

Suggested Modifications to ASTM Test Method E 477

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ASTM E-477 is the current standard test method used in North America for evaluating the acoustic and aerodynamic performance of duct silencers. The test method uses, at a minimum, a source chamber, a test duct (that includes a test specimen), and a reverberation chamber. If testing under flow is desired, the system also requires a fan chamber that can provide quiet airflow through the test duct. The results of the test method yield silencer insertion loss, self-generated noise, both as a function of acoustic frequency and flow velocity, and pressure drop. There are several problems with the current test method, some that are being addressed by the ASTM working group that is responsible for the development and maintenance of this standard. This article highlights the most significant problems associated with the current standard and proposes modifications to the standard that should, if adopted, improve the intralaboratory reproducibility of the test results.

For decades the commercial duct silencer industry throughout North America has relied on ASTM E 477¹ as a test standard for measuring the dynamic insertion loss, self-generated noise, and pressure drop of passive duct silencers. Historically, there has been great concern in the acoustical consulting community regarding the accuracy and reliability of manufacturers' acoustical performance data for duct silencers. Round-robin test results have shown relatively poor agreement between several NVLAP-certified (National Voluntary Laboratory Accreditation Program) testing labs over a wide frequency range. There are several possible reasons why different labs can get significantly different answers when testing the same silencer. Some of these reasons are possibly due to the unique physical characteristics of the individual labs, but there are problems with the standard itself that also contribute to this situation. This article identifies specific deficiencies in the current standard and presents recommendations for modifications that should improve the agreement in future round-robin tests.

Background

Currently the ASTM E 477 test procedure has three components:

- Determine the insertion loss of the test specimen, which could be a duct silencer or a section of acoustically lined ductwork, as a function of air flow and acoustic frequency.
- Determine the pressure drop of the test specimen as a function of air flow.
- Determine the self-generated flow noise of the test specimen as a function of acoustic frequency and air flow.

All acoustic measurements are conducted in one-third-octave bands. These three characteristics (insertion loss, pressure drop, and self-noise) define the overall performance of the duct silencer. There is a fourth component that is not evaluated in the current version of the standard, and that is the sound power radiated by the casing of the silencer. While casing -radiated noise from a duct silencer is not an important issue in most applications, there are some situations where this can be important. This matter will be discussed in greater detail later in this article.

Figure 1 presents a generic drawing of a typical E 477 lab that is equipped to measure acoustical performance with air flow. (There is at least one lab in the U.S. that is designed to measure insertion loss of duct silencers and acoustically lined ductwork in accordance with ASTM E 477 without air flow, but such a facility cannot measure pressure drop or self-generated noise, which are critical performance factors of duct silencers.)

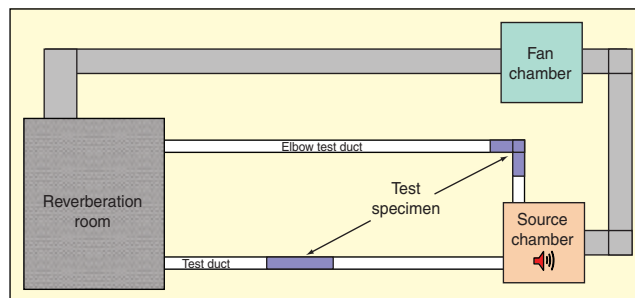


Figure 1. Typical E 477 lab layout.

The main components of the E 477 lab are the:

- Signal source chamber
- Test duct
- The reverberation chamber
- Fan chamber with connecting ductwork

The source chamber contains one or more loudspeakers that generate a high level of pink noise (equal energy/percent frequency, 1/f). Typical sound levels inside the source chamber range from 110 to 130 dBA during testing. Noise from the loudspeaker propagates down the test duct through the test specimen into the reverberation chamber. According to the standard, the test duct must be constructed of minimum 14-gauge (2-mm -thick) steel to minimize breakout, but some labs use steel ductwork as heavy as 6.3-mm (0.25-inch) thick. The overall length of the test duct is usually somewhere between 15 m (50 ft) and 30 m (100 ft).

When testing elbow silencers, the test duct may also contain a 90-degree elbow. The reverberation chamber is used to measure the total sound power radiated by the test duct opening using the methodology specified in ANSI S12.51 (ISO 3741). For measurements with air flow, a separate fan chamber is required with connecting ductwork. The fan chamber and connecting ductwork must be designed to reduce the fan-generated noise to an insignificant level throughout the frequency range of interest. This typically requires vibration isolators on the fan, silencers at the fan inlet and outlet, and silencers in connecting ductwork.

In addition, for measurements with positive (sound propagating in the same direction as the air) and negative (sound propagating in the opposite direction) air flow, the fan chamber must be designed to create air flow in both directions. This can be accomplished using a reversible fan, a fan that can easily be rotated inside the fan chamber, or using internal dampers or doors to change air flow direction without modifying the fan's rotation or orientation. Operating the fan with a variable-frequency drive is very helpful for achieving the desired flow rate for each test condition.

Round-Robin Test Results

There have been at least three round robins conducted in the last 10 years to ascertain the precision of the ASTM E 477 test method for determining the acoustical performance of duct silencers. The test silencers ranged in length from 0.91 m (3 ft) to 3 m (10 ft). The number of test labs for each round robin varied from a low of four to a high of six. The sample size is limited because of the number of test facilities available. In North America there are only seven known labs known that have facilities to test duct silencers with air flow.

Figures 2 and 3 present the measured repeatability and reproducibility standard deviations for one of the round robin tests. From these results we can easily see that all of the labs tend to get approximately the same answer when they repeat the test several times (as shown by the repeatability curves marked by solid black

Based on a paper presented at Noise-Con 10, Institute of Noise Control Engineering, Baltimore, MD, 2010.

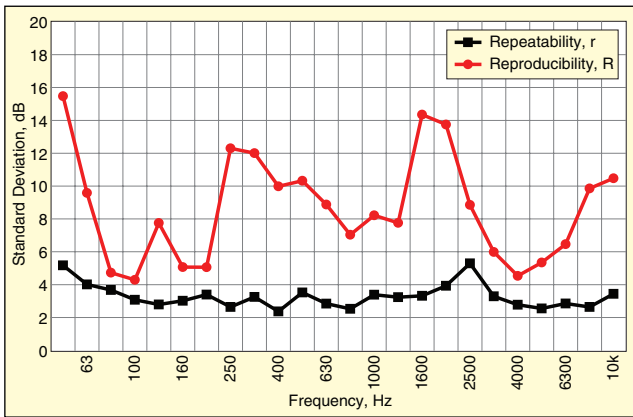


Figure 2. Insertion-loss, round-robin statistics from 2003 tests.

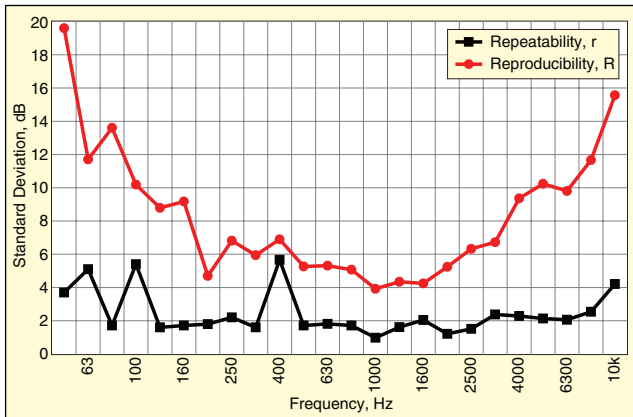


Figure 3. Self-generated-noise, round-robin statistics from 2003 tests.

squares). When different labs test the same specimen, however, there is a wide range of variation in the results (as shown by the reproducibility curves marked by solid red circles). In terms of insertion loss, the reproducibility is poorest at 50 Hz, but reproducibility is also unacceptable in the 250 to 2500 Hz and 5000 to 10,000 Hz frequency regions as well. The reproducibility of flow-generated noise is also extremely poor at low frequencies and again at high frequencies (see Figure 3). In the mid-frequency region, the flow-generated noise reproducibility is much better but certainly not as good as it should be. We do not attempt to address issues that impact the accuracy of flow-generated noise.

Standard Deficiencies

There are several deficiencies in the current standard, and this article focuses on three areas that may have the greatest impact on the poor precision exhibited by the round-robin test results:

- Source chamber characteristics
- Flanking sound transmission
- Empty duct resonances

The first two areas are currently being addressed by the ASTM working group in charge of maintaining the standard, and I hope that a new standard will soon be approved that will correct these deficiencies. The third area is being neglected by the working group for the time being but will likely be addressed soon after the next version of the standard is published.

Source Chamber Characteristics. In the current version of the standard (ASTM E 477-06a), there are very few requirements for the source chamber. There is no minimum size suggested (other than being large enough to install the ductwork and loudspeaker), and there are no acoustical performance standards (other than a requirement that the interior surfaces of the chamber contain a minimal amount of sound-absorbing material). The source chamber is a critical component of the test method, and it is worthy of an acoustical performance specification. The most important feature of the source chamber is to generate a constant, high-level, acoustic signal that will create a constant, in-duct sound power level at the inlet of the test specimen with or without the test specimen

in the test duct. If the presence of the test specimen in the test duct changes the impedance seen by the loudspeaker, then the sound power radiated by the loudspeaker may be different when the test specimen is removed or inserted into the test duct. Such a condition could certainly change the measured insertion loss of the test specimen.

The following modifications are recommended to Section 6.2 of the standard to improve the characteristics of the source chamber:

- Require a measurement microphone (with a windscreen if air flow is present) to be placed at a fixed location inside the source chamber near the radiating surface of the loudspeaker. The signal from this microphone should be monitored and analyzed simultaneously by the same data acquisition system that is used to collect the data from the microphone(s) in the reverberation chamber. If when comparing the empty duct test to the test with the test specimen, the sound pressure level in the source chamber deviates by more than 1 dB in any frequency band, the test is invalid and should be repeated until the variation is less than 1 dB.
- Recommend a minimum size of 10 cubic meters for the source chamber. This will provide adequate space for placing the loudspeaker(s) and the monitor microphone without obstructing airflow.

Flanking Sound Transmission. Flanking sound is any sound that travels from the source chamber to the reverberation chamber that does not pass through the test specimen. Like ambient noise, flanking sound will limit the laboratory's ability to measure insertion loss. However, unlike ambient noise (which can easily be measured), flanking sound typically goes totally unnoticed, because it is present only when the source chamber is operating. The round-robin tests noted earlier were all conducted using the 1999 version of the standard, which had no requirement to measure the flanking sound transmission, let alone correct data for flanking effects. The 1999 version of the standard made suggestions as to how to assess the magnitude of the flanking sound, but there were no specific recommendations as to how to perform the flanking test and certainly no requirement that it be done. In the current version of the standard, a flanking noise testing is required, but only once a year – and still there aren't enough details as to how to perform the flanking noise test.

The insertion loss of most straight-through silencers (and certainly including all of the duct silencers used in the round-robin testing reported here) typically increases with frequency from 50 to 1,000 Hz, then decreases with frequency above 2,000 Hz. The insertion loss of a high-performance silencer at mid frequencies can easily exceed 50 or even 60 dB. Taking into consideration the signal losses in the source chamber and in the test specimen, it is easy to see that this does not leave much signal left to reach the reverberation chamber in the mid-frequency region. In fact, flanking noise is likely the dominant sound transmission path in this frequency region for many labs, especially when testing a high-performance silencer. If flanking noise is not properly evaluated, it could cause wide variability in the insertion loss results when comparing results from lab to lab. Flanking sound radiating from the walls of the source chamber, the walls of the test duct prior to the test specimen, and sound transmission through the facility floor can reach the reverberation chamber via various paths. Flanking problems can only be corrected by modifying the design of the test facility.

Increasing the transmission loss of the source and reverberation chamber walls, ceiling, and doors is one thing that should be considered to control the airborne flanking path. Also, improving attenuation of the airborne sound transmission path via the return air ductwork that connects the source chamber to the reverberation chamber via the fan chamber should be considered. Mounting the source chamber and the reverberation chamber on an independent isolated (floating) slab is an effective means of controlling the structure-borne path through the floor. But the most common flanking sound path is via the test duct itself. Because of the high-intensity sound inside the test duct between the source chamber and the test specimen, breakout in this area is often very significant,



Figure 4. Test duct showing lagged rectangular ductwork prior to test specimen with duct downstream encased inside a spiral round duct.

particularly if the test duct is rectangular in shape. This breakout noise can then enter the reverberation chamber via entry doors or penetrate back into the test duct on the other side of the test specimen and pass into the reverberation chamber virtually unhindered. Providing additional shielding of the test duct upstream and downstream of the test specimen is the most effective way to minimize this flanking sound transmission path.

Figure 4 shows the test duct of one lab prior to the installation of the test specimen. The test duct has a square cross section that is 0.61 m (2 ft) wide. The construction of the test duct is 6.35-mm (1/4-inch) plate steel throughout (except for the test specimen). The ductwork between the source chamber and the test specimen is lagged with gypsum board and an outer shell of sheet steel. The ductwork between the test specimen and the reverberation chamber is encased in a 0.91-m (3-ft) diameter spiral round duct with the space between the inner square and outer round duct filled with fiberglass insulation. This particular lab is the exception, since most labs do not have this extensive breakout sound control in their test duct.

Fortunately, there is a relatively simple and easy method to accurately measure the flanking sound transmission for an E 477 test. All that is required is to insert a plug in the test duct next to the test specimen (on the reverberation-room side) as shown in Figure 5. The plug should consist of two solid sheets of minimum 14-gauge (2 mm-thick) steel separated by at least 0.61 m (2 ft), with the inner space completely filled with fiberglass or mineral wool insulation (see Figure 6). The acoustic plug cannot be placed on the source chamber side of the test specimen, because the reflective surface facing the noise source will create standing waves that do not normally appear inside the test duct. Placing the plug in that location would also increase the sound level inside the test duct and overestimate the true flanking noise.

Because the length and casing construction of the test specimen may vary with the test specimen, these variations will change the amount of breakout noise that is radiated from the section of the test duct between the source chamber and the test specimen. Therefore, it is necessary to measure the flanking noise contribution for each duct silencer test, not just once a year as required by the current standard. Fortunately, the test is quick and easy to perform once the acoustic plug is fabricated. Because the acoustic plug totally blocks the test duct from any possibility of air flow, only a single flanking noise test is required for each silencer.

Empty Duct Resonances. The poor lab-to-lab reproducibility of insertion loss at low frequencies is likely due to several factors, including low modal density in the reverberation chamber, influence of background noise, and flanking sound transmission as discussed above. However, there is a fourth mechanism that might be the most important of all, especially in labs with good flanking sound control. This fourth mechanism is empty duct resonances. When measuring the insertion loss of a test specimen, the standard requires a measurement with and without the test specimen in the

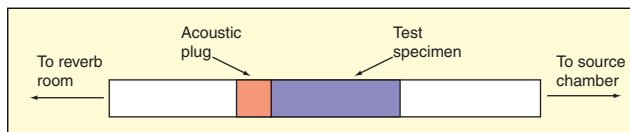


Figure 5. Recommended plug location and design for flanking noise test.

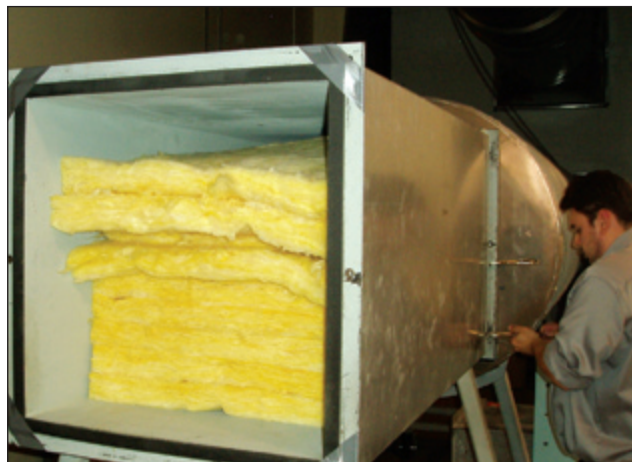


Figure 6. Inside view of acoustic plug prior to installation of cover plate.

test duct. The standard also requires an abrupt duct termination at the inside surface of the reverberation chamber. The abrupt duct termination is required to accurately assess the end reflection loss at this interface, which is used for determining the sound power level of the self-generated flow noise.

Because of the abrupt change in cross-sectional area at each end of the duct, there is a resulting acoustic impedance mismatch. This impedance mismatch causes the low-frequency acoustic waves to reflect back into the duct. For a duct of the size that is typically found in an E 477 lab, the end reflection loss with an abrupt termination is negligible at frequencies above 250 Hz. Below that, the end reflection increases with decreasing frequency, and at 63 Hz, the end reflection loss is nearly 10 dB, corresponding to a sound power reflection coefficient close to unity. In addition, the empty test duct also will exhibit strong acoustic resonances at low frequencies. These “organ-pipe” resonances are created by the repeated internal reflection of sound at each end of the duct and can be calculated using the equation:

$$f_n = nc / 2L \quad (1)$$

where:

- n = integer defining order of mode
- c = speed of sound inside duct
- L = length of empty duct
- f_n = resonance frequency, Hz

The acoustic resonances appear only at low frequencies, because the end reflection is negligible above 250 Hz. Without reflections at both ends of the test duct, the resonances will not occur. The location and spacing of these resonances will depend on the overall length of the test duct, but they generally fall into the 5-100 Hz range.

Figure 7 presents the measured spectra at various times and locations during a duct silencer insertion loss measurement. In this lab, overall length of the test duct is 15.2 m (50 ft), so the calculated acoustic resonances for the empty test duct are: 11, 22, 33, 44, 55, and 66 Hz, etc. Note the strong peaks at each of these resonance frequencies during the empty duct test. Note also that these peaks are not present in the source chamber or in the reverberation chamber when the test specimen is installed in the test duct. Clearly, the duct resonances are impacting the sound power radiating from the test duct opening. The net result is that the insertion loss is overestimated at the duct resonances, and it is underestimated at the anti-resonances between each resonance. At some frequencies, the insertion loss will actually measure as a negative value (see Figure 8). The resonance frequencies will vary with the length of the test duct, and the strength of the resonances

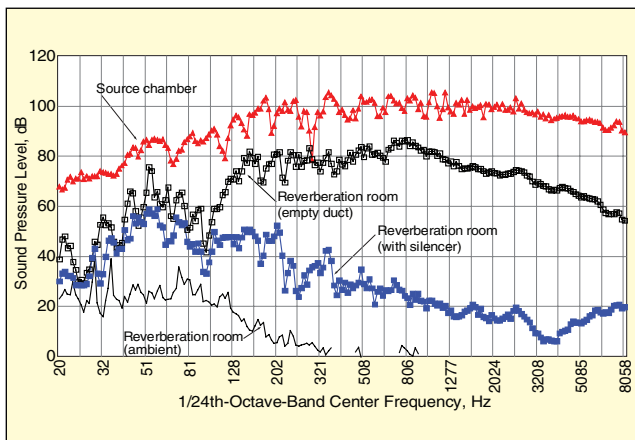


Figure 7. Source signal spectra measured in source chamber and reverberation chamber.

will be greater in test ducts with heavier duct construction. Since every lab has a different test duct length and construction, the empty duct resonances will vary significantly from lab to lab.

There are two ways to eliminate the problems created by these empty duct resonances:

- Reduce the impedance mismatch at the duct termination by inserting an impedance matching device (exponential horn) between the test duct and the reverberation chamber.
- Insert a modal filter in the test duct between the source chamber and the test specimen that will damp any low-frequency resonances.

The idea of inserting an exponential horn at the end of the test duct was discussed previously.² While this approach works in theory, most existing labs do not have the space required to construct an assembly large enough to work well down to the 50 Hz lower limit of the standard. The idea of a modal filter in the test duct is presented in the ISO standard (ISO 11691) for measuring insertion loss of duct silencers, but this approach has the inherent problem of further reducing the signal-to-noise ratio with the test specimen in place, because the attenuation of the modal filter will reduce the incident intensity at the test specimen and the resulting sound level in the reverberation chamber. This would result in even greater problems with flanking sound transmission.

A better idea is to eliminate the empty duct test entirely. This could be accomplished by using a reference silencer with a known transmission loss in the test duct location. The insertion loss of the test specimen would be compared against the transmission loss of the reference silencer in the same way that a reference sound source is used to measure the sound power of a noise source in a reverberation chamber using the comparison method. The only problem with this approach is deciding how to calibrate the insertion loss of the reference silencer. Certainly, an E 477 lab would not be the best choice because of the empty duct resonance problems mentioned above.

Another option would be to increase the cross dimensions of the entire test duct to a point where the end reflection was negligible throughout the frequency range of interest. If the desired low-frequency limit is 50 Hz, this would require a test duct larger than 10 square feet. Such a duct would not be feasible from a cost and space standpoint, since the minimum length of the test duct is about 20 times the duct cross dimension. Probably the best method for calibration would be to use acoustic intensity to measure the incident and transmitted power of the reference silencer inside the test duct. The calibration would only be required for the no flow condition. If the E 477 lab does not have the required instrumentation and expertise to conduct the required intensity measurements, this service could be provided by an independent calibration agency.

Breakout. Breakout is defined as the noise that radiates from the outer shell of a duct to the surrounding environment. Most duct silencers manufactured for commercial HVAC systems in North America have an external shell constructed of relatively lightweight steel (approximately 0.9 mm thick, or 22 gauge). Heavier outer

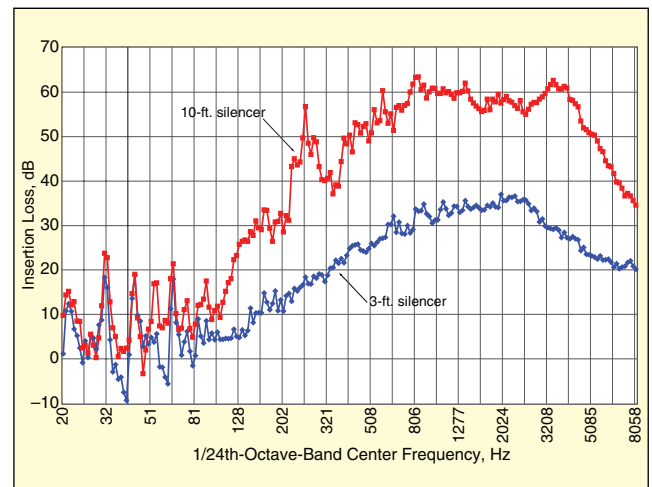


Figure 8. Measured insertion loss for two different silencers.


shells are available (special order) from most silencer manufacturers, but the extra cost to fabricate and ship these heavier silencers has no real benefit in most applications. The primary reason for using heavy-gauge steel in duct silencers is to reduce the breakout noise, since a heavier shell will generally provide a higher transmission loss through the wall of the duct. When duct silencers have to be installed above or inside a noise-sensitive space, breakout noise can be a very important matter. However, it should be noted that, some of the attenuation provided by a duct silencer is due to energy loss resulting from breakout from the silencer casing. This is especially true of rectangular silencers in the low-frequency bands. As a result, the insertion loss of a silencer provided with a heavier gauge outer shell may provide less insertion loss at low frequencies than the identical silencer with a lighter-gauge outer shell.

Presently there is no standard test method for measuring the breakout noise from ductwork or duct silencers, although a new working group has recently been created in ASTM to study this issue. There are two possible test methods, one using ANSI S12.51 (ISO 3741) in a reverberation chamber, and the other using acoustic intensity. If a reverberation chamber is used, the test specimen would have to be located inside the reverberation chamber with an inlet and outlet duct that had sufficient lagging to effectively eliminate the radiated noise from the inlet and outlet ductwork. This would obviously require a special test setup with extensive duct lagging. The acoustic intensity option is the most appealing, because it could probably be measured while the test specimen is inserted in the E 477 test duct for the insertion loss test.

Summary

We have identified three deficiencies in the current ASTM E 477 test method and suggested one new test that could be incorporated into the standard. The highlighted deficiencies are likely the cause of poor lab-to-lab reproducibility exhibited by recent round-robin tests. Problems associated with the source chamber can be identified and rectified by requiring a measurement microphone inside the source chamber and enforcing a source chamber qualification in the standard. Problems with flanking sound transmission can be identified and rectified by enforcing a flanking noise test with each and every silencer test. Problems with empty duct resonances can be avoided entirely by eliminating the empty duct portion of the test and replacing it with a calibrated reference silencer. Finally, a new test within ASTM E 477 is suggested to measure breakout noise from the silencer casing using acoustic intensity.

References

1. ASTM E 477-06a, *Standard Test Method for Measuring Acoustical and Airflow Performance of Duct Liner Materials and Prefabricated Silencers*, ASTM International, 2006.
2. J. Lilly and J. Partain, "Dynamic Insertion Loss Measurements of Duct Silencers at Low Frequencies," *Proceedings of Noise-Con 2000*, Institute of Noise Control Engineers, 2000. 

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