A Test System for Free-Field Qualification of Anechoic Chambers

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Qualification of anechoic and hemi-anechoic chambers is intended to demonstrate that a chamber adequately supports free-field conditions for a given test sample. However, the common practice of measuring widely spaced points along a traverse line is an inadequate measure of inverse square law performance, particularly for frequencies at and above 1000 Hz. On the other hand, continuous traverses yield a more complete picture of the capabilities and limitations of an anechoic space. A new qualification measurement system has been developed at Georgia Tech to allow for easily repeatable, automated continuous traverse measurements. The highly portable system makes use of Labview™ and MATLAB™ tools to perform, control and analyze a complete traverse test, giving real-time access to the data and immediate processing and analysis of the results. This article will describe the new system, present data taken for an anechoic chamber and demonstrate the benefits of this system over current methods.

Anechoic chambers are a common feature in many laboratories of industry, academia and government. Of critical concern to those who have acquired these facilities is the initial qualification of their free-field performance, which identifies the region of the interior volume of the chamber that yields free-field behavior. Measurements made to qualify a chamber are often tedious to perform and difficult to repeat. The qualification methods prescribed by ANSI S12.35 and ISO 3745 standards are fundamentally the same and can be summed up as follows: A microphone is moved continuously along radial paths (traverses) from a sound source and the sound pressure levels are recorded. These measured levels are compared with those predicted by the inverse square law; pass/fail determination is based upon the permissible differences between them, as a function of frequency.[1,2]

The test system described in this article was developed through attempts to qualify a newly constructed anechoic chamber at the Georgia Institute of Technology. Initial tests were made using discrete measurement points, manually setting one or more microphones at one foot intervals along a traverse, as is common practice. The resulting data were wildly inconsistent and unrepeatable. The cause of the inconsistencies was found to be the inability to produce repeatable microphone and source positions. The continuous traverse system was then developed in pursuit of a repeatable test method. In the spirit of this goal, the system was also designed to allow for real-time assessment of a free-field space to aid in the quick evaluation of changes in the test field, in the test sources, etc., where such changes are frequently performed in the conduct of a chamber qualification effort.

As both the ANSI S12.35 and ISO 3745 standards are readily available, this article will concentrate only on those procedural details directly relevant to the measurement system. The qualification data presented here were measured in accordance with the procedures and tolerances defined by these standards.

Discrete vs. Continuous Spatial Sampling. ANSI S12.35 and ISO 3745 both call for a continuously moving microphone. A continuous traverse is obtained when one continuously moves a microphone along a radial path, while continuously recording data. A continuous traverse generally yields pressure measurements that represent a very fine or continuous spatial resolution along the traverse. In contrast, a discrete traverse is obtained when one moves a microphone in discrete steps along a radial, with the microphone motionless during data acquisition at each microphone location.

As of this writing, the accepted practice is to employ discrete traverses for qualification purposes, generally with much lower spatial resolution as compared to a continuous traverse. Much of the qualification data presented in the literature have been based on discrete traverses.[3-14] The discrete traverse method generally uses measurements at 0.5 to 1 ft spacing. Even though some more recent discrete traverses have employed finer spacing,[3,13] they still represent a coarse sampling of the test sound field.

Only a limited number of publications have documented continuous traverses.[15-17] In contrast to discrete traverse methods, continuous traverses show a great deal more structure and complexity in the sound field generated by the test source. Indeed, in examining the published continuous data, it is not difficult to realize that discrete traverse methods will miss much of the structure of the sound field, particularly at higher frequencies. Further, a discrete traverse could easily miss regions where the chamber's free-field performance is unacceptable. This observation was reinforced through the theoretical modeling of Duda[18] and the experimental observations of Cunefare,[19] and will be demonstrated once more in the traverse data presented in this paper.

One common argument in favor of discrete traverse tests is the ease of performing such a test using common laboratory equipment. This article demonstrates that a continuous traverse test may be performed with greater ease and in a shorter amount of time, while yielding more meaningful and repeatable results. The self-contained system presented here is highly specialized, portable and may be easily adapted to the qualification of any chamber. With the exception of the motor and motion control components (described in a later section), this system can also be replicated using common acoustical laboratory equipment.

Qualification Analysis. There are several methods for computing the deviation of measured radial decay from theoretical free-field performance. Two such methods are discussed and utilized here: the fixed and optimal reference methods.

The deviation from the inverse square law is determined by

$$\Delta L_{pi} = L_{pi} - L_p(r_i) \tag{1}$$

where L_{pi} is the sound pressure level at each traverse measurement position, and $L_p(r_i)$ is the sound pressure level at distance r_i estimated by the inverse square law.

The most common method for evaluating the deviation uses the measured sound pressure level at a given reference position from the source (typically 3 ft in the U.S.) and applies the inverse square law to compute levels at other distances. For labeling purposes, this approach is termed the fixed reference method. In the fixed reference method, the theoretical sound pressure levels along a traverse are computed by:

$$L_p(r_i) = L_p(r_{ref}) - 20\log_{10}\left[\frac{r_i}{r_{ref}}\right] \tag{2}$$

where $L_p(r_{ref})$ is the sound pressure level at a selected reference or normalization distance r_{ref}.

The second method, the optimal reference method, estimates a source strength and source center offset location that yields a theoretical decay to optimally match the observed decay. The optimal reference method is based on the fact that the true acoustic center of a sound source may not coincide with a visually identifiable point on or near the source. For the optimal

Figure 1. Sound sources used for qualification test.

reference method, the theoretical free-field decay is computed from

$$L_p(r_i) = 20\log_{10}\left[\frac{a}{r_i - r_o}\right] \quad (3)$$

where a represents the apparent strength of the sound source and r_o is an offset distance between the physical location of the source and its apparent acoustic center. The a and r_o parameters are computed from the measured sound pressure levels along a traverse as

$$a = \frac{\left(\sum_{i=1}^{N} r_i\right)^2 - N\sum_{i=1}^{N} r_i^2}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N\sum_{i=1}^{N} r_i q_i} \quad (4)$$

and

$$r_o = -\left[\frac{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} r_i q_i - \sum_{i=1}^{N} r_i^2 \sum_{i=1}^{N} q_i}{\sum_{i=1}^{N} r_i \sum_{i=1}^{N} q_i - N\sum_{i=1}^{N} r_i q_i}\right] \quad (5)$$

where

$$q_i = 10^{-0.05 L_{pi}} \quad (6)$$

In Equations 4 and 5, N is the number of measurements along the traverse, and the L_{pi} and r_i are as defined above.

The optimal reference method requires that data be evaluated over a specified range of distance. The maximum distance from the source is typically constrained by the geometry and configuration of the chamber under test. The nearest point on the traverse to the test source should be in the far-field of the source, where $1/r$ spreading is obtained. The current standards do not define the minimum distance between the traverse microphone and the sound source. However, the current draft for revision of ISO 3745 defines this minimum distance as 0.5 m for 100 Hz or more and

$$r = 95/f \quad (7)$$

for frequencies f less than 100 Hz. The derivation of Equation 7 shows that $(kr)^2 > 3$. The ISO 3745 draft further stipulates that computed values of r_o greater than twice the maximum source dimension 'fail' the qualification.

Continuous Measurement System

A measurement system was developed to perform continuous qualification traverses, comprised of a sound source, reference microphone, microphone traverse system and data acquisition system. Each of these four major components is described below.

Sound Sources and Excitation System. As this article does not report advancement in this component, sources are only briefly described here. For this study, three sound sources were used to cover the designed frequency range of the chamber, 80-10,000 Hz. Sources are shown in Figure 1. The sources were constructed in accordance with the recommendations in ISO 3745 and mounted near the chamber center. The sources were excited with pure tones using a function generator and amplifier.

Figure 2. Traverse line and microphone, source and stationary reference microphone (located above source).

Reference Microphone. In order to monitor the stability of the source signal as a quality measure of the traverse data, a random incidence microphone (1/2 in. Larson-Davis, model 2560) was placed in an arbitrary, stationary position in the chamber. This microphone was used by the qualification system to record acoustic pressure over the course of each test. The use of such a reference microphone is not stipulated in the current standards. A reference microphone can be seen with other system components in Figure 2.

Traverse Microphone System. Measuring the inverse square law deviation requires accurate knowledge of the separation distance between the test source and the traverse microphone. Therefore, the objective of the microphone traverse system is to move a microphone in a continuous, repeatable manner. This system is comprised of a traverse line, a microphone carriage, a take-up line, a system of pulleys and a take-up spool.

The traverse line is a 1.6 mm braided steel cable, chosen as a balance between strength and small acoustic profile. The traverse line is anchored to opposite faces of the chamber and made taut using a turnbuckle at one end of the line. A random-incidence microphone (1/2 in. Larson-Davis, model 2560) is connected to the traverse line by a wire carriage as depicted in Figure 3. Plastic sleeves on the carriage allow it to move smoothly and quietly along the traverse line. The microphone carriage is pulled up the traverse line by a take-up line. The take-up line is routed to the exterior of the chamber through a pulley system to a take-up spool mounted on a motion control system.

To avoid slipping on the traverse line and to ensure constant traverse velocity, the microphone carriage is always pulled up the traverse line against gravity, either toward or away from the

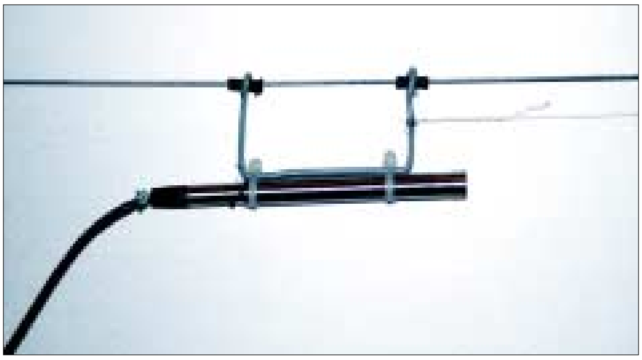

Figure 3. Traverse microphone and carriage.

sound source, depending on the test orientation. The traverse direction is accounted for in the post-processing of the measurement system.

The take-up line is fused Kevlar fishing line (“Fire Line” 20 lb. test). This 0.13 mm diameter line was chosen to ensure that there would be negligible change in the take-up spool’s diameter as line collected on it. Also, the take-up line exhibited no measurable stretch for this application and therefore resulted in highly stable and repeatable movement and positioning of the microphone (a take-up-line that can stretch leads to jerky, erratic motion of the microphone carriage as it ‘stick-slips’ along the traverse wire).

The pulley system routes the take-up line outside the chamber via a cable-pass-through pipe, which penetrates the chamber wall from outside to inside. Additional pulleys on the outside of the chamber guide the line onto the take-up spool. Lightweight Harken marine-grade compact ball-bearing pulleys are used throughout, as ordinary pulleys produced squeaks while in motion, contaminating the test data.

To ensure microphone motion along the traverse line at a constant velocity from one known position to another, the take-up spool rotates through a known total angle at constant angular speed. In this manner, the traverse system meets the design objective of accurate separation distance data.

Motion and measurement system. Motion control of the traverse microphone system and data acquisition are handled simultaneously using a PC equipped with a National Instruments motion control board and a National Instruments data acquisition board. The system is controlled using a single Labview Virtual Instrument (VI). The VI was designed to allow for motion control and data acquisition, independently and/or simultaneously. In this fashion, the VI is able to step through and control all phases of qualification: traverse motion, acoustic level measurement, qualification measurement and qualification post-processing. Components of the motion and measurement system are shown in Figure 4.

Motion control of the microphone traverse system is accomplished by mounting the take-up spool to a rotary table driven by a stepper motor (Superior Electric Slo-Syn Motor, Model M062-L809). The stepper motor is controlled using the National Instruments Flexmotion PCI board, which is in turn controlled by the VI. The stepper motor is located outside the chamber in order to eliminate motor noise from the measurement data.

Acoustic level measurement is performed using two input channels of a National Instruments data acquisition PCI board (Model 4552) with octave band analysis capabilities. Band analysis of full, 1/3 or 1/12 octave measurements may be selected by the user. A free-run capability using exponential averaging has been implemented in the VI to allow the user to set source levels above the ambient room level as necessary. In contrast to free-run measurements, acoustic level measurement during the continuous traverse requires separate averaging for each sample. Because the microphone moves without interruption, time averaging also means spatial averaging. Therefore, separate (no overlap) and sequential linear averages are made over the traverse duration, such that each linear average is made for a discrete segment of the traverse. Each segment is constrained to be small compared to the wavelength of the test frequencies being excited, to ensure that all information about the traverse is preserved in the measurement. A spatial resolution of 100 samples per wavelength is a good sampling of the traverse field and is utilized by the VI to setup each traverse. The time required for each linearly averaged sample along the traverse is also dependent on test frequency. For an adequately averaged band level measurement at each sample, a time sample with a duration of at least 100 periods of the lowest excitation frequency is recorded and averaged for each sample along the traverse (1000 or more periods are required for random noise excitation). The required minimum duration of each traverse measurement is the product of these two quantities: the time sample of each linear average times the number of averaged samples along the traverse length. All of these test parameters are computed and utilized by the VI, based on the input parameters of traverse length and test frequency information.

Figure 4. Motion and measurement system.

Qualification measurements are made once source levels are set and the traverse microphone is placed in its starting location. At that point, the motion and measurement system is triggered to simultaneously set the traverse microphone in motion, pulling the microphone up the traverse line, while acquiring and averaging the microphone band level data (using the process described above). The VI display is updated in real time with each sample along the traverse and its deviation from the inverse square law (based on the reference method). This gives the user instantaneous access to the detailed structure of the acoustic field and pass/fail feedback for the measurement.

Each continuous traverse measurement is taken in a single stage of data collection, lasting approximately 2-4 minutes per traverse. By contrast, data taken at discrete spatial intervals typically requires manual repositioning of the microphone between each individual measurement point, resulting in a long and tedious measurement process.

As a final stage of the traverse measurement, the data are stored to disk and post-processed using a MATLAB session running within Labview. All information for post-processing is input to the Labview VI and stored with the data. Any source offset from the traverse line is corrected in the distance-vector using a cosine correction. When the configuration of the traverse line requires the microphone to be pulled toward the source, the distance-vector and level data are reversed, yielding data as if the microphone had moved away from the source. The data are fit according to the optimal reference method outlined previously for definitive pass/fail based on standard criterion.

Qualification Data

The purpose of this article is to introduce the measurement system and not to evaluate a particular chamber. Therefore, traverse data are presented as an example of test system output, for one case only, into a lower corner of the tested anechoic

Figure 5. Screen capture of the Labview Virtual Instrument for traverse qualification measurement.

chamber. Room corners typically generate a more complex acoustic field, so a corner measurement was chosen to highlight the capabilities of the measurement system. Results from pure tone tests are presented here for similar demonstrative reasons.

A screen capture of the Labview VI is shown in Figure 5. The VI is designed to step the user through the basic stages of a qualification test and provide the user with real time information regarding the quality of the test data and the performance of the acoustic field of the test room.

The user is guided through the qualification test stages by utilizing the sequential controls along the left edge of the VI window seen in Figure 5. Stages 1-3 allow the user to completely control the traverse microphone motion. Stages 4-5 setup and perform octave band measurement of the two microphones. The qualification test is performed in Stage 6, where the test system is triggered for simultaneous motion and data acquisition over the traverse span. Additional information and notes about the qualification test are entered in Stage 7. Finally, qualification data are stored and post-processed in Stages 8-9.

Four plot displays are shown in the VI window. The two lower plots display the instantaneous octave band levels of the two microphones. The upper plot displays the microphone levels recorded for each sample along the traverse, updated in real time as the traverse microphone is pulled along. This is illustrated in Figure 5, as the screen capture occurred when the traverse measurement was approximately 3/4 complete. The traverse microphone had been pulled 80 in. toward the source and 589 of 755 data samples had been recorded. The traverse plots were in the process of displaying real time data as the microphone moved toward the source (from right to left on the display). The middle plot shows the resulting deviation from the inverse square law, based on the fixed reference method. This plot is also updated in real time, giving the user immediate insight into the free-field behavior of the acoustic field while the microphone was still in motion.

Sound level data for the reference microphone are shown in both upper plots of Figure 5. The reference microphone signal is a direct measure of source stability at the test frequencies. In the case of an unstable source, the traverse data may be corrected by subtracting the reference signal. However, because qualification measurements can be repeated very quickly using this system and an unstable source signal may indicate damage to the source, it may be more prudent to correct any excitation system issues and repeat the test.

Figure 6 presents a complete traverse qualification data set, obtained using the test system and processed using the MATLAB code. Deviation from free-field performance is plotted versus distance from the source, over the designed frequency range of the tested chamber. The frequency labels along the right vertical axis define the position of the 0 dB deviation for that frequency; the dashed lines above and below the 0 dB line are the permissible variations from free-field performance as defined by ISO 3745. The discrete data points shown in the figure were obtained by sampling and processing the traverse data at discrete intervals of 1 ft. This example shows how the discrete spacing fails to capture the complexity of the free-field deviation over the traverse span at frequencies as low as 500 Hz, and especially at frequencies above 1 kHz.

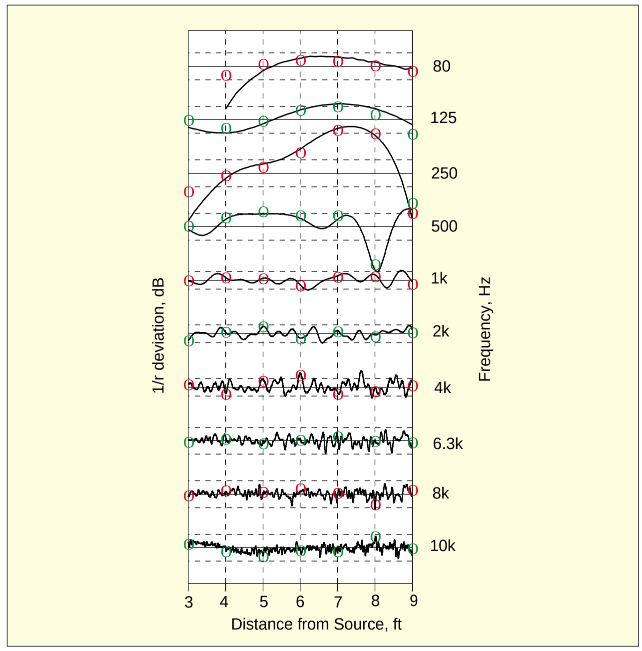

Figure 6. Qualification data for an anechoic chamber, continuous traverse into lower corner opposite room door. Discrete data points are estimated for an equivalent measurement set, with data taken at 1 ft intervals.

Conclusions

The anechoic qualification measurement system presented here was developed to make continuous traverse measurements feasible, efficient and straightforward. The test system developed at the Georgia Institute of Technology, which utilizes motion control and data acquisition components supplied by National Instruments and the processing capability of MATLAB, achieved both of these goals with great success. Results obtained using this system are highly repeatable and yield detailed information about the free-field behavior of the acoustic field. The test method has advantages over the current common test method, which makes discrete measurements at one ft intervals. Additionally, the continuous traverse test was a simpler and faster test to perform. This state-of-the-art test system should be an extremely useful tool in the qualification of anechoic rooms, especially as such facilities become more common in laboratories around the world.

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