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# An Evaluation of the Additional Acoustic Power Needed to Overcome the Effects of a Test-Article's Absorption During Reverberant Chamber Acoustic Testing of Spaceflight Hardware

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## Abstract

The exposure of a customer's aerospace test-article to a simulated acoustic launch environment is typically performed in a reverberant acoustic test chamber. The acoustic pre-test runs that will ensure that the sound pressure levels of this environment can indeed be met by a test facility are normally performed without a test-article dynamic simulator of representative acoustic absorption and size. If an acoustic test facility's available acoustic power capability becomes maximized with the test-article installed during the actual test then the customer's environment requirement may become compromised. In order to understand the risk of not achieving the customer's in-tolerance spectrum requirement with the test-article installed, an acoustic power margin evaluation as a function of frequency may be performed by the test facility. The method for this evaluation of acoustic power will be discussed in this paper. This method was recently applied at the NASA Glenn Research Center Plum Brook Station's Reverberant Acoustic Test Facility for the SpaceX Falcon 9 Payload Fairing acoustic test program.

## Introduction

Exposing aerospace test-articles (e.g., spacecraft and payload fairings) to simulated, launch-event, high intensity acoustics is accomplished by one of two methods.

Aerospace test-articles may be exposed to a direct acoustic field created by a shroud of dynamic speakers that are in close proximity to the test-article. This test method is commonly referred as the Direct Field Acoustic Test (DFAT) method.

Reverberant acoustic testing is the other method. With this more established method, a reverberant acoustic field is created within a large chamber and excites the aerospace test-article which is installed in the chamber. One advantage of using reverberant acoustic testing, over the DFAT, is when a customer's acoustic spectrum requirements exceeds a 148 dB overall sound pressure level (OASPL). Such high pressure levels are beyond the current capability of DFAT.

For reverberant acoustic testing, it is recommended (Ref. 1) that the volume of the test-article is no greater than 10 percent of the empty chamber's volume in order to ensure that the presence of the test-article does not interfere with the spatial uniformity of the reverberant field. Many of the (approximately 25) active reverberation chambers throughout the world are capable of meeting the 10 percent test-article/chamber ratio volume guideline for many aerospace test-articles. These test facilities all have their own unique shape, volume, wall surface absorption, and compliment of noise sources/coupled horns.

Less unique is the sound medium in the chamber during test, being either that of gaseous nitrogen (GN2) with its corresponding low oxygen level (typically < 10 percent oxygen), or low-humidity compressed air. GN2 is the preferred gas due to its cleanliness, and its lower absorptive characteristics above 4 KHz.

The Reverberant Acoustic Test Facility (RATF) at the NASA Glenn Research Center Plum Brook Station in Sandusky, Ohio is an example of a large-volume (101,000 $ft^3$), very powerful (163 dB OASPL) reverberant acoustic test chamber (Refs. 2 and 3) which uses GN2. Figure 1 is a photograph of the SpaceX Falcon 9 Payload Fairing in this NASA test chamber. The volume of the Falcon 9 test-article was 10 percent of the NASA RATF's empty chamber volume.




Figure 1.—The SpaceX Falcon 9 Payload Fairing was successfully tested at the NASA Glenn Research Center Plum Brook Station's Reverberant Acoustic Test Facility (RATF) during May to June 2013.

This paper describes a method to mitigate the test risk of achieving a customer's target sound pressure level (SPL) spectrum during reverberant acoustic testing due to the absorption inherent to the test-article. Each particular test-article will have its own absorption values which may be estimated as a function of frequency. Typically, both the target SPL spectrum and the test-article's absorption are stated at the one-third octave band (OTOB) center frequencies.

To address the effects of the test-article's absorption on quantifying the maximum achievable SPL versus OTOB frequencies of a company's reverberant acoustic test chamber, the following parameters are needed:

1. The test chamber's linear dimensions (width, depth, and height) and geometry. (If the chamber's shape is not rectangular in each plane, then chamber drawings should be provided. It's also advisable to have drawings that include the layout of the chamber's horns and vents, in order to determine those surface areas).
2. The Reverberation Time ($RT_{60}$) values per OTOB for the empty chamber condition (i.e. no test-article inside the chamber).
3. The Reverberation Time ($RT_{60}$) values per OTOB for the chamber with the test-article installed.

The $RT_{60}$ values are determined from the measured decay rates in the chamber, and are equal to the time in seconds for 60 dB of decay to occur after the sound excitation source has been turned off. If the $RT_{60}$ values (in items 2 and 3 above) are not available, they may be calculated from a recording of the time-history decays of sound inside the chamber. The Interrupted-Noise Method (Refs. 4 and 5) is one approach that is often used to record and measure *RT* values. Because of the noise source excitation levels and the microphones' dynamic range limits due to their sensitivity, it is often necessary to extrapolate to an $RT_{60}$ value from a lesser decay, such as a $RT_{20}$ value.

As an example with this Interrupted-Noise Method, a $RT_{20}$ calculation may be performed with a minimum of 35 to 40 dB of dynamic range from the excitation level to the measurable background noise level. This dynamic range is made up of: the required 5 dB of early roll-off decay when the excitation noise source is turned off, a minimum 20 dB of actual linear decay, and an allowance of a 10 dB margin above the background noise floor. This $RT_{20}$ value is then simply extrapolated to the $RT_{60}$ value. (A direct measurement of $RT_{60}$ would require a dynamic range of 75 dB from the excitation level to the background noise level, which is often not attainable in test.). Figure 2 illustrates the Interrupted-Noise Method for decay measurements.

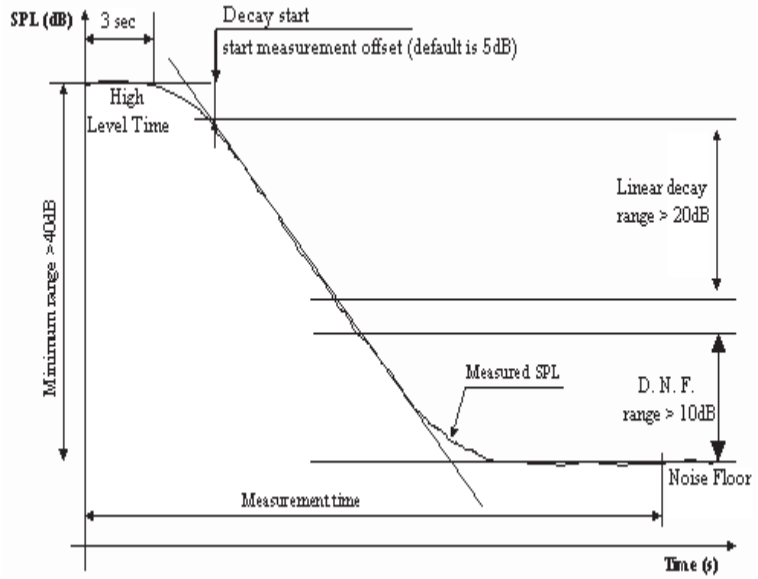



Figure 2.—ISO354 Interrupted Noise Method of determining reverberant room decay rates.

Before the delivery of the customer's test-article to the acoustic test facility, it is common practice to perform initial empty chamber testing to the customer's specified acoustic target SPL spectrum. This empty chamber testing determines what compliment of horns and modulators are best suited to meet the spectral levels. This target level testing would be sufficient only if the test-article's absorption is assumed to be insignificant. If the test-article's absorption is expected to be significant then further attention is required to address the additional acoustic power needed within the chamber to overcome this acoustic power sink.

Therefore a method is needed to estimate these absorption effects when the test-article's absorption is significant (i.e., account for the additional acoustic power required).

## Method for Determination of Additional Acoustic Power

The following steps are the approach taken to determine if the empty chamber test was performed with adequate sound power to ensure that the target SPL spectrum can be reached when testing with the test-article installed in the chamber.

**Step A—Overview of Fundamental Acoustic Equations**: Review the fundamental acoustic equations (Ref. 6) related to a reverberant acoustic chamber test.

The SPL in the reverberant chamber is calculated by a power balance between the chamber's input power and the power dissipated due to absorption and other energy loss mechanisms within the chamber. The spatial averaged mean-square sound pressure, $\langle p^2 \rangle$, in the chamber is given by the Room Equation (Eq. (1)):

$$\left\langle p^2 \right\rangle = W_c \frac{4\rho c}{R_c} \tag{1}$$

where $W_c$ is the acoustic power input to the chamber in watts, $R_c$ is the room constant in $m^2$, $\rho$ is the density of the gas within the chamber in $kg/m^3$, and $c$ is the speed of sound of the gas in m/s.

The room constant, $R_c$, defined in Equation (2), is determined from the absorption of the chamber surfaces and from the gas absorption, and has units of metric Sabines ($m^2$),

$$R_c = \sum_i S_i \alpha_i + 4mV \tag{2}$$

where $S_i$ is the area of each $i^{th}$ surface of the room, $\alpha_i$ is the diffuse field surface absorption coefficient of each $i^{th}$ surface, $V$ is the volume of the room in $m^3$, and the "$m$" is the energy absorption coefficient of the gas with units of inverse meters ($m^{-1}$). For an empty chamber the summation of the individual surface area absorptions in metric Sabines accounts for all walls, floor, and ceiling surfaces, plus the chamber's horns and vents openings.

The (metric) Sabine Equation (Eq. (3)) relates the room constant to the room's reverberation time, $RT_{60}$.

$$R_c = \frac{V}{1.086c} \frac{60}{RT_{60}} \tag{3}$$

The $RT_{60}$ values equals the time in seconds in each OTOB for 60 dB of decay to occur after the sound source has been turned off.

The Room Equation (Eq. (1)) combined with Sabine's equation (Eq. (3)), results in an expression of the mean-square acoustic pressure as a function of the reverberation time, as provided in Equation (4),

$$\left\langle p^2 \right\rangle = W_c \frac{4.343}{60} \frac{\rho c^2}{V} RT_{60} \tag{4}$$

where, $W_c$ is the acoustic power input to the chamber in watts, $RT_{60}$ is the reverberation time of the chamber in seconds, $V$ is the chamber volume in $m^3$, ρ is the density of the gas within the chamber in $kg/m^3$, and $c$ is the speed of sound of the gas in m/s.

The compact relationship between the SPL and the acoustic Power Level (PWL) in the chamber can be expressed in decibels (dB) by Equation (5). This equation is valid for metric units and when GN2 is the gaseous sound medium in the chamber,

$$\text{SPL} = \text{PWL} + 10 \log (RT_{60}) - 10 \log (V) + 14.17 \text{ dB} \tag{5}$$

where, SPL is the measured Sound Pressure Level in the chamber in dB relative to 20 micro-Pascals, PWL is the measured acoustic Power Level in the chamber, in dB relative to 1 pico-watt, $RT_{60}$ is the reverberation time for sound to decay 60 dB, in seconds, and $V$ is the volume of the test chamber in $m^3$.

The introduction of the test-article affects the above equations by decreasing the chamber's volume ($V$), and increasing the total surface absorption due to the $S_i\alpha_i$ contribution of the test-article.

The reverberation time is obtained from the measured decay rate, $d$ in dB/sec (Eq. (6)).

$$RT_{60} = \frac{60}{d} \tag{6}$$

The decay rate of the chamber with the test-article will be larger relative to the decay rate for the empty chamber test. The $RT_{60}$ of the chamber with the test-article will thus be shorter than the $RT_{60}$ for the empty chamber test. This change in $RT_{60}$ indicates that additional acoustic power will be necessary to meet the same target spectrum with the test-article in the chamber.

**Step B—Obtain the Reverberation Times of the Empty Chamber**: Perform tests to determine the Reverberation Time of the empty chamber condition ($RT_{60\ EC}$) for each OTOB frequency, and the subsequent calculation of the acoustic absorption (in units of metric Sabines).

These $RT_{60}$ decay measurements may be obtained by utilizing the test facility's existing noise sources (modulators/horns) via the Interrupted Noise Method (Refs. 4 and 5) as previously discussed. Alternatively, the Interrupted Noise Method can be applied to obtain the decay measurements by utilizing conventional dynamic speakers as the noise source. The dynamic speaker excitation source would be less costly from both a facility operations and labor resources perspective, and it would also be easier and quicker to implement. Note, using dynamic speakers as the sound source instead of the chamber's noise generators may affect the relative decay rates for frequencies above 1 KHz (where the gas dominates the total absorption), especially if GN2 is used as the sound medium for the actual test-article acoustic test.

**Step C—Estimate the Test-Article Absorption**: As mentioned earlier, it is necessary to include the effects of the test-article's acoustic absorption when performing the empty chamber tests to ensure that adequate acoustic power will be available when time comes to perform the test with the test-article inside the chamber.

Based on experience, evaluate the customer's test-article configuration (i.e., its shape, size, construction, materials, cavities, surface area) and its expected acoustic absorption to *estimate* a delta dB to be added to each OTOB of the customer's target spectrum. So for example, to account for the test-article absorption a +4 dB could be added to the customer's acoustic test SPL at each OTOB when performing the empty chamber test. Note, it is not necessary that the estimated delta dB be uniform as applied to all OTOBs.

**Step D—Perform Empty Chamber Test using Bolstered Test Levels**: Perform the empty chamber test with bolstered acoustic test spectrum which includes the delta dB estimate from the previous step. Confidence to proceed with the actual test-article's full-level test is achieved only if the bolstered SPLs can be reached successfully in this empty chamber test.

If the bolstered SPLs were not achieved for any OTOB, then other modulator/horn combinations, drive-signal filter bandwidth settings, and modulator pressure flows may be adjusted to reach the bolstered SPLs. If none of these adjustments work, then it is necessary to discuss the situation, maximum achievable SPLs, and assumptions (of Step C) with the customer. As one can see, this test should be performed months before the arrival of the test-article at the test facility in order to mitigate risk and allow time to achieve the bolstered SPLs.

**Step E—Perform Empty Chamber Test using Bolstered Test Levels, Again**: Assuming the previous step was successful, it is prudent to repeat this bolstered SPL empty chamber test shortly before the test-article is placed inside the acoustic chamber. This re-test provides confidence that the chamber's acoustic characteristics have not changed over time; in addition, this provides a timely check-out of all the necessary acoustic control and noise generation equipment and systems.

**Step F—Obtain the Reverberation Times of Chamber with Test-Article Installed**: Assuming success for Step E above, perform a low level (i.e., –12 dB from the customer's full level target spectrum) with the test-article installed in the chamber. At the end of this –12 dB exposure, continue to record the microphones' decay rates to derive the $RT_{60}$, in each OTOB, for the chamber with the test-article ($RT_{60\ C\ w/TA}$).

Note that Step F can alternatively be performed using conventional dynamic speakers in lieu of the chamber's noise modulators and horns. Using the dynamic speakers for this step should result in a savings of effort, schedule and cost.

**Step G—Calculate actual delta dB**: Knowing the reverberation times from Steps B and F, one can now calculate the *actual* delta SPL values needed to overcome the test-article's absorption. Rearranging Equation (5) to solve for PWL for the two tests conditions of: (1) empty chamber (*EC*), and (2) chamber with test-article (*C w/TA*), results in Equations (7) and (8).

$$\mathrm{PWL}_{EC} = \mathrm{SPL}_{EC} - 10 \log (RT_{60\ EC}) + 10 \log (V_{EC}) - 14.17 \text{ dB} \tag{7}$$

$$\mathrm{PWL}_{C\ w/TA} = \mathrm{SPL}_{C\ w/TA} - 10 \log (RT_{60\ C\ w/TA}) + 10 \log (V_{C\ w/TA}) - 14.17 \text{ dB} \tag{8}$$

Combining Equations (7) and (8) by setting $\mathrm{PWL}_{EC} = \mathrm{PWL}_{C\ w/TA}$ (i.e., the modulators produce the same amount of power for both cases), one can solve for the change in SPL, from hereafter known as "*delta dB*." The calculated delta dB is provided in Equation (9).

$$\mathrm{SPL}_{EC} - \mathrm{SPL}_{C\ w/TA} = -10 \log (RT_{60\ C\ w/TA}) + 10 \log (V_{C\ w/TA}) + 10 \log (RT_{60\ EC}) - 10 \log (V_{EC}) \tag{9}$$

Defining the volume of the chamber with the test-article as:

$$V_{C\ w/TA} = (V_{EC} - V_{TA}), \text{ where } V_{TA} = \text{actual volume of test-article} \tag{10}$$

and substituting Equation (10) into Equation (9) results in,

$$\mathrm{SPL}_{EC} - \mathrm{SPL}_{C\ w/TA} = 10 \log (RT_{60\ EC}) - 10 \log (RT_{60\ C\ w/TA}) + 10 \log (V_{EC} - V_{TA}) - 10 \log (V_{EC}) \tag{11}$$

Equation (11) may be reduced to Equation (12) as follows,

$$\mathrm{SPL}_{EC} - \mathrm{SPL}_{C\ w/TA} = 10 \log (RT_{60\ EC} / RT_{60\ C\ w/TA}) + 10 \log ((V_{EC} - V_{TA}) / (V_{EC})) \tag{12}$$

With the definition of "delta dB" = $\mathrm{SPL}_{EC} - \mathrm{SPL}_{C\ w/TA}$, this may now be reduced to Equation (13),

$$\text{delta dB} = 10 \log [(RT_{60\ EC} / RT_{60\ C\ w/TA}) \times (1 - (V_{TA} / V_{EC}))] \tag{13}$$

For the special case when the volume of the test-article ($V_{TA}$) is less than 10 percent of the volume of the empty chamber ($V_{EC}$), then Equation (13) simplifies to the approximation given in Equation (14).

$$\text{delta dB} \approx 10 \log \left[ RT_{60\,EC} / RT_{60\,C\,w/TA} \right] \tag{14}$$

By using the derived Equation (13), the actual delta dB is computed. If this actual delta dB does not exceed the estimated delta dB (from Step C) that was applied in the empty chamber testing (Steps D/E), then the risk of having potential deficient acoustic power due to the test-article absorption has been successfully mitigated. In this scenario, proceed with the customer's test plan to eventually expose the test-article to the full-level target spectrum.

However, if this actual delta dB (from Step G, Eq. (13)) exceeds the estimated delta dB (from Step C) that was applied in the empty chamber testing (Steps D/E) in an OTOB, then options need to be discussed with the customer for this scenario. Note, having an exceedance is not a statement of the facility's limitation to reach these higher SPLs, but rather that its capability to do so has not yet been demonstrated. As such, one option would be to subtract this exceedance from the customer's target spectrum (i.e., lowering the target SPL for the affected OTOBs). This would result in testing closer to the lower test tolerance value of the customer's test target spectrum. Another option, although programmatically undesirable, would be to remove the test-article from the chamber, and repeat the empty chamber measurements (Step B) with the now known delta dB.

Examples of these two scenarios are illustrated in Figure 3. In Figure 3, a +4 dB of delta dB was predicted/used for both of the test-article's absorption during their empty chamber tests. A notional representation of the two test-articles' calculated delta dB (from their low-level test measurements) are also shown in Figure 3. The calculated delta dB for Test-Article A is below the applied predicted delta SPL dB and therefore the full level testing can proceed with confidence, with minimal risk relative to the test chamber's available acoustic power. However, the situation is different for Test-Article B where the calculated delta dB exceeds the applied predicted delta dB in two of the OTOBs (at the 160 Hz and 200 Hz OTOBs). In this case, options would be discussed with the customer on how to proceed; primary to these discussions would be the amount of the exceedance (e.g., 0.5 dB would be more tolerable than say 2 dB).

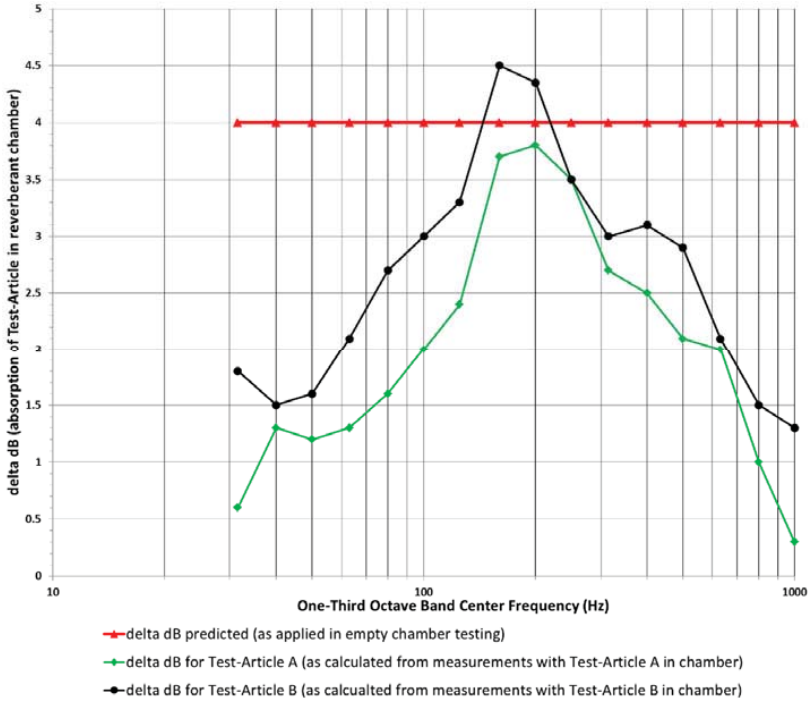



Figure 3.—Illustration of delta SPL dB for two notional test-articles.

## Summary

It is important to realize that some test-articles may have significant sound absorption that may challenge the acoustic power capabilities of a test facility. Therefore, to mitigate this risk of not being able to meet the customer's target spectrum, it is prudent to demonstrate early-on an increased acoustic power capability which compensates for this test-article absorption. This paper describes a concise method to reduce this risk when testing aerospace test-articles which have significant absorption. This method was successfully applied during the SpaceX Falcon 9 Payload Fairing acoustic test program at the NASA Glenn Research Center Plum Brook Station's RATF.

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