## Chapter 1

# Acoustic anechoic termination of the waveguide in the measuring system of ducted silencers

***Andrzej Dobrucki, Przemysław Plaskota, Romuald Bolejko***
Wrocław University of Science and Technology

DOI: 10.54215/Noise_Control_2022_A_Digital_Monograph_Dobrucki_A_Plaskota_P_Bolejko_R

**Abstract**
The paper presents the assumptions and design of an anechoic termination fulfilling the requirements of the European Standard EN ISO 7235:2009 for systems for measurement of acoustic parameters of ducted silencers. The duct must remain open to ensure the airflow. The attenuation of the reflected wave is ensured by both the absorption of the wave by the sound absorbing material surrounding the duct and an appropriate termination shape to ensure impedance matching. Horn shaped terminations are most used here. Exponential horns are often used, but catenoid horns have better properties. The various types of anechoic termination are described in European Standards EN ISO 5136:2009 and EN ISO 7235:2009. The Standard EN ISO 7235 requires that the standing wave ratio for the acoustic pressure does not exceed the value to 0.3 at the lowest measurement frequency. Three catenoidal anechoic terminations were designed for waveguides with cross-sections 250 × 250 mm, 450 × 450 mm and 800 × 800 mm used in the duct silencer measurement system compliant with EN ISO 7235:2009 standard. The catenoidal part is located on both ends of the anechoic termination. For the duct with a smaller cross-section, it is placed on two sides of the central duct with flow, while for the duct with a larger cross-section it is placed on four sides. The height of the smaller termination is equal to 1060 mm and the height and width of the larger termination is 2024 mm. The length of the termination in both cases is 3900 mm because of geometrical limitation of the measurement room. The measurement of the constructed anechoic termination shows that it meets the conditions of the standard above the 1/3-octave band with a center frequency of 50 Hz.

**Keywords:** ducted silencer, measurement, anechoic termination, catenoidal horn

## 1. Introduction

In order to ensure optimum transmission of the acoustic wave power in the waveguide, it is important to prevent the occurrence of wave reflections on discontinuities in the cross-section. Such reflections occur when the waveguide cross-section changes, when the waveguide branches and at the end of the waveguide. Part of the power of an acoustic wave is reflected from a discontinuity, resulting in a standing wave. The standing wave ratio, defined as the ratio of the energy density of the reflected wave to the energy density of the incident wave, is a measure of the reflected power. This coefficient can take values from 0 to 1. A standing wave coefficient of 1 means full internal reflection from a discontinuity, i.e., all energy of the incident wave is reflected. This situation occurs, for example, when a wave is reflected from the rigid end of a waveguide. A standing wave coefficient of 0 means that there is no reflection, and all the wave energy is transmitted. This situation occurs if the acoustic impedance of the waveguide is equal to its acoustic impedance at the end. Then all the wave energy is transmitted to the impedance loading the end of the waveguide. There is no perfect anechoic termination. With any discontinuity there will be reflected waves. The anechoic termination is designed in such a way that these reflections are as small as possible under the given conditions. Two solutions are used. The first is to terminate the waveguide with a sound-absorbing material, e.g., mineral wool or glass wool. The absorption of the wave energy by the sound absorbing material is greater the larger the amount of sound absorbing material is. The constructions made of such material in the form of wedges or pyramids are also used. This solution can be used if there is no air flow in the waveguide. A second solution is to use an impedance matching system at the end of the waveguide in the form of a horn, which is a pipe with a uniformly varying cross-section. The horn matches the impedance at the beginning, causing the wave to be radiated into space through the other end. This solution can be used for a waveguide with flow. Both solutions have their disadvantages, manifesting themselves primarily in the low frequency range. For terminations in the form of sound-absorbing materials or structures, their absorbing properties decrease in this frequency range. For horns, the impedance matching deteriorates with decreasing frequency. Many horns used in practice have a limiting frequency below which there is no wave motion in the horn and then the use of a horn is meaningless. Finally, a mixed solution is possible - using both a horn and a sound-absorbing material.

## 2. The catenoidal horn

The catenoidal horn belongs to the so-called Salmon horns family. The dependence of the area on the distance from the horn inlet for this family is described by the formula [1]:

$$S(x) = S_1\left(cosh\frac{mx}{2} + Tsinh\frac{mx}{2}\right)^2 \tag{1}$$

where:

$x$ – distance from the horn inlet (throat), $S_1$ – throat surface, $T$ – family parameter, $m$ – flare constant. For different parameter values $T$ the following horns are obtained: $T = 0$ – catenoidal horn, $T = 1$ – exponential horn, $T = \infty$ – conical horn.

All horns of Salmon family, except the conical, have a limiting frequency, below of which in the horn the wave motion does not exist, and the horn does not work. The limiting frequencies of all Salmon horns are expressed by the formula:

$$f_{low} = \frac{mc}{4\pi} \tag{2}$$

where:

$c$ – the sound speed in the medium, for air at the temperature 20°C, $c$ = 343 m/s.

It should be noted, however, that the value of $m$ for each horn with the same geometrical parameters (throat area, mouth area, length) are different and therefore the limiting frequencies are also different.

Above the limiting frequency, the impedance at the horn inlet (throat) changes rapidly to the matching value. A conical horn has a limiting frequency of zero, but the impedance at the throat increases very slowly and reaches the matching value at the highest frequency. For this reason, it pays to use only horns with $T$ values between 0 and 1. For an exponential horn, the matching frequency value is about twice the cut-off frequency, while for a catenoidal horn, the matching is obtained immediately above the cut-off frequency. The catenoidal horn introduces high distortion and is therefore rarely used in systems where the quality of the transmitted sound is important. In noise control solutions, however, it is worth using this horn.

Finally, the dependence the area $S$ on the distance $x$ is given for the catenoidal horn by the formula:

$$S(x) = S_1 cosh^2\left(\frac{mx}{2}\right). \tag{3}$$

The impedance at the throat of the catenoidal horn under ideal matching conditions is:

$$Z_1(f) = \frac{\rho_0 c}{S_1} \cdot \frac{1}{\sqrt{1 - \left(\frac{mc}{4\pi f}\right)^2}} \tag{4}$$

and is pure acoustic resistance. A perfect match is obtained for a horn of infinite length. For a horn of finite length, the impedance has a real and imaginary part and is given by the formula [2]:

$$Z_1 = \frac{\rho_0 c}{S_1} \cdot \frac{jk}{\sqrt{k^2 - \frac{m^2}{4}}} \cdot \frac{jk \frac{\rho_0 c}{S_2 Z_2} tan\left(\sqrt{k^2 - \frac{m^2}{4}} l\right) - \frac{m}{2} tanh\left(\frac{ml}{2}\right) tan\left(\sqrt{k^2 - \frac{m^2}{4}} l\right) + \sqrt{k^2 - \frac{m^2}{4}}}{jk \frac{\rho_0 c}{S_2 Z_2} - \frac{m}{2} tanh\left(\frac{ml}{2}\right) - \sqrt{k^2 - \frac{m^2}{4}} tan\left(\sqrt{k^2 - \frac{m^2}{4}} l\right)} \tag{5}$$

where:

$k$ – the wavenumber, $Z_2$ – impedance at the outlet (mouth) of the horn. The impedance $Z_1$ has both the real and imaginary parts.

## 3. Measurement of ducted silencers: standard EN ISO 7235:2009

The procedures for measuring the acoustic performance of duct silencers are described in the European Standard EN ISO 7235:2009. Acoustics – Laboratory measurement procedures for ducted silencers and air-terminal units – Insertion loss, flow noise and total pressure loss [3]. The procedures described in this standard include measurements under airflow and no-airflow conditions. The basic measurand with which the indicated acoustic parameters are determined is the sound power. Methods are described for measuring sound power under diffuse field conditions in reverberation chambers, and for travelling wave conditions. Measurements can be carried out without air flow and with air flow. This paper describes the anechoic termination of a waveguide, used for traveling wave measurements with the possibility of measurements with airflow. The measurement installation works in an airflow looped circuit. It consists of a sound source, a waveguide connecting the source to the silencer under test together with adapters, a measurement waveguide and an anechoic termination, behind which is a fan generating the flow with silencers at the input and output to suppress its noise and instruments to measure pressure and flow velocity. The pipe after the fan is connected to the sound source. The standard [3] requires that the standing wave ratio of the sound pressure, defined as the ratio of the amplitudes of the reflected and incident waves at the anechoic termination from the measuring waveguide, should not exceed the value $r_p = 0.3$, i.e., the energy absorption coefficient $\alpha$ should meet the condition:

$$\alpha = 1 - r_p^2 \geq 0.91 \tag{6}$$

in the frequency range between 50 Hz and the limiting frequency above which a wave in a waveguide cannot be considered as plane due to the formation of higher-order modes. In the case described, the waveguide has a square shape, for which the upper limiting frequency is [3]:

$$f_H = \frac{0.5\,c}{a} \tag{7}$$

where:

$a$ – side of the square.

Standard [3] shows an example of an anechoic termination consisting of a double-sided catenoid part and a tubular connector. In the center of the termination there is a waveguide with a connecting pipe cross-section, and on the sides, there is an attenuator with a stepped catenoid shape, and a pipe part filled with sound-absorbing material. Other anechoic termination solutions can be found in the European Standard [4].

## 4. Design of catenoidal anechoic termination

This chapter presents the design of a double-sided catenoidal anechoic termination used in an installation for the measurement of acoustic silencers according to EN ISO 7235:2009. This installation is carried out at BH-RES company in Rzeszow. In this design, the catenoid shape is composed of conical segments connecting to each other. The cross-sectional area of the anechoic termination consists of two parts: a square waveguide of side $a$, through which the medium can flow, and a catenoidal part, placed along two or four sides of the waveguide. The side of the waveguide to which the catenoidal part adjoins is perforated with a perforation ratio of 60%. The interior of the catenoid part is filled with a sound absorbing material: mineral wool with a density of 40 kg/m$^3$. The side walls of the catenoidal part are an extension of the corresponding side of the waveguide. The cross-sectional area of the waveguide containing the waveguide part and $n$ catenoid parts is expressed by the formula:

$$S(x) = a^2 + n \cdot a \cdot \mathrm{h}(x) \tag{8}$$

where:

$n = 2$ or 4, $h(x)$ – external profile of the catenoid part. The shape of the catenoid profile is given by the formula (9):

$$h(x) = \frac{a}{n}\left[cosh^2\left(\frac{mx}{2}\right) - 1\right]. \tag{9}$$

Calculations were performed for a limiting frequency of 50 Hz and for three sides of the cross-section: $a = 0.25$ m, 0.45 m and 0.8 m. For a horn with side $a = 0.25$ m, $n = 2$ was assumed (the catenoid part is placed on two opposite walls of the waveguide), while for a waveguide with side $a = 0.8$ $n = 4$ was assumed (the catenoid part is placed on all four walls of the waveguide). For the intermediate case $a = 0.45$ m calculations were performed for two variants: $n = 2$ and $n = 4$. Based on formulas (2) and (3) the flare constant $m = 1.8$ m$^{-1}$ was determined. The upper limited frequencies according to formula (7) are: for the channel with $a = 0.25$ m, $f_h = 688$ Hz, for $a = 0.45$ m, $f_h = 382$ Hz and for $a = 0.8$ m, $f_h = 215$ Hz. Calculations of $h(x)$ were performed every 30 cm in the range from $x = 0$ to 1.5 m, then the cross-section is constant up to the value of $x = 2.4$ m, after which it decreases symmetrically to $x = 3.9$ m.

The results of the calculations are given in Table below.

**Table.** Profile of the catenoid section of a single side of an anechoic termination

| **Channel** | **0.25 x 0.25 m** | **0.45 x 0.45 m** | **0.45 x 0.45 m** | **0.8 x 0.8 m** |
|---|---|---|---|---|
| **Variant** | ***N = 2*** | ***N = 2*** | ***N = 4*** | ***N = 4*** |
| ***x* [m]** | ***h(x)* [m]** | ***h(x)* [m]** | ***h(x)* [m]** | ***h(x)* [m]** |
| 0 | 0 | 0 | 0 | 0 |
| 0.3 | 0.009 | 0.017 | 0.008 | 0.015 |
| 0.6 | 0.040 | 0.072 | 0.036 | 0.064 |
| 0.9 | 0.102 | 0.183 | 0.091 | 0.163 |
| 1.2 | 0.212 | 0.382 | 0.191 | 0.339 |
| 1.5 | 0.405 | 0.728 | 0.364 | 0.647 |
| 1.8 | 0.405 | 0.728 | 0.364 | 0.647 |
| 2.1 | 0.405 | 0.728 | 0.364 | 0.647 |
| 2.4 | 0.405 | 0.728 | 0.364 | 0.647 |
| 2.7 | 0.212 | 0.382 | 0.191 | 0.339 |
| 3.0 | 0.102 | 0.183 | 0.091 | 0.163 |
| 3.3 | 0.040 | 0.072 | 0.036 | 0.064 |
| 3.6 | 0.009 | 0.017 | 0.008 | 0.015 |
| 3.9 | 0 | 0 | 0 | 0 |

The largest width and height are for the anechoic termination with a waveguide of $a = 0.8$ m. They amount to $2 \times 0.647 + 0{,}8 = 2.094$ m each.

The anechoic termination profiles for $a = 0.25$ ($n = 2$) and for $a = 0.8$ ($n = 4$) are shown in the Figures 1 and 2.

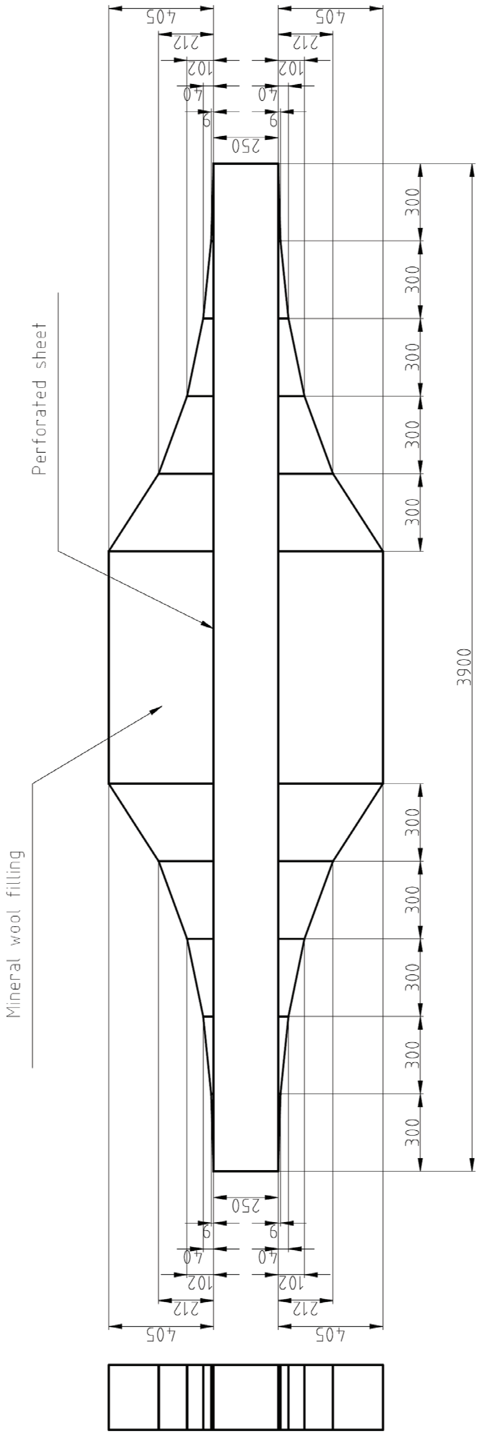

**Figure 1.** Cross-section and profile of the anechoic termination for the waveguide 0.25 × 0.25 m

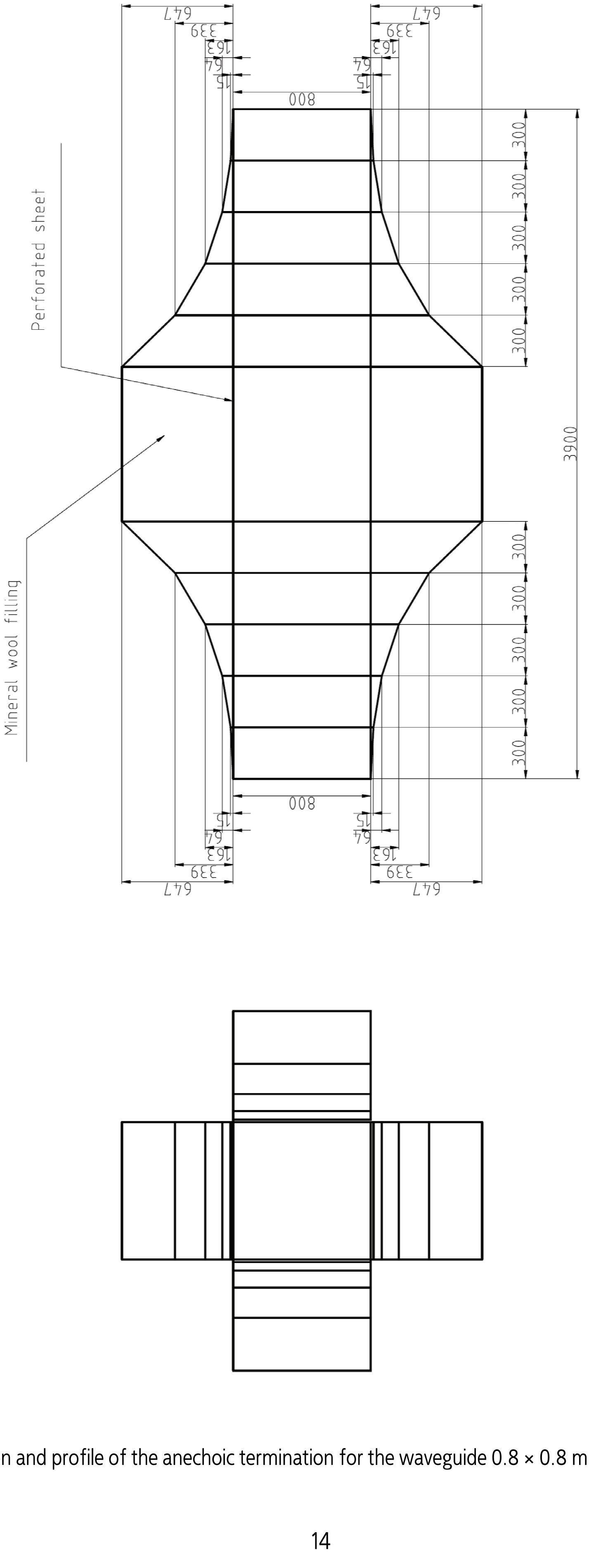

**Figure 2.** Cross-section and profile of the anechoic termination for the waveguide 0.8 × 0.8 m

At present, only the anechoic termination for the largest waveguide with a waveguide cross- section of 0.8 × 0.8 m has been realized and measured. Figure 3 shows one catenoidal section of the anechoic termination before assembly.

**Figure 3.** The anechoic termination before assembly

For this anechoic termination, the absorption coefficient as a function of frequency was measured. The measurement results are shown in Figure 4.

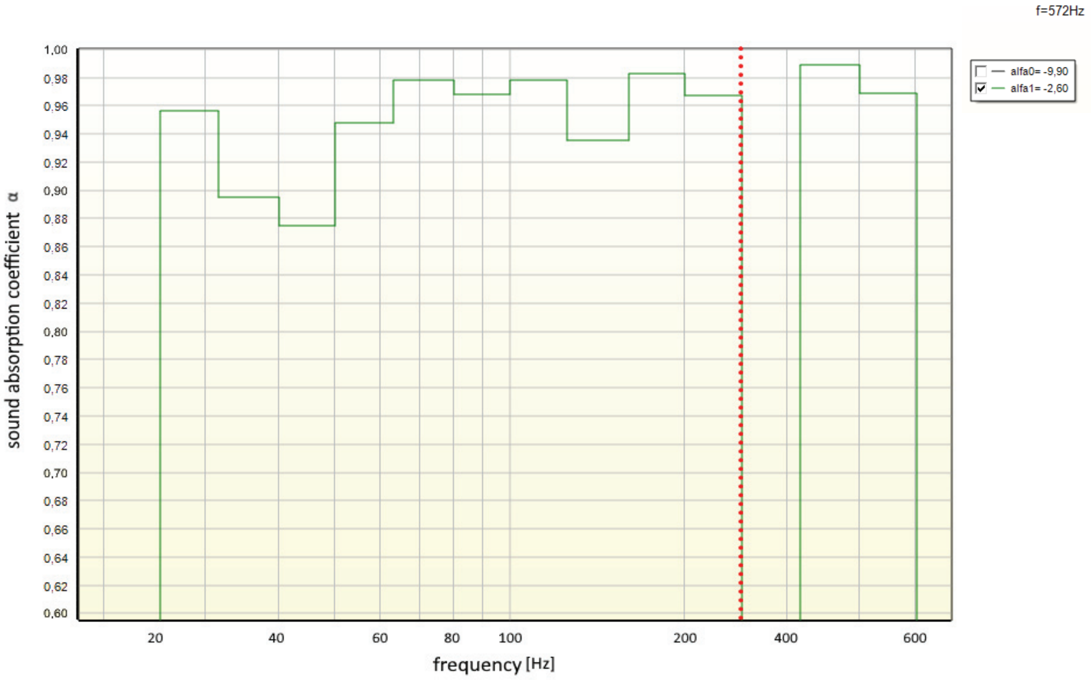

**Figure 4.** Measured sound absorption coefficient of the 80 × 80 cm anechoic termination

Condition (6) is satisfied in the frequency range above the 1/3-octave band of 50 Hz. The frequency of 572 Hz, for which a sharp drop in absorption coefficient is seen, lies above the required frequency of 215 Hz for this termination and is caused by the cover the microphone position and the nodal line of the waveguide.

## 5. Conclusions

In anti-noise solutions, the most difficult task is to ensure high attenuation in the low frequency range. This applies both to noise transmitted through obstacles (walls, partitions) and that transmitted in waveguides. Inadequate attenuation results in reflected waves which interferes with the travelling wave and creates standing waves. To prevent this, sound-absorbing materials or horns are used at the end of the waveguide. Hybrid solutions are most effective, and catenoid horns are best used as horns. Since it is extremely difficult to precisely manufacture a catenoid termination, shape approximation using stepped ducts is used. In this work, catenoidal shape approximation is used using tapered sections made of flat sections of sheet metal mounted at an angle that changes according to the chain curve. The interior of the main waveguide is not filled with sound absorbing material to ensure airflow. Sound absorbing material is used in panels mounted on the sides of the square main waveguide. The panels can in the simplest case be mounted on one side. To reduce the size of the whole structure, mounting on two or four sides is used. Waveguide terminations have been designed for three sizes of main waveguide cross-sections. So far, one termination has been implemented for the largest cross-section. Very good results were obtained, and the termination meets the requirements of the standard. The large cross-section is the most difficult case, so it is expected that the results will be even better for the other cross-sections.

## References

[1] Dobrucki A. Podstawy akustyki [Foundation of acoustics]. Wroclaw: Oficyna Wydawnicza Politechniki Wrocławskiej; 1987. p. 149-151.

[2] Myers K. Design of a Catenoidal Shaped Anechoic Termination, Master's Theses. 41. Michigan: Western Michigan University; 2012. p. 34-40.

[3] European Standard EN ISO 7235:2009. Acoustics – Laboratory measurement procedures for ducted silencers and air-terminal units – Insertion loss, flow noise and total pressure loss.

[4] European Standard EN ISO 5136:2009. Acoustics – Determination of sound power radiated into a duct by fans and other air-moving devices – In-duct method. Annex E.