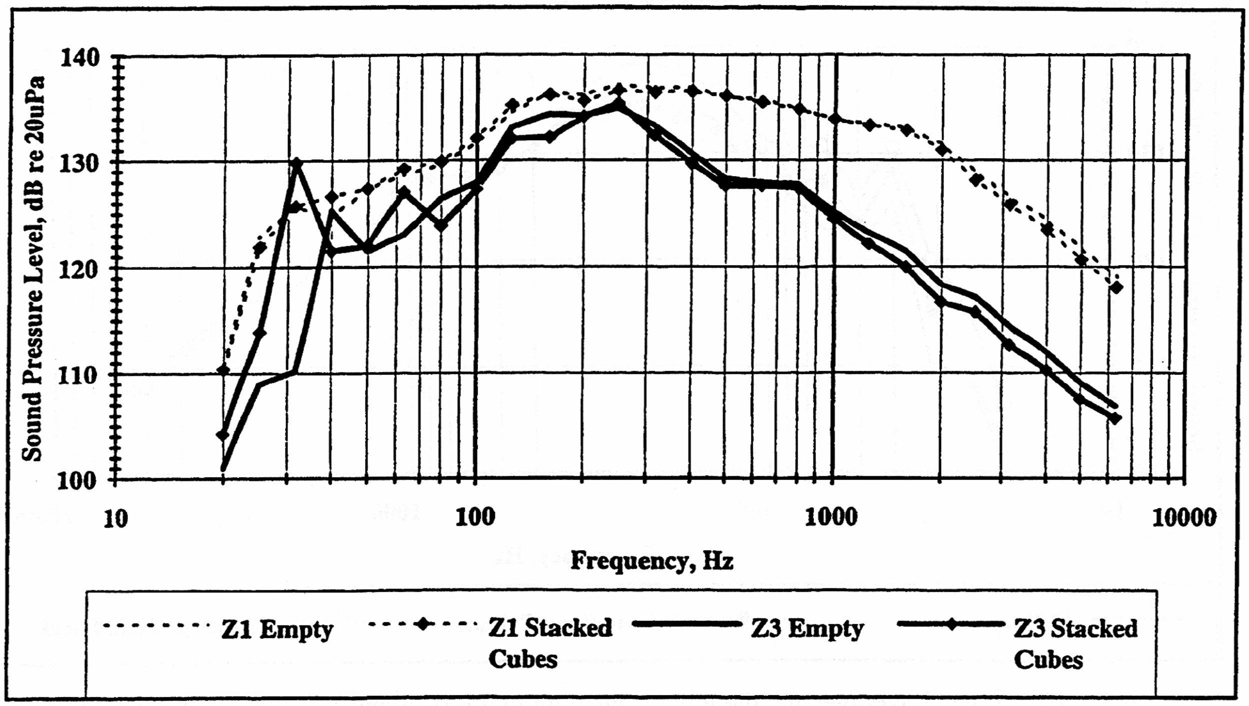



Figure 9.—Zonal averages (Z1,Z3) for the empty and stacked cubes tests.

Looking at the difference between the empty and the medium cylindrical Zone 3 test data in figure 6, one sees a relatively small fill effect, on the order of 2 to 3 dB at the low frequencies. The minor negative fill at high frequencies is believed to be due to typical spacecraft absorption effects. Correcting the fill factor for differences in the external Zone 1 test levels would result in a small correction. These last two points apply to all four test configurations.

Figure 7 compares the empty and the large cylindrical fill test data for Zones 1 and 3. The measured fill effect is around 6 dB at the low frequencies. Note that due to the large volume fill, the fill effect is positive out to 1000 Hz.

As can be seen in figure 10, the test measured fill is significantly larger for the large cylindrical test compared to the medium cylindrical test. This is in line with pretest expectations and predictions and is due to the large cylindrical unit's increased payload volume and decreased distance between the spacecraft mockup and the PLF's wall.

Figure 8 compares the Zones 1 and 3 data for the empty and the large square tests. If payload volume fill is the major factor in the fill effect as expected, then one would expect the Zone 3 fill for this case to be similar to that of the medium cylindrical case, since they are within 8% of each other in volume. Figure 11 illustrates this to be the case. The primary difference is that the 63 Hz acoustic mode is responding in the large square test much more than it did in the medium cylindrical test. This demonstrates that the presence of a payload/PLF combination creates unique acoustic modes within the PLF.

Figure 9 compares the empty and stacked cubes test data for Zones 1 and 3. The concept that acoustic modes within the fairing are dependent on the payload/PLF combination is again illustrated by figure 12, which compares the empty, large square fill and the stacked cubes fill test data. The 40 Hz peak seen in the large square test data has shifted to 32 Hz in the stacked cubes test data. Narrowband analysis shows

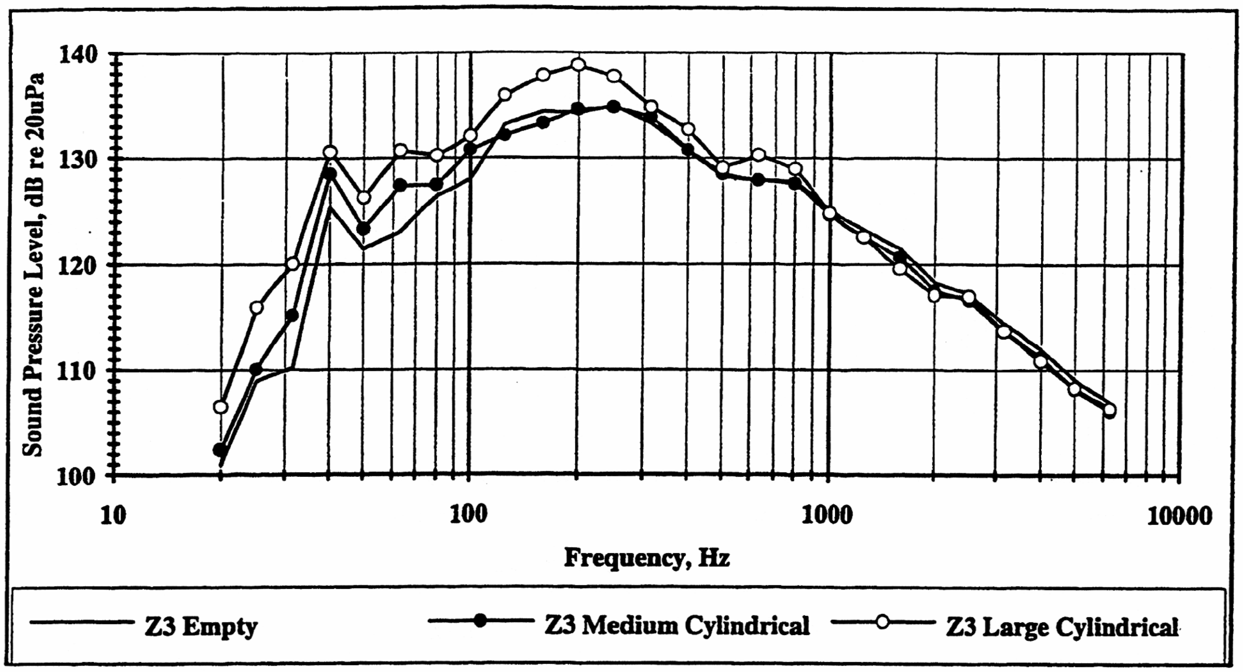



Figure 10.—Zone 3 averages for the empty, medium cylindrical and large cyclindrical tests.

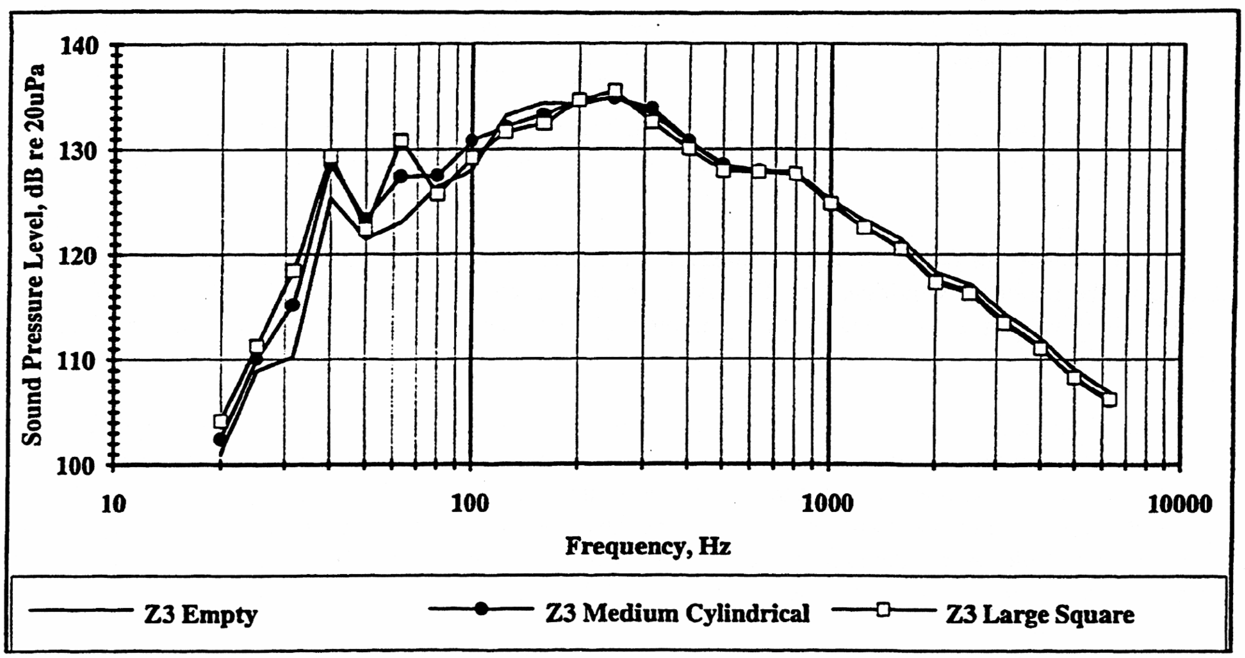



Figure 11.—Zone 3 averages for the empty, medium cylindrical and large square tests.

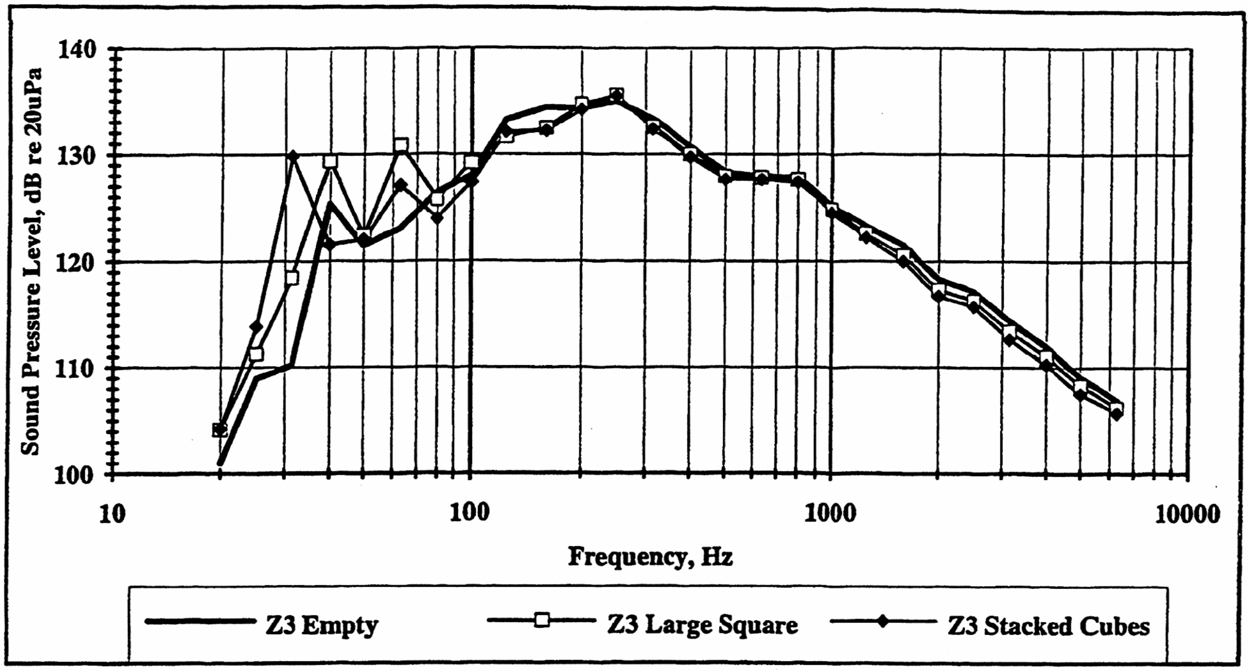



Figure 12.—Zone 3 averages for the empty, large square and stacked cubes tests.

that this first circumferential acoustic mode has also shifted between the empty test (#1) and all the filled tests (#2–5), but had previously stayed within the same 40 Hz 1/3 octave band [5].

The test data for Zone 3, the filled cylindrical region, is summarized in table I. This paper concentrates on the fill effects in the cylindrical filled region, but other areas will be briefly addressed here with some general statements. The SPLs in the cone region is not greatly affected by the cylindrical region's fill. The SPL's in the boattail region were slightly negative (–1 to –2 dB), perhaps due to the mockups blocking the acoustic path to the boattail. The vibration of the avionics boxes on the equipment module were less in the filled tests than in the empty test and nearly the same for all four filled tests. This may indicate that structureborne vibration is the driver for these boxes. Further test data may be found in references 5 and 6.

## Fill Effect Theory

Statistical Energy Analysis (SEA) is commonly used to predict the acoustic levels within an ELV fairing using either the VAPEPS or PLFNOISE computer codes. Although there are slight differences in these codes, they both implement the fundamental concepts of SEA and provide predictions that fit well with flight data for PLF's that have low payload fills.

The SEA computer codes mentioned above cannot currently predict the fill effect. However, the SEA theory can be extended for this purpose. Using SEA the equations governing the response of the PLF interior acoustic space are expressed in terms of the modal energy of the space. Modal energy is defined as the timeaverage kinetic plus potential energy of a mode averaged over all modes of the acoustic space that have resonance frequencies in a given frequency band, typically a one-third-octave band. The space-avenge meansquare acoustic pressure in the PLF interior in a one-third-octave band can be written in terms of the average modal energy as

TABLE I.—TEST SPL FOR ZONE 3 CYLINDRICAL REGION
(dB, ref 2OuPa)

| Frequency Hz | Empty | Medium Cylindrical | Large Cylindrical | Large Square | Stacked Cubes |
|---|---|---|---|---|---|
| 20 | 101.0 | 102.4 | 106.5 | 104.1 | 104.2 |
| 25 | 108.9 | 110.0 | 115.9 | 111.3 | 113.9 |
| 31.5 | 110.2 | 115.2 | 120.1 | 118.4 | 129.8 |
| 40 | 125.3 | 128.5 | 130.6 | 129.3 | 121.5 |
| 50 | 121.5 | 123.3 | 126.3 | 122.4 | 122.0 |
| 63 | 123.0 | 127.4 | 130.7 | 130.8 | 127.1 |
| 80 | 126.4 | 127.4 | 130.2 | 125.7 | 123.9 |
| 100 | 128.0 | 130.8 | 132.0 | 129.2 | 127.3 |
| 125 | 133.2 | 132.1 | 1359 | 131.6 | 132.1 |
| 160 | 134.4 | 133.3 | 137.8 | 132.4 | 132.2 |
| 200 | 134.3 | 134.6 | 138.8 | 134.6 | 134.1 |
| 250 | 135.0 | 134.8 | 137.7 | 135.5 | 135.4 |
| 315 | 133.3 | 133.9 | 134.8 | 132.5 | 132.4 |
| 400 | 130.7 | 130.8 | 132.7 | 130.0 | 129.7 |
| 500 | 128.3 | 128.5 | 129.1 | 127.9 | 127.6 |
| 630 | 127.9 | 127.9 | 130.3 | 127.8 | 127.6 |
| 800 | 127.8 | 127.6 | 129.0 | 127.6 | 127.4 |
| 1000 | 125.1 | 124.7 | 124.8 | 124.8 | 124.5 |
| 1250 | 123.2 | 122.6 | 122.5 | 122.5 | 122.2 |
| 1600 | 121.5 | 120.7 | 119.6 | 120.5 | 120.0 |
| 2000 | 118.3 | 117.6 | 117.0 | 117.3 | 116.7 |
| 2500 | 117.2 | 116.6 | 116.9 | 116.3 | 115.7 |
| 3150 | 114.4 | 113.7 | 113.7 | 113.4 | 112.7 |
| 4000 | 112.0 | 111.2 | 110.8 | 111.1 | 110.3 |
| 5000 | 109.1 | 108.2 | 108.3 | 108.3 | 107.5 |
| 6300 | 106.9 | 106.0 | 106.3 | 106.2 | 105.7 |
| OA5PL | 142.7 | 142.8 | 145.7 | 142.7 | 142.3 |

$$\left\{p_i^2\right\} = \rho_i \, c_i^2 \left(\frac{N_i}{V_i}\right) e_i \tag{1}$$

where $\rho_i$ is the acoustic density, $c_i$ is the acoustic speed of sound, $N_i$ is the number of acoustic modes with resonance frequencies within the one-third-octave band, $V_i$ is the volume of the acoustic space, and $e_i$ is the average modal energy. Using this equation one obtains a general prediction of the fill factor,

$$Fill\ Factor = 10\,Log_{10}\left[\frac{V_{emtpy}\ N_{filled}\ e_{filled}}{V_{filled}\ N_{empty}\ e_{empty}}\right]$$

where subscripts refer to the empty and filled conditions.

A simplified prediction of the fill factor is obtained by assuming that the payload fill does not change the modal energy of the interior space, so that the ratio of the filled to empty modal energies can be set to one. Within the limitations of this assumption the fill factor depends only on the volume ratio and the ratio of the number of modes in the filled and unfilled space.

For large diameter PLF’s and at higher frequencies, the number of acoustic modes in a given one-thirdoctave band can be estimated using the product of the modal density and the frequency bandwidth. The modal density of the empty PLF interior acoustic space is proportional to the volume of the space and is given by

$$N_{empty} = 4\pi \frac{f^2}{c_o^3} V_{empty} \left[1 + \phi_1\right] \Delta f \tag{3}$$

where $f$ is the band-center frequency in Hertz, $\Delta f$ is the frequency bandwidth, and $\phi_1$ is a correction term to account for boundary conditions at the edges of the space. The correction term is generally small and is often neglected in acoustic analysis programs, such as VAPEPS. The modal density for the filled space can be determined by modelling the interior space between the fairing wall and the payload as a two-dimensional annular space. In this case the correction term cannot be ignored and the modal density is given by

$$N_{filled} = 4\pi \frac{f^2}{c_o^3} V_{filled} \left[1 + \frac{c_o}{2fH}\right] \Delta f \tag{4}$$

where $H$ is the thickness of the two-dimensional space or the gap distance between the faking and the payload. The ratio of the number of modes for the filled and unfilled space can be written as

$$\frac{N_{filled}}{N_{empty}} = \frac{V_{filled}}{V_{empty}} \frac{\left[1 + \frac{c_o}{2fH}\right]}{\left[1 + \phi_1\right]} \tag{5}$$

At low frequencies this ratio becomes very large, suggesting large fill factors. However, it should be recognized that the number of modes is an integer variable. Thus, when the product of modal density and bandwidth is less than one, the modal density formulation should not be used and the number of modes should be set to either one, if the band contains an acoustic mode, or zero, if no mode exists. Since the acoustic environment will be very low in frequency bands where no modes exist, the condition in which either the filled or empty acoustic space has no modes can be ignored. Thus, an upper limit on the ratio of the number of modes is set at one. This condition can be achieved by letting the correction term $\phi_1$ be

$$\phi_1 = \frac{V_{filled}}{V_{empty}} \frac{c_o}{2fH} \tag{6}$$

The simplified SEA prediction of the fill factor becomes

$$FF = 10\ Log_{10} \left[ \frac{1 + \frac{c_o}{2fH}}{1 + \left[\frac{V_{filled}}{V_{empty}}\right] \frac{c_o}{2fH}} \right] \tag{7}$$

At high frequencies the fill factor approaches zero, while at low frequencies the fill factor depends only on the ratio of the empty to filled volumes. Both limits are consistent with the currently used fill factors.

## Test Versus Predicted Fill Factors

The equations from the previous section were utilized to make fill factor predictions for all four test mockups prior to testing. This theory was originally developed by Dr. Manning, under contract to NASA LeRC [2 and 7].

The test measured fill factors are the difference in the Zone 3 averages between the filled and empty configurations. The test derived fill factors are obtained by correcting the test measured fill factors with the test to test external SPL differences (Zone 1).

The test data fill factors presented in this paper are the difference of zonal means. Test fill factors based on the difference of zonal statistical P95%150% levels were also calculated and resulted in very similar, slightly lower fill factors.

The pretest theoretical predictions agreed well with the test derived fill factors. In general, the predictions closely approximated the test data, with some exceptions. These predictions versus the fill factors obtained from the test are given in figures 13 to 16 and table II.

Some larger than predicted fill factors were seen at some frequencies in the test data. These deviations are due to two causes.

First, some higher than predicted fill factors were due to a low empty fairing SPL, as opposed to a high filled fairing SPL. This occurred at 32 Hz for all four fills and to some extent at 63 Hz, particularly for the medium cylindrical fill. Since fill factors are typically added to empty PLF specifications, which are themselves normally smoothed envelopes, the discrepancy between the measured and the predicted fill factors is not seen as a problem. That is, adding the predicted fill to a smoothed empty specification will result in an appropriate filled acoustic environment.

The second cause of deviation from the fill effect prediction was due to a unique shifting of modes between different fairing/payload combinations. This occurred most vividly with the 19.5 dB/-5.7 dB fills seen in the stacked cubes configuration at 32 Hz/40 Hz (fig. 16). As previously explained this was due to the empty test's acoustic mode at the 40 Hz band shifting to the 32 Hz band when filled with the stacked cubes. Similar mode shifting also occurred at 63 Hz for all the filled tests.

The SEA prediction provides statistical estimates of modal densities but can not predict individual modes. When modal densities are small, such as at low frequencies, tracking individual acoustic modes may be important. If a payload is susceptible to low frequency acoustics it may be necessary to perform an acoustical modal analysis or finite element analysis to identify the low frequency modes for the specific geometry of the payload/fairing. For the Atlas PLF/mockups tested, the SEA theory predicted very well at 80 Hz and above.

It is therefore thought that the SEA theoretical prediction for the fill factor, as presented in this paper, is appropriate for general usage. It is strongly believed that enveloping all the fill factors would unfairly penalize payload programs, since most exceedances to the theory appear due to a unique fairing/payload combination effect. This is particularly true at the lower frequencies, where modal density is low and individual modes may shift.

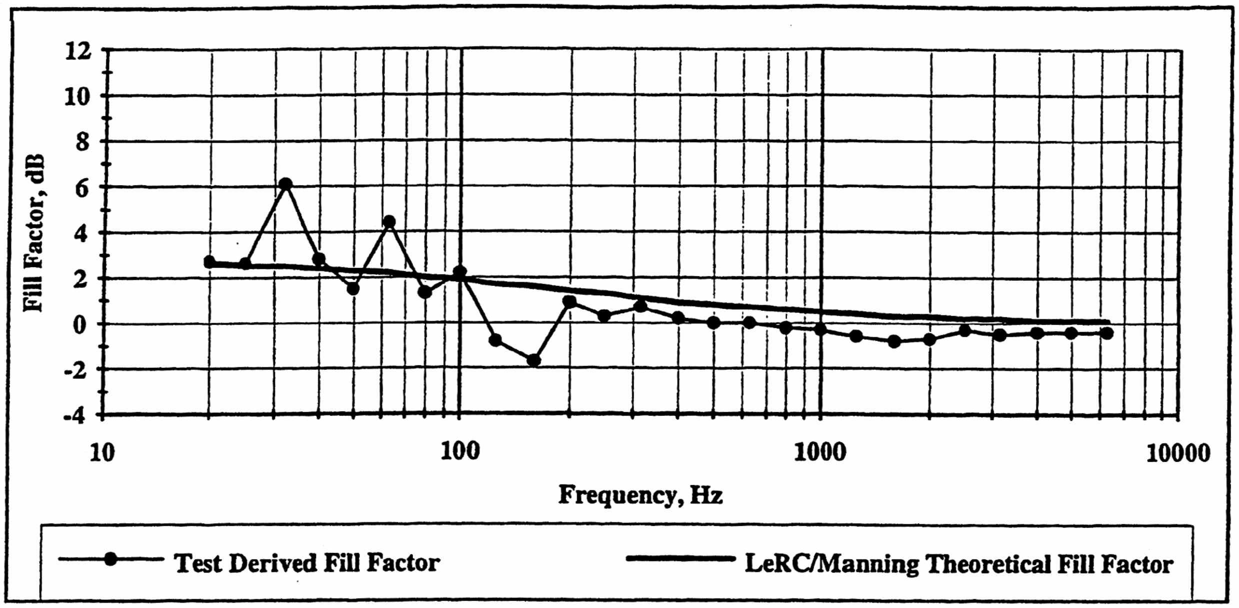



Figure 13.—Comparison of fill factor predictions for medium cylindrical fill/zone 3.

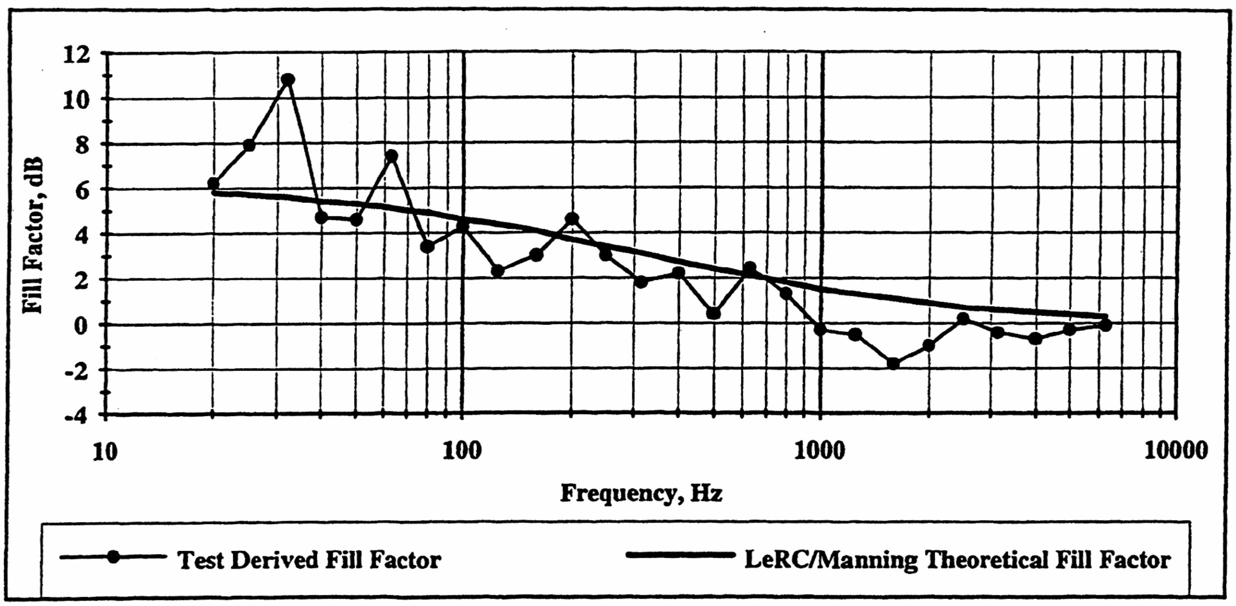



Figure 14.—Comparison of fill factor predictions for large cylindrical fill/zone 3.

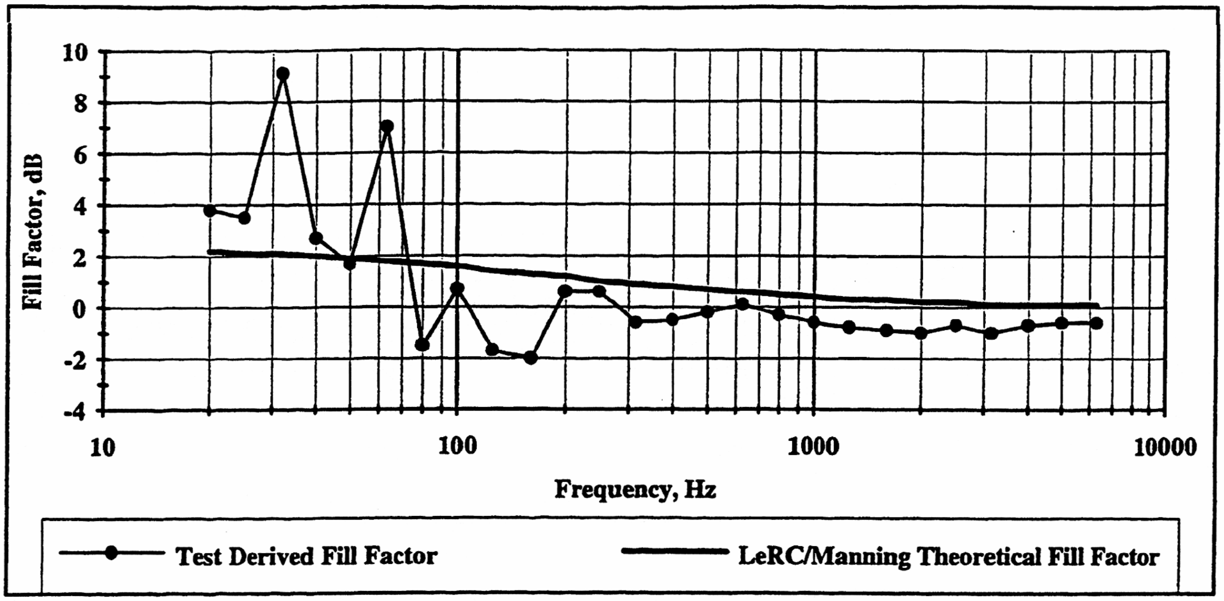



Figure 15.—Comparison of fill factor predictions for large square fill/zone 3.

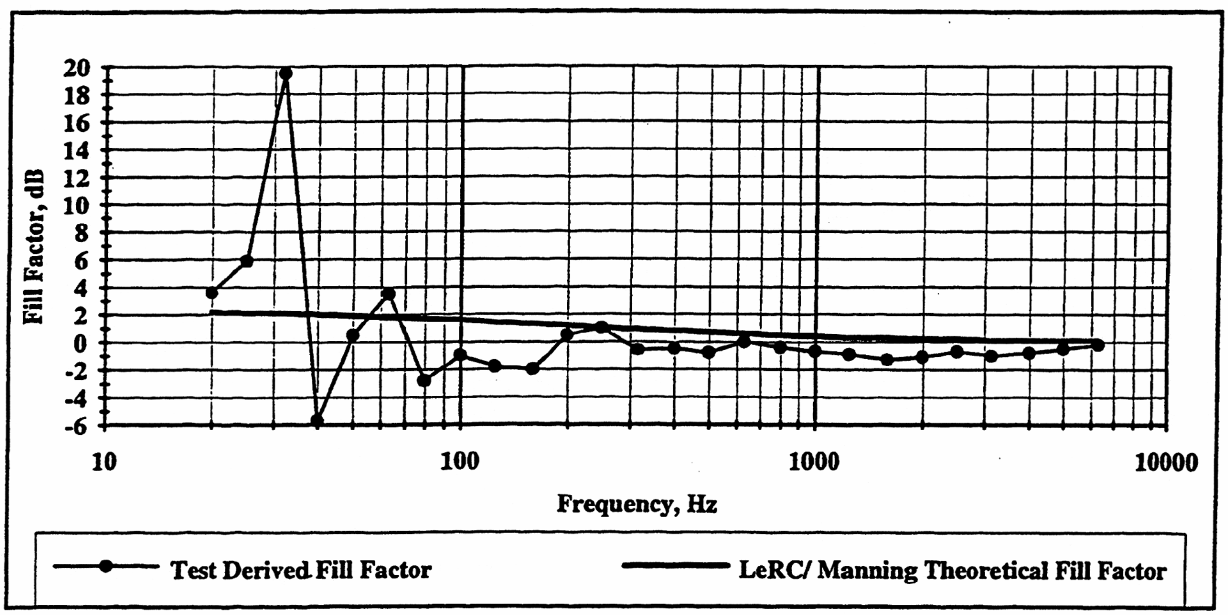



Figure 16.—Comparison of fill factor predictions for stacked cubes fill/zone 3.

TABLE II.—PREDICTED FILL FACTORS VERSUS TEST FILL FACTORS (DB) (ZONE 3, PLF CYLINDRICAL REGION)

Medium Cylindrical Fill

| Frequency Hz | Prediction (a) | Test Derived (b) | Test Measured |
|---|---|---|---|
| 20 | 2.6 | 2.7 | 1.4 |
| 25 | 2.5 | 2.6 | 1.1 |
| 32 | 2.5 | 6.1 | 5.0 |
| 40 | 2.4 | 2.2 | 3.2 |
| 50 | 2.3 | 1.5 | 1.9 |
| 63 | 2.2 | 4.4 | 4.4 |
| 80 | 2.0 | 1.3 | 1.0 |
| 100 | 1.9 | 2.2 | 2.8 |
| 125 | 1.7 | –0.8 | –1.1 |
| 160 | 1.6 | –1.7 | –1.1 |
| 200 | 1.4 | 0.9 | 0.3 |
| 250 | 1.3 | 0.3 | –0.2 |
| 315 | 1.1 | 0.7 | 0.6 |
| 400 | 0.9 | 0.2 | 0.1 |
| 500 | 0.8 | 0.0 | 0.2 |
| 630 | 0.7 | 0.0 | 0.0 |
| 800 | 0.6 | –0.2 | –0.2 |
| 1000 | 0.5 | –0.3 | –0.5 |
| 1250 | 0.4 | –0.6 | –0.7 |
| 1600 | 0.3 | –0.8 | –0.8 |
| 2000 | 0.3 | –0.7 | –0.8 |
| 2500 | 0.2 | –0.3 | –0.6 |
| 3150 | 0.2 | –0.5 | –0.8 |
| 4000 | 0.1 | –0.4 | –0.8 |
| 5000 | 0.1 | –0.4 | –0.9 |
| 6300 | 0.1 | –0.4 | –0.9 |

Large Cylindrical Fill

| Frequency Hz | Prediction (a) | Test Derived (b) | Test Measured |
|---|---|---|---|
| 20 | 5.8 | 6.2 | 5.5 |
| 25 | 5.7 | 7.9 | 7.0 |
| 32 | 5.6 | 10.8 | 9.9 |
| 40 | 5.4 | 4.7 | 5.3 |
| 50 | 5.3 | 4.6 | 4.8 |
| 63 | 5.1 | 7.4 | 7.7 |
| 80 | 4.9 | 3.4 | 3.8 |
| 100 | 4.6 | 4.3 | 4.1 |
| 125 | 4.4 | 2.3 | 2.7 |
| 160 | 4.1 | 3.0 | 3.4 |
| 200 | 3.7 | 4.6 | 4.5 |
| 250 | 3.4 | 3.0 | 2.8 |
| 315 | 3.1 | 1.8 | 1.5 |
| 400 | 2.7 | 2.2 | 2.1 |
| 500 | 2.4 | 0.4 | 0.8 |
| 630 | 2.1 | 2.4 | 2.4 |
| 800 | 1.8 | 1.3 | 1.2 |
| 1000 | 1.5 | –0.3 | –0.3 |
| 1250 | 1.3 | –0.5 | –0.7 |
| 1600 | 1.1 | –1.8 | –1.9 |
| 2000 | 0.9 | –1.0 | –1.3 |
| 2500 | 0.7 | 0.2 | –0.3 |
| 3150 | 0.6 | –0.4 | –0.7 |
| 4000 | 0.5 | –0.7 | –1.1 |
| 5000 | 0.4 | –0.3 | –0.8 |
| 6300 | 0.3 | –0.1 | –0.5 |

Large Square Fill

| Frequency Hz | Prediction (a) | Test Derived (b) | Test Measured |
|---|---|---|---|
| 20 | 2.2 | 3.8 | 3.2 |
| 25 | 2.1 | 3.5 | 2.3 |
| 32 | 2.1 | 9.1 | 8.3 |
| 40 | 2.0 | 2.7 | 4.0 |
| 50 | 1.9 | 1.7 | 0.9 |
| 63 | 1.8 | 7.0 | 7.8 |
| 30 | 1.7 | –1.5 | –0.7 |
| 100 | 1.6 | 0.7 | 1.2 |
| 125 | 1.4 | –1.7 | –1.6 |
| 160 | 1.3 | –2.0 | –2.0 |
| 200 | 1.2 | 0.6 | 0.4 |
| 250 | 1.0 | 0.6 | 0.6 |
| 315 | 0.9 | –0.6 | –0.8 |
| 400 | 0.8 | –0.5 | –0.7 |
| 500 | 0.7 | –0.2 | –0.4 |
| 630 | 0.6 | –0.1 | –0.1 |
| 100 | 0.5 | –0.3 | –0.2 |
| 1000 | 0.4 | –0.6 | –0.3 |
| 1250 | 0.3 | –0.2 | –0.7 |
| 1600 | 0.3 | –0.9 | –1.0 |
| 2000 | 0.2 | –1.0 | –1.1 |
| 2500 | 0.2 | –0.7 | –0.9 |
| 3150 | 0.1 | –1.0 | –1.0 |
| 4000 | 0.1 | –0.7 | –0.9 |
| 5000 | 0.1 | –0.6 | –0.8 |
| 6300 | 0.1 | –0.6 | –0.7 |

Stacked Cubes Fill

| Frequency Hz | Prediction (a) | Test Derived (b) | Test Measured |
|---|---|---|---|
| 20 | 2.2 | 3.6 | 3.2 |
| 25 | 2.1 | 5.9 | 5.0 |
| 32 | 2.1 | 19.5 | 19.6 |
| 40 | 2.0 | –5.7 | –3.8 |
| 50 | 1.9 | 0.5 | 0.6 |
| 63 | 1.8 | 3.5 | 4.0 |
| 80 | 1.7 | –2.8 | –2.5 |
| 100 | 1.6 | –1.0 | –0.7 |
| 125 | 1.4 | –1.8 | –1.1 |
| 160 | 1.3 | –2.0 | –2.2 |
| 200 | 1.2 | 0.5 | –0.1 |
| 250 | 1.0 | 1.0 | 0.5 |
| 315 | 0.9 | –0.6 | –0.9 |
| 400 | 0.8 | –0.5 | –0.9 |
| 500 | 0.7 | –0.8 | –0.6 |
| 630 | 0.4 | 0.0 | –0.3 |
| 800 | 0.5 | –0.4 | –0.4 |
| 1000 | 0.4 | –0.7 | –0.6 |
| 1250 | 0.3 | –0.9 | –1.0 |
| 1600 | 0.3 | –1.3 | –1.5 |
| 2000 | 0.2 | –1.1 | –1.7 |
| 2500 | 0.1 | –0.7 | –1.4 |
| 3150 | 0.1 | –1.0 | –1.8 |
| 4000 | 0.1 | –0.8 | –1.7 |
| 5000 | 0.1 | –0.5 | –1.6 |
| 6300 | 0.1 | –0.2 | –1.2 |

(a) Prediction based on LeRC/Manning Fill Factor Theory;
(b) The lest derived III) laden an obtained by correcting the test measured fill (anon with the test to test external SPL differences.

# NASA Fill Effect Standard

In 1993, a concerted effort was made within the NASA engineering community to develop agency-wide standards for many disciplines, one being vibroacoustics. Such standards will ensure consistency of hardware verification in the exchange of flight hardware in multicenter projects. Among the items defined in the NASA Payload Vibroacoustic Standard [8] will be the Fill Effect Standard.

Based on the results of our fill effect test program and previous research, the NASA Vibroacoustics Standards Panel has incorporated the following acoustic fill effect implementation methodology into the standard document:

(1) Calculate the payload volume, $Vol_{payload}$, in a zone of interest.
(2) Calculate the empty fairing/cargo bay volume (with the same length as the payload zone), $Vol_{empty}$.
(3) Use the results of Steps 1-2, to calculate the ratio of the payload volume to the empty fairing/cargo bay volume, $Vol_{ratio}$

$$Vol_{ratio} = \frac{Vol_{payload}}{Vol_{empty}} \tag{8}$$

(4) Calculate an average gap distance ($H$) between the payload surface and the fairing/cargo bay surface.
(5) Use the following equation to calculate the acoustic fill effect in decibels, as a function of frequency ($f$).

The fill factor design chart (fig. 17) is based on Eq. 9.

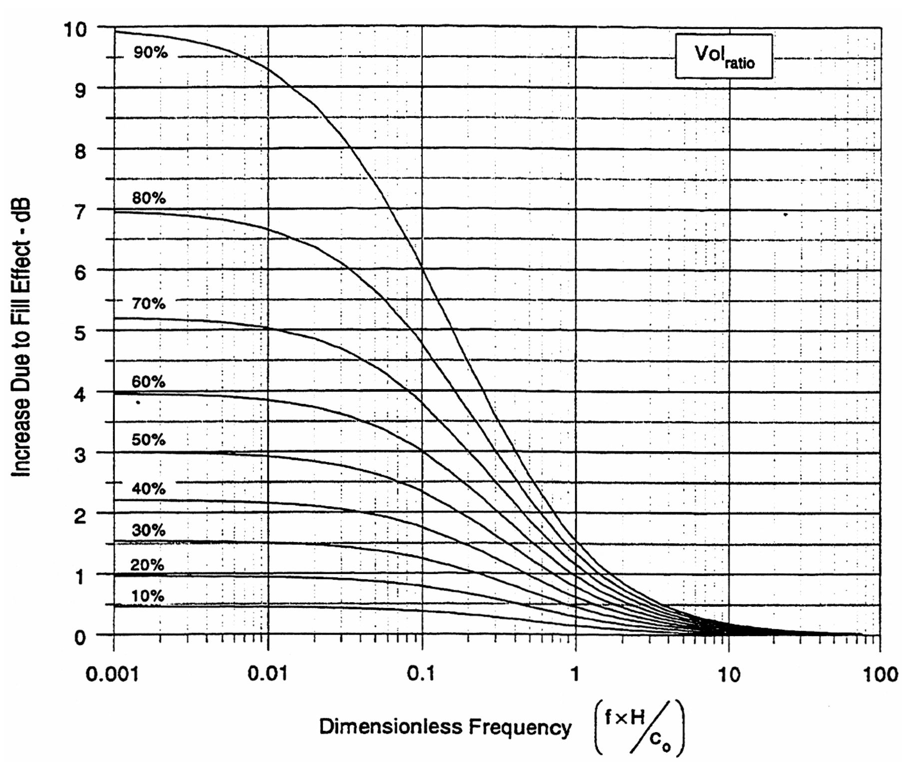



Figure 17.—Fill factor design chart.

$$Fill\ Factor(dB) = 10\ Log_{10}\left[\frac{\left[1+\frac{c_o}{2fH}\right]}{1+\left[\frac{c_o}{2fH}\left(1-Vol_{ratio}\right)\right]}\right] \quad (9)$$

where,

$c_o$ is the speed of sound in air (typically 13,560 in./sec)

$f$ is the one-third octave band center frequency (Hertz)

$H$ is the gap distance between the payload and the failing/cargo bay wall (inches)

$Vol_{ratio}$ is the volume ratio of the payload volume to the empty fairing/cargo bay volume, for a given payload zone length.

(6) Add the fill effect results of Step 5 to the acoustic levels specified for the empty fairing/cargo bay. (Example: 4 dB fill effect +130 dB empty SPL = 134 filled SPL.)

Note that Eq. 9 is identical to Eq. 7 given previously, but presented in a slightly different format.

The following fill effect considerations were also suggested for the standard:

The fill effect should only be applied to payloads which exhibit extensive volumetric displacements. If the payload is highly unsynunetric or has discrete structures or appendages, then engineering judgement needs to be utilized in applying the fill effect

Fill effects greater than those predicted are possible in individual one-third octave bands at low frequencies. These exceedances are due to the unique payloads which causes shifting of acoustic modes (ref. 5). If the payload structure is acoustically sensitive at low frequencies, then further analysis such as an acoustic finite element analysis may be warranted.

Because of the unique acoustic modes created for each payload and fairing/cargo bay combination, caution should be used when interpreting flight data fill effects and applying them to another payload and fairing/cargo bay combination, which is geometrically dissimilar.

## Conclusions

Since the acoustic fill factor is a major design and test driver for payload hardware, NASA LeRC and GDSSD combined to perform a well controlled test program, which resulted in excellent quality test data. The objectives of this test program, to determine the acoustic fill factor for a number of payload fills were met.

The test data qualitatively confirms the current understanding of the fill factor, including: (1) increasing payload radial fill results in higher fill factor, (2) payload volume fill is critical parameter, (3) fill factors are highest at low frequencies.

Quantitatively it was found that the test fill factors correlated well with the predicted fill factors, based on the theory presented in this paper. Some deviations below 80 Hz were found and explained in this paper. The presence of the payload caused individual acoustic modes in the fairing to shift lower in frequency. Such shifting seems to be unique to each fairing/payload combination.

The results of this test program are used to validate a NASA agency-wide fill effect standard which is presented in this paper.

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**13. ABSTRACT *(Maximum 200 words)***

NASA Lewis Research Center, in conjunction with General Dynamics Space Systems Division, has performed a test program to investigate the acoustic fill effect for an unblanketed payload fairing for a variety of payload simulators. This paper will discuss this test program and fill factor test data, and make comparisons with theoretical predictions. This paper will also address the NASA acoustic fill effect standard which was verified from the test data analysis.

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