Restoring and Upgrading a Reverberation Room Test Suite

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This article presents the upgrades and improvements needed to bring an old and seldom-used reverberation room test suite up to current standards. The upgrades and improvements included eliminating a below-floor pit that was open to the reverberation room, improving the acoustical diffusion within the room, enlarging the opening between the reverberation room and an adjacent anechoic chamber, renovating the anechoic receiving chamber, constructing an innovative sound transmission loss test fixture, and installing a high-power sound system.

A Ford Motor Company test suite consisting of a large 497 m^3 (17,591 ft^3) reverberation room adjacent to a full anechoic room that was constructed about 1960. Following the construction of new testing facilities about 1992, this test suite was largely deactivated. Interest by Ford to reactivate the test suite led to the identification, design, and implementation of renovations and improvements needed to bring the test suite up to current testing standards and best practices.

Original Test Suite

Figures 1 and 2 show the original test suite including the below-floor pit that contained a four-post shaker that would excite a vehicle through vertical vibratory excitation of the four wheels and tires. The vehicle was positioned within the reverberation room above an open grating that separated the reverberation room from the pit.

This arrangement allowed the room volume of the open pit to acoustically couple to an already oversized reverberation room. The added volume plus the odd and less-than-ideal combined room shape of the two coupled spaces resulted in a reverberant sound field that produced large variances in third-octave sound levels measured between microphone positions in the reverberation room. This variation introduced a high degree of uncertainty to acoustical measurements conducted in the reverberation room and rendered the testing suite unsuitable for precision measurements.

In addition, other issues were noted for the existing test suite. A 1.52-m high × 2.28-m wide (3'9"× 7'6") opening in the wall between the reverberation room and adjacent full anechoic room was intended to serve for sound-transmission-loss (STL) testing of both large automotive sections (known as "bucks") as well as flat sample materials. As shown in Figure 3, this opening was covered by a pair of massive hinged doors that blocked sound from passing between the two rooms when they were not being used for STL tests.

These doors and perimeter frame of the opening impeded installation and acoustic sealing of both automotive bucks and a flat-sample holding frame placed in the opening for STL measurements. The existing STL sample holding fixture was a simple wood frame with a square center hole in which samples could be clamped and manually sealed in place for each test. This fixture created not only a tedious process to install, seal, and test each sample, but also tied up both the reverberation room and anechoic room while sample installation/removal was being conducted. Furthermore, the sample holding frame was built of plywood and wood framing, which by itself was not a very massive construction but would undoubtedly cause flanking limitations in the STL measurements. In addition, the opening coupled to an adjacent anechoic room that had full 1.5-m (5 feet) deep wedges resulting in an anechoic room cut-off frequency of approximately 80 Hz.

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Figure 1. Original reverberation room with open floor grating covering below-floor pit, floor-to-ceiling corner drapery enclosure, and retracted drapery.

Figure 2. Original pit below reverberation room with four-post vehicle shaker.

Figures 3 and 4 show the wedges covering the STL opening were removable, but in two sections which could only be removed (and re-installed) by sliding them through the STL opening from inside the reverberation room. This was not only an awkward and difficult exercise, but it prevented the anechoic wedge treatment from being re-installed without removing the entire STL fixture (or buck) from the opening. As a result, any ongoing STL measurements had to be interrupted in the event that the anechoic characteristics of the anechoic room were needed for other tests conducted in the anechoic space.

With the two sections of wedges removed, a rectangular tunnel was formed on the anechoic (back) side of the STL fixture by the wedges that remained and surrounded the removed sections. This tunnel had anechoic wedges along the bottom surface, which impeded physical access to the backside of the STL opening and made it difficult to install and position the receiving room microphone at the appropriate position behind the test sample.

A third issue was that the existing sound system could not produce a high enough sound level within the reverberation room to test the STL of high-performing barrier materials and assemblies. The existing sound system was primarily being employed for conducting acoustical transparency measurements on vehicles

Figure 3. Reverberation room side of original STL opening showing the backside of removable anechoic wedges and the original STL fixture (on floor, to far right).

Figure 4. Anechoic side of original STL opening with removable wedge sections in place.

brought into the reverberation room.

Renovated Test Suite

Bringing the reverberation room and adjacent anechoic room up to current standards required renovating the test suite to address several issues that influence the accuracy and repeatability of acoustical measurements. The renovation work included:

- Eliminating and replacing an open floor grating that covered the below-floor pit with a poured concrete floor.
- Eliminating draperies and drapery enclosures originally installed in four of the five room corners.
- Installating stationary diffusers to improve acoustical diffusion within the room.
- Enlarging the opening between the reverberation room and an adjacent anechoic chamber.
- Constructing an innovative STL test fixture.
- Reconfiguring the anechoic wedges covering the receiving side of the STL opening to make removal and replacement easier and to allow access to the opening
- Installing a new, high-power sound system.

The original large volume reverberation room appears to have been designed and built using some rudimentary architectural acoustics design principals. These principals include simplistic splaying of room walls (thereby creating five non-parallel rooms walls), and introducing heavy velour-like draperies that would cover two of the five room walls as well as retract and recess into wooden enclosures in four of the five room corners. Both techniques suggested reliance on variable-acoustics techniques that have been traditionally employed by architectural designers attempting to control or adjust room acoustic response. However, the presence of such draperies in a reverberation room is not endorsed by any testing standard and is considered to be quite unorthodox for an acoustics laboratory. Also, the use of splayed room walls is often promoted by designers as "overcoming (or preventing) the existence of room modes."

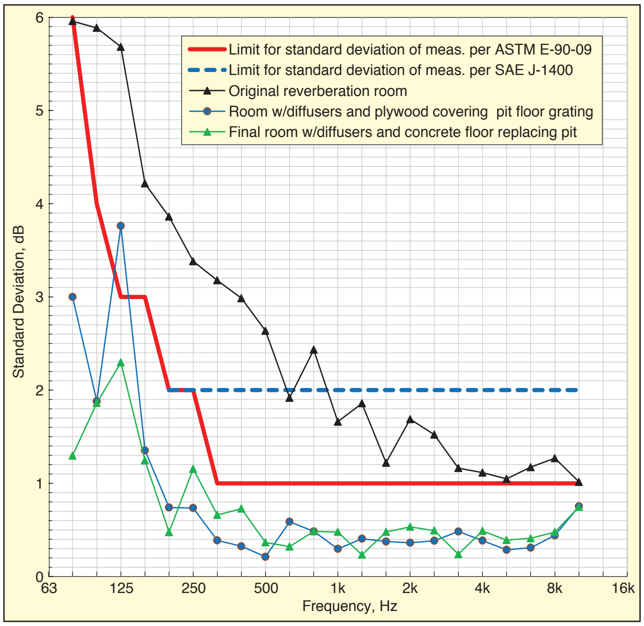

Figure 5. Standard deviation in steady-state sound levels per frequency band for various conditions of the 497-m^3 reverberation room.

In addition, the 497 m^3 interior volume was considerably larger than the 200 m^3 room volume normally recommended for a reverberation room.[1] This room volume coupled through an open floor grating to the volume of the below-floor pit. However, this floor grate covered opening occurred in only a portion of the room and essentially formed two intersecting coupled volumes rather than one large volumetric expansion of the room. The result of this unorthodox size, shape, and reverberation room configuration was believed to be the cause of excessively large variations in the steady-state sound pressure levels measured from various microphone positions within the room.

Steady-State Signal Diffusion

Figure 5 shows the results of standard deviation (SD) versus third-octave band frequency of the steady-state sound pressure levels measured at nine statistically independent microphone positions in the original reverberation room. In this condition, the below-floor pit was covered with an open floor grating (floor grating was as originally installed and uncovered), and the draperies were retracted into the corner drapery enclosures. For reference purposes, the figure shows the limits of standard deviation versus frequency band for measurements made in accordance with ASTM E90[2] and SAE J1400.[3] The SAE J1400 limit is less stringent than the E90 limit, except at 200 and 250 Hz, where both limits coincide. The J1400 limit is undefined below 200 Hz.

Based on the standard deviation of steady-state pressure levels measured in the original reverberation room, Figure 5 shows that the acoustical diffusion in the original reverberation room is unacceptable for acoustical measurements of steady-state signals. Improving this condition was judged to be requisite to being able to qualify this reverberation room as a source room for repeatable STL measurements.

Improving Room Diffusion

Testing results of the steady-state SD measured in the original reverberation room lead to developing a plan for improving the diffusion in the room. Modeling the room interior acoustical response was conducted using a room acoustics and sound system software package normally used in architectural acoustics for evaluating all types of interior spaces. The modeling routine employs acoustic ray tracing and served as a guide to understanding sound reflections within this nonrectangular room. This allowed the virtual introduction of stationary diffusers on wall and ceiling surfaces

Figure 6. One of four removable wedge carts.

Figure 7. Anechoic room side view of the STL opening showing revised anechoic wedges surrounding opening and physical access behind the opening.

Figure 8. Anechoic side of the STL fixture showing two removable wedge carts in place and two removed for access to back of fixture.

and evaluation of changes in room reflection patterns.

Previous work[4,5] in reverberation rooms of small to standard volume (200 m^3) had shown that stationary diffusers with a convex surfaces strategically installed on wall and ceiling surfaces were sufficient to produce the acoustical diffusion in the room necessary to achieve low values of standard deviation for both steady-state and transient test signals.

After completing the renovation, tests of room diffusion were also conducted for transient signals to assess whether the acoustical diffusion characteristics of the renovated room were up to a level acceptable for the most stringent of current standards. However, that compliance was not intended to demonstrate that this reverberation room is completely acceptable for conducting all tests covered by those respective standards. This room was considered to be too large in terms of cubic interior volume to conduct sound absorption tests at frequencies of 2000 Hz and above per ASTM C423. This is because of the high level of sound absorption created by air at those frequencies in this nearly 500-m^3 room. In accordance with ASTM C423, for a reverberation room that produces valid sound absorption data at 4000 Hz (or higher), the ideal room volume should be 200 m^3.

An interim set of tests was conducted to evaluate the effectiveness of the installed diffusers before the below-floor pit was isolated from the reverberation room. For these tests, the floor grating was temporarily covered with plywood sheets to reduce the coupling between the reverberation room and the volume of the floor pit below.

Measurements of the standard deviation for a steady-state signal were made during this interim condition. Results shown in Figure 5 showed that the steady-state diffusion was significantly improved and met the requirements of ASTM E90 at all frequencies except 125 Hz. In this band, some residual coupling between the reverberation room and below-floor pit was believed to be responsible for this excursion.

These tests were repeated following removal and replacement of the floor grating with a concrete floor, painting walls and floor, and installing a new, high-power sound system. Results of SD tests conducted for this final condition of the room are also shown in Figure 5. These results show that the SD requirements of ASTM E90 were met in all frequency bands.

Transient Signal Diffusion

A second diffusion test to evaluate the completed reverberation room was conducted to measure the standard deviation between microphone positions when the sound field was excited by a transient signal. This was conducted in accordance with ASTM C423. The later diffusion test was believed to be a much more rigorous test of room diffusion and is more difficult to achieve. Nonetheless, it was included in this qualification procedure to demonstrate how well the diffusion in the improved reverberation room now meets standard limits for both steady-state and transient signal excitation.

Qualification of the reverberation room required measuring the variation in sound pressure level between microphone positions in third-octave bands (for the steady-state diffusion test) and in the one-third-octave band decay rate (for the transient test). In this case, we were seeking to establish whether the diffusion of the bare reverberation room met the requirements. As a result, decay rate measurements were only made in the reverberation room with no test specimen. Table 1 shows that the standard deviation of decay rate variations meets the criteria delineated in Appendix A3 of the ASTM C423 standard, which is defined for third-octave frequency bands from 100 to 5000 Hz.

New STL Fixture

A major reason for resurrecting and renovating this reverberation room test suite was to regain the ability to conduct sound trans-

Figure 9. High-power loudspeaker system located in one corner opposite the STL opening (along with three stationary diffusers).

mission loss (STL) testing capabilities of both large automotive sections (or 'bucks') and flat sample materials. The enlargement of the opening between the reverberation room and adjacent anechoic room was conducted as part of the construction changes made to this test suite. This was done in conjunction with the design, fabrication, installation, and certification of an industry-unique system of removable and interchangeable inserts for STL testing. This system is described in detail in a separate, associated paper.[6]

Wedge Reconfiguration

The existing anechoic room was built using traditional glass-fiber wedges. Over the many years of service, some of the wedge tips had become damaged, and others were soiled. In addition, removable wedge sections covering the original STL opening were difficult to remove and reinstall, impeding use of the opening for testing. As a part of the overall test suite renovation, the entire section of wedges behind the STL opening was removed.

Once the wedges were removed, the anechoic room floor grating was extended to the room wall beneath the opening to permit access during enlargement of the STL opening. This change also allowed access to the backside of the opening for testing personnel. In addition, the removed anechoic wedges were reconfigured into four rolling cart structures that allowed these four wedge sections to be readily installed and removed. Figure 6 shows one of the wedge carts.

The four carts permitted a portion or the entire STL opening to be wedge covered, depending upon whether the buck or the STL fixture is installed. Figure 7 shows the anechoic side of the STL opening without any of the wedge carts in place. Figure 8 shows the backside of the STL fixture with two of the wedge carts flanking the fixture opening. Figures 7 and 8 both show the extended floor grating and illustrate how the space behind the STL opening is now physically accessible with all or some of the wedge carts removed.

Table 1. Comparison of third-octave standard deviation measured at nine microphone positions for a transient signal in reverberation room compared to ASTM C423 limits.

Frequency, Hz	Measured Std. Deviation	ASTM C423 SD Limits	Meets Limits?
100	0.11	0.11	Yes
125	0.07	0.07	Yes
160	0.04	0.04	Yes
200	0.03	0.03	Yes
250	0.03	0.03	Yes
315	0.03	0.03	Yes
400	0.03	0.03	Yes
500	0.02	0.02	Yes
630	0.01	0.02	Yes
800	0.01	0.02	Yes
1000	0.01	0.02	Yes
1250	0.01	0.02	Yes
1600	0.01	0.02	Yes
2000	0.01	0.02	Yes
2500	0.01	0.02	Yes
3150	0.01	0.02	Yes
4000	0.01	0.02	Yes
5000	0.01	0.02	Yes
6300	0.01	*	-
8000	0.01	*	-
10,000	0.01	*	-

*Limits in these bands undefined in this standard

New High-Power Sound System

A new high-power sound system was provided and installed for generating high levels of broadband, random noise as the reverberation room source signal (see Figure 9). This system included a system controller that generates broadband random ("pink") noise, third-octave-band equalization crossovers for dividing the signal into pass bands to serve individual drivers and separate channels of audio power amplification.

In addition, the controller included signal monitoring and control features with settable thresholds and compression circuitry to limit the output voltage sent to each power amplifier. These limiter circuits were each ultimately set to limit the voltage produced by a power amplifier so that it does not exceed the safe operating voltage of the loudspeaker driver it's powering, based upon the driver manufacturer's long-term power handling rating for the device. This assures that the loudspeaker system will not be overdriven or operated in a range likely to cause driver failure.

Another feature of the sound system was a signal cut-off function that included sensors on each of two doors into the reverberation room. This system required that both doors be in a closed and latched position before the sound system would generate sound, and would immediately interrupt the system signal should one of the doors be opened while the sound system is producing sound. The intent is to limit accidental exposure of an individual to sound levels well in excess of 100 dBA should they inadvertently open one of the room doors.

One difficulty was discovered while conducting the qualification tests of the STL fixture. These tests required the greatest output from the sound system where the performance of the barrier material under test is the highest. For a high-performing STL sample, such as the double-wall control sample described in SAE J1400, the STL performance rises dramatically with frequency so that STL values in excess of 86 dB are achieved at the highest frequency band of 10,000 Hz.

Performance this high requires that the output of the sound system be sufficient to overcome both 86 dB of STL performance, and the background noise in the receiving room (due primarily to the noise floor of the measuring instruments). It must also be high enough to produce a signal level in the receiving room that is at least 12 dB above the noise floor to minimize the need for background noise correction. These requirements meant being able to produce third-octave-band sound pressure levels of at least 105 dB in the reverberant sound field of the source room.

One of the challenges presented by this requirement were the limitations of commercially available electroacoustic transducers (loudspeakers) to produce such high levels of sound at extreme frequencies. Despite what may be implied to the contrary in the literature published by loudspeaker manufacturers, horn and compression drivers do not produce the same frequency response at full-rated power as they do when tested at their rated sensitivity of typically 1 Watt measured at 1 m. Rather, compression drivers are subject to "mass law limitations" in radiating sound at increasing frequency. This phenomenon is essentially the inability of a mass to vibrate (accelerate) fast enough at higher frequencies to maintain the same sound power output while overcoming the collapsing directivity pattern.[7]

In addition, the inordinately large reverberation room volume resulted in highly excessive sound absorption by the air in the room. This higher air absorption resulted in significantly lower sound levels at high frequency bands above 4000 Hz in the reverberant field of a 500-m^3 room than are found in a smaller room such as a reference 200-m^3 room. For this reason, a sound system found to produce sufficient sound levels for conducting STL measurements at the highest frequency bands of 8000 and 10,000 Hz in a 200-m^3 reverberation room can be inadequate for conducting STL measurements in a 500-m^3 room.

To overcome both of these issues, it was necessary to further divide the sound spectrum into smaller pass bands for producing noise. In this case, four ranges of loudspeaker pass bands were needed.

Conclusions

A 50-year-old acoustics laboratory had been reactivated and brought up to current standards by making several modifications, improvements, and upgrades:

- Eliminating a below-floor pit.
- Improving the acoustical diffusion for both steady-state and transient noise signals.
- Installing a high-power sound system in the reverberant source room.
- Enlarging the opening between the source room and anechoic receiving room.
- Reconfiguring wedges covering and surrounding the test opening.
- Providing an innovative sound transmission loss fixture
- Installing a high power reverberation room sound system.

Dedication

The article is dedicated to the memory of Keith Kennedy, the founder of Construction Fabricators, Inc. Keith was a humble and conscientious contractor who, with his three sons, worked diligently behind the scenes building numerous world class acoustical laboratories including many automotive related testing facilities. Keith has left the world with a large and yet not well known legacy.

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