Applied Innovative Research, ISSN 2581-8198, Vol. 4, Issue 2 - 4, Year 2023

Scaling laws for acoustic duct performance measurement

D. Veerababu, B. Shivateja and B. Venkatesham*[1],
Nikhil Bhalerao, NDEVARA Nsr prasad, Anvesh kumar GOKARNAM[2]
[1]Indian Institute of Technology Hyderabad, Kandi, Sangareddy, Telangana. India 502285
[2]Bombardier Transportation India Private Limited (Alstom)
Financial District, Nanakaramguda, Telangana, India 500032

Abstract

Acoustic treatment of HVAC ducts used in industrial applications, trains, and other environments is critical to effectively attenuate sound and maintain comfortable noise levels according to set norms. These applications generally use long ducts that may sometimes have a complicated geometry. Acoustic performance for such complex duct configurations doesn't align with ASHRAE standards. Expensive testing facilities are required to conduct experiments to assess the acoustic performance of such long ducts, which is not always feasible. In such scenarios, the duct model could be scaled down as per the facilities available. This article goes through the scaling principles that must be followed to model the duct in a scaled-down version. The scaling laws are virtually tested to validate the concept using Finite Element Analysis (FEA).

Keywords:FEA, HVAC ducts, Acoustic performance, Scaling law

1. Introduction

Heating, Ventilation, and Air Conditioning (HVAC) ducts are used to distribute heated or cooled air throughout an enclosure. The air is delivered through a network of supply and return ducts connected to a central air handler. These ducts are widely used in a variety of applications, including trains, manufacturing plants, commercial complexes, and so on. Acoustic treatment is required to effectively attenuate sound and maintain acceptable noise levels in accordance with established standards [1, 2]. Long ducts with complex geometries are typically used in these applications.

The ASHRAE standard discusses sound attenuation in symmetric and uniform duct configurations [1]. The study of attenuation of sound in asymmetric long ducts requires experimental verification for which expensive testing facilities are needed, which is not always practical. Depending on the facilities available, the duct model might be scaled down in some circumstances.

In many engineering domains, scaled models is utilised to study problems that would otherwise need exorbitantly expensive testing facilities. Using scale models to explore the attenuation of HVAC ductwork appears to be another practical use. KangpingRuan [3] summarises scale modelling rules for assessing the attenuation of heating, ventilation, and air conditioning ducts. The frequency ratio is inversely proportional to the size ratio in a standard scaling strategy. Scaling rules for sound absorption and breakout transmission loss are also established. Nan Zhang [4] has discussed scaling laws for sound

---

Corresponding authors: (Email : venkatesham@iith.ac.in) transmission in air, across a membrane, and through a sound-absorbing substance. In this paper, scaling principles for a scaled-down model are established and analytically validated using Finite Element Analysis (FEA).

2. Duct Description

An HVAC duct of total length ($L_{overall}$) of 18.56m used in a metro car consists of two straight sections of lengths 4.880 (L_1) and 3.626 m with a cross-section 250 × 400 mm and one tapering section of 10.05m length with a cross-section of 477.1 × 1195.5 mm at one end and 250 × 400mm at the other end, as shown in Fig. 1.

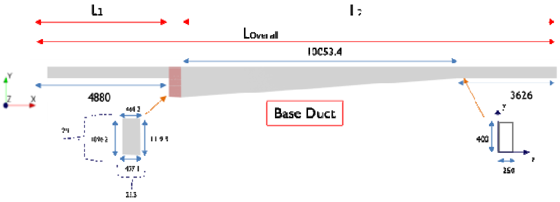

Fig.1 : Simplified duct geometry

3. Direct Frequency Response

The Direct Frequency Response (DFR) is a computational procedure used to compute the response of an acoustic, vibro-acoustic, or aeroacoustics system in physical coordinates to a specific stimulus. For varying circular frequency ($\omega = 2\pi f$), the following system of equations is built up and solved:

$$(\boldsymbol{K} + j\omega\boldsymbol{C} - \omega^2\boldsymbol{M})x(\omega) = \boldsymbol{F}(\omega)$$

where, $\boldsymbol{F}(\omega)$ is the external excitation as a function of ω, generating values of the unknown vector $x(\omega)$ for each iteration ω.

The domain is divided into number of small tetrahedron elements (HyperWorks). The maximum size of the element is kept below one-sixth of the minimum wavelength present in the analysis. The DFR analysis is carried out by applying a plane wave excitation at the inlet and anechoic terminal boundary condition at the outlet. As the boundary conditions cannot be applied directly on to the 3-D elements, 2-D face elements have been extracted from the inlet as well as the outlet. The central region of the duct is assigned with the properties of air, whereas the annular region associated with lining is assigned with the properties of the complex-medium. The outer surface of the duct is assumed to be acoustically rigid, that is, the sound cannot break-in and/or break-out of the duct system. This is the same procedure used to calculate the transmission loss as per the following formula

$$TL = 10 \log \frac{W_i}{W_t} \quad (2)$$

The modal analysis is carried out in a similar way except that the annular region is also assigned with the properties of air as the modal analysis cannot take into the effect of equivalent complex-medium properties of the acoustic absorptive lining. In addition, both the inlet and outlets are assigned with rigid boundary conditions.

The first step in the acoustic analysis is to understand the dynamic characteristics (natural frequencies, mode shape) of the duct system. An acoustic modal analysis is performed to determine the natural frequencies and mode shapes of a duct system. The predicted mode shapes are compared with the direct frequency response of the duct system to understand the influence of mode shapes, dominant modes, and mode participation factors. Fig. 2 compares pressure distribution results from direct frequency response (for rigid boundaries and air medium) and mode shapes from modal analysis in the frequency range from 10 to 50 Hz. It is observed that pressure distribution and mode shapes are closely matched at low frequencies. As the frequency increases, the mode participation of multiple modes increases, and mode shapes and pressure distribution keep deviating.

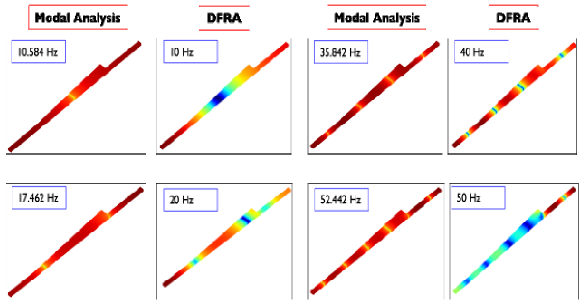

Fig.2: Comparison of mode shapes with the acoustic pressure distribution from Direct Frequency Response analysis.

4. Scaling Laws

The scaling laws are proportionality relations of any parameter associated with an object (or system) with its length scale. The scaling law $Area \propto length^2$ can be used in geometry. This law states that the area of a geo-metric figure shown in Fig.3a scales as l^2. If keeping the geometric shape unchanged, the size is changed the area of the figure will change in proportion to the square of the length scale. So, $\mathrm{A1{:}A2{:}A3} = 1{:}1/4 : 1/64$. If only one dimension is scaled, the area will also scale as linear power of that length scale. Fig.3b shows two figures where only the vertical dimension changes. So, if A1 and A2 be the areas of the two figures, $\mathrm{A1{:}A2} = 1{:}\lambda$. [7]

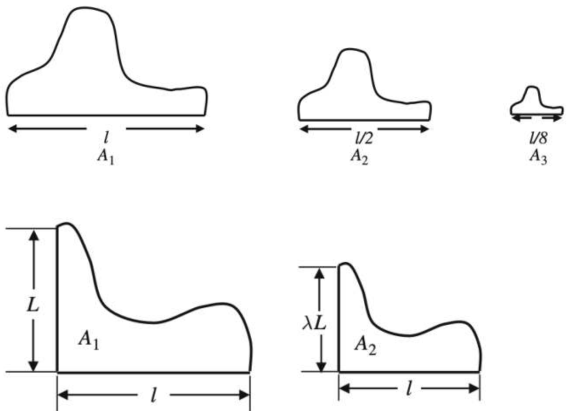

Fig.3 — Symmetric (a) and unsymmetric (b) scaling

Assuming same fluid properties both unscaled and scaled models, the scaling rule can be further simplified as,

$$f_1 l_1 = f_2 l_2 \qquad (3)$$

the frequency of the full and scale models is inversely proportional to their geometrical dimensions.

Along with the duct size, the absorptive material used for lining shouldbe scaled over its cross-section (thickness t) to maintain the same behavior. This scaling law is summarized below.

$$\frac{f_1 t_1}{R_{s1}} = \frac{f_2 t_2}{R_{s2}} \qquad (4)$$

The flow resistivity of the lining materials in the original and scaled duct models is represented by R_{s1} and R_{s2}, respectively. According to the flow resistances of the materials should be similar (i.e., $R_{s1} \approx R_{s2}$). Suppose it can be assumed that the flow resistance is proportional to the material density. In that case, the flow resistance will remain constant if the scaled amount compresses the material.

Acoustic attenuation is known to be proportional to length and P/S, the ratio of lined perimeter (P) to flow area S. So, transmission loss (TL) is given as []

$$TL_l = L_h \frac{l}{h} \qquad (5)$$

where L_h is called the attenuation per channel height. It is critical to establish that the TL for the full and scaled models should be the same to attain similar performance.

Let us consider a rectangular duct whose all sides are lined whose opening cross-section is $2y * x$. Wetted perimeter and cross-sectional area for this configuration will be $P = 4x$, $S = 2yx$, respectively. Then P/S ratio will be

$$\frac{P}{S} = \frac{2}{y} \qquad (6)$$

On uniformly scaling the duct by a factor C then the scaled dimension (y') can be written as

$$y' = Cy \qquad (7)$$

then, P/S ratio for the scaled model will become

$$\left(\frac{P}{S}\right)' = \frac{2}{y'} = \frac{2}{Cy} \qquad (8)$$

Transmission Loss for the original duct can be written as,

$$(TL_l)_{original} = TL_h \cdot l \cdot \frac{2}{y} \qquad (9)$$

and TL for the scaled model is expressed as,

$$(TL_l)_{scaled} = TL_h \cdot l' \cdot \left(\frac{P}{S}\right)' \qquad (11)$$

substituting Equation 8 in Equation 10,

$$(TL_l)_{scaled} = TL_h \cdot Cl \cdot \frac{2}{Cy} \qquad (12)$$

thus,

$$(TL_l)_{original} = (TL_l)_{scaled}$$

On substituting $l_1 = l$ and $l_2 = Cl$ in Equation 3, the frequency for the scaled model can be found.

$$f_s = \frac{f_0 l_0}{l_s} = \frac{f_0}{C} \qquad (13)$$

For scaling down the original duct operating at a frequency of 1000 Hz by0.1 factor, then the operating frequency of the scaled model will be 10000Hz to achieve the same TL.

5. Results and Discussion

A finite element model is developed for full and 0.1x scaled ducts without acoustic material. The transmission loss as a function of the frequency of both models is shown in Fig. 4. Due to confidentiality reasons Y axis of the graphs are not shown. The frequency for the original (0-1000 Hz) and scaled model (0-10000 Hz) is superimposed as per the scaling law, and the graph demonstrates similar behavior.

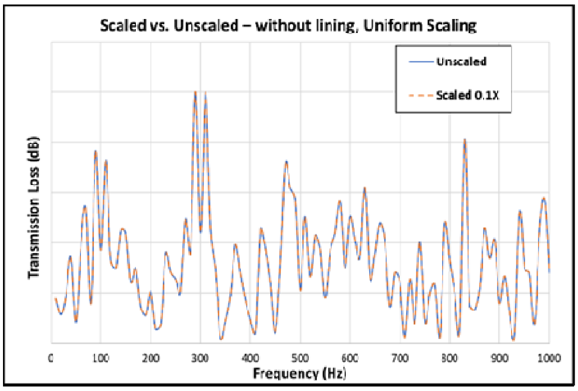

Fig.4 — TL comparison for original duct and 0.1x scaled duct

But scaling by 0.1x is practically impossible per the absorptive material scaling rule that was established in Equation 4; achieving the required material thickness and flow resistivity is unattainable. As a result, 0.5x factor scale down is chosen, which satisfies all of the scaling constraints. The simulation findings for the 20 mm lined original duct in a frequency range from 0 to 3000 Hz and 0.5x scaled duct in a frequency range from 0 to 6000 Hz are superimposed and observed good agreement.

Fig. 5 demonstrates the TL of 20 mm lined full-length dimensions and 0.5x scaled ducts as a function of frequency. The frequency for the original (0-3000 Hz) and scaled model (0-6000 Hz) is superimposed, and good agreement is observed between them.

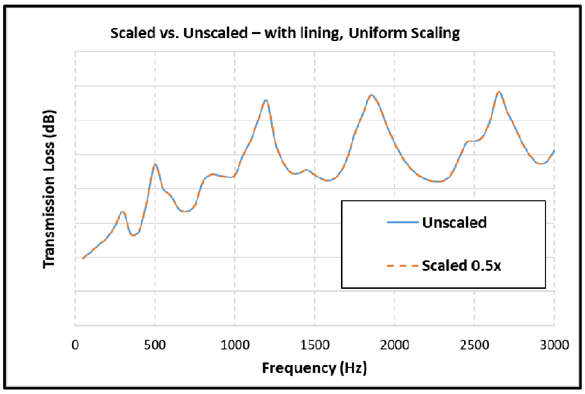

Fig.5 — TL comparison for 20 mm lined original duct and 0.5x scaled duct

The duct is scaled 0.6x and 0.25x along the most extended dimension (along length) in this approach. Fig. 6 compares the TL of the mentioned scale with the base model. Non-uniform scaling for the base duct configuration does not provide the same TL because of change in significant duct modes.

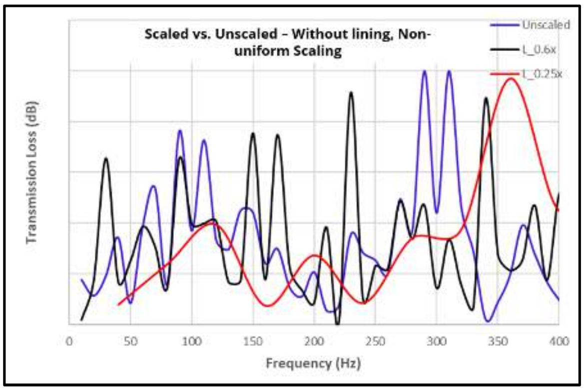

Fig.6 — TL comparison for original duct, 0.6x and 0.25x scaled duct

Summary

The laboratory experiment on the acoustic performance of long and complex ducts poses a complex situation. When there are insufficient facilities available for carrying out experiments, it is important to resort to a scaled-down modelling approach. Scaling rules for dimensions, sound sources, and materials are developed in this work in such a way that the acoustic performance (transmission loss) of both models is kept the same. The uniform scaling of a geometrically complex duct is demonstrated with the help of an example computation. This demonstration shows how the finite element approach can be used to predict the TL of a scaled and full-length duct. The same procedure is used for a lined duct. The material thickness needs to be selected according to the practical conditions. In the future, experimental validation of scaled and full-length acoustic performance investigations will be conducted.

Acknowledgement

The authors would like to express their gratitude to the Indian Institute of Technology Hyderabad for providing experimental facilities and Alstom India Pvt Ltd for financial support.

References

[1] B. Venkatesham, Mayank Tiwari and M.L. Munjal, “Prediction of Breakout Noise from Acoustically Lagged Rectangular HVAC Ducts”, Journal of Building Acoustics, 16(4), 313-328, 2009

[2] ASHRAE Handbook – Fundamentals (2017), American Society of Heating Refrigerating and Air-Conditioning Engineers Inc.

[3] KangpingRuan, "Numerical and Experimental Techniques for assessing the acoustic performance of Duct Systems above the plane wave cut-off frequency" (2018). Theses and Dissertations--Mechanical Engineering. 120.

[4] Nan Zhang, "Scale models of acoustic scattering problems including barriers and sound absorption" (2018). Theses and Dissertations--Mechanical Engineering. 119.

[5] Nagaraja Jade, Venkatesham. B, “Experimental Study of Breakout Noise Characteristics of a Flexible Rectangular Duct”, Mechanical Systems and Signal Processing, 108, 156-172, 2018

[6] Actran 17 User’s Guide - Volume 1 Installation, Operations, Theory and Utilities (2016), Free Field Technologies SA

[7] A Ghosh. (2011). Scaling Laws. In: Chakraborty, S. (eds) Mechanics Over Micro and Nano Scales. Springer, New York, NY. https://doi.org/ 10.1007/978-1-4419-9601-5_2