Journal of Sound and Vibration 357 (2015) 233–244

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Revisiting the Nelson–Morfey scaling law for flow noise from duct constrictions

Oscar Kårekull [a,b,*], Gunilla Efraimsson [a,c], Mats Åbom [a]

[a] KTH Flow Centre-Aeronautical and Vehicle Engineering, 100 44 Stockholm, Sweden
[b] Fläkt Woods, 551 84 Jönköping, Sweden
[c] Centre for ECO^2 Vehicle Design, Aeronautical and Vehicle Engineering, 100 44 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 24 November 2014
Received in revised form
4 June 2015
Accepted 10 June 2015
Handling Editor: Y. Auregan
Available online 20 August 2015

ABSTRACT

The semi-empirical scaling law by Nelson and Morfey [1] predicts the noise generation from constrictions in ducts with low Mach number flows. The results presented here demonstrate that the original model loses accuracy for constrictions of high pressure loss. A generalization based on a momentum flux assumption of the dipole forces is suggested and is evaluated against measurement results for orifice geometries of higher pressure loss than earlier evaluated. A prediction model including constrictions at flow duct terminations is also suggested. Improved accuracy for the predictions of the new model is found for orifice geometries of high pressure loss inside and at the end of ducts. The extended model is finally evaluated by measurements on a regular ventilation air terminal device.

1. Introduction

Noise generated from flow separation in duct constrictions is, at low Mach number flows, traditionally described using compact dipoles. Assuming homogeneous inflow, semi-empirical scaling laws have successfully been used for the noise prediction [1]. The level and frequency distribution of the generated noise will depend on the flow speed and the specific geometry. The dependency of the detailed geometry as well as the acoustic boundary conditions will increase for lower frequencies [2].

Generally, to avoid a decreased energy efficiency, a duct constriction is designed to have a low pressure loss. Situations where the flow needs to be strongly restricted or the flow direction needs to be drastically changed will lead to higher pressure losses, e.g. in air terminal devices, i.e., ventilation duct end constrictions. In these situations, as will be shown by the new data presented here, the accuracy of the original noise prediction [1] decreases dramatically. In this paper, a new model is presented which also holds for constrictions of high pressure loss and includes the effect of constrictions at the end of flow ducts. Nonlinear aeroacoustic phenomena, such as whistling, are not described by the prediction model.

In 1981, Nelson and Morfey [1] suggested a noise prediction model for aerodynamic sound production in low speed flow ducts. The model was derived using dipole characteristics of the noise sources together with the assumption that the rms fluctuating drag force acting on the component is proportional to the steady-state drag force. The steady-state drag force was determined by measurements of the constriction pressure drop and the duct cross-section area. The use of a pressure-loss-dependent expression for the constriction openness was introduced by Oldham and Ukpoho [3] to generalize the model by Nelson and Morfey. A number of publications [4–12] have then later evaluated the semi-empirical scaling laws and their

* Corresponding author at: Fläkt Woods, 551 84 Jönköping, Sweden.

http://dx.doi.org/10.1016/j.jsv.2015.06.019

generality by introducing measurement data of different geometries. Kårekull et al. [2] have recently reviewed and presented these publications, including some new data, in a consistent way and suggested source strength spectra for different types of geometries. In addition, Spalart [13] has investigated the precise implications of acoustic analogies for low Mach number aerodynamic noise e.g. the contribution by quadrupoles in the presence of dipoles. Numerical methods for low Mach number aeroacoustics can be based on Curle's analogy, which needs to be modified, e.g., as suggested by Schram [14], to handle aeroacoustic sources in a duct. De Jong and Golliard [15] have recently suggested the selection of characteristic velocity and dimension from RANS simulations together with a noise-level scaling from the surface acoustic power.

This paper intends to go back to the original model [1] and study the choice of reference area in the steady-state drag force definition and secondly to evaluate the possibility of using the noise prediction model for constrictions at the end of flow ducts. The present paper is organized as follows. The original model and the suggested modifications are presented in Section 2. The measurement setup and test objects are described in Section 3. Finally, the measurement results are presented and the accuracy of the suggested model is analysed in Section 4.

2. Models for flow noise prediction

2.1. The original model

The noise prediction model by Nelson and Morfey [1], valid for constrictions in low Mach number flow ducts, is here presented in a form derived in [2] that better highlights the physical mechanisms involved. Only dipole sound sources related to the flow separation are included and the effect of disturbed inflow, i.e. changed mean flow velocity profile and increased turbulence, is neglected. The sound pressure up or downstream of the constriction is defined as the product of a force, F, and a function describing the radiation properties, R. The sound power in a frequency band, generated in the downstream direction of the duct, is in the frequency domain given by[1]

$$W_D = R(He) S_{FF}(St) \tag{1}$$

where S_{FF} is the force auto-spectrum as a function of the Strouhal number (St) and R is the radiation resistance for an infinite duct as a function of the Helmholtz number (He). With the assumption that the force auto-spectrum can be split into a frequency independent mean force part, $\overline{F}$, and a source strength spectrum part, K^2, the sound power can be described by

$$W_D = R(He)\overline{F}^2 K^2(St). \tag{2}$$

For compact or point source characteristics, the noise sources are seen to radiate from a known point or cross section corresponding to a reference area A. Using the duct area as reference area [1], the mean force can be related to the pressure drop over the constriction by

$$\overline{F} = A \cdot \Delta P \tag{3}$$

where ΔP is the stagnation pressure drop of the constriction. For an in-duct constriction, the static pressure drop equals the stagnation pressure drop over the constriction while the dynamic pressure is equal before and after the constriction. Eqs. (2) and (3) yield the dimensionless source strength or reference spectrum, K^2, as a function of the Strouhal number given by

$$K^2(St) = \frac{W_D}{R(He) A^2 \Delta P^2} \tag{4}$$

where W_D is the generated sound power travelling downstream in the duct. In Ref. [2] arguments for that the dimensionless reference spectrum K^2 should be a collapse for all similar flow constrictions are presented.

The radiation resistance is dependent on the duct dimensions and is frequency independent in the plane wave regime. However, for higher wavenumbers above the duct cut on wavenumber, all propagating modes needs to be considered. The average radiation resistances, rewritten from Ref. [3] for circular ducts and from Ref. [1] for rectangular ducts, are given by

$$R_{\text{pl.w.}} = \frac{1}{2A\rho_0 c_0}, \quad k < k_0 \tag{5}$$

$$R_{\text{circ.d.}} = \frac{k^2(1 + (3\pi/4rk))}{12\pi\rho_0 c_0}, \quad k > k_0 \tag{6}$$

$$R_{\text{rect.d.}} = \frac{k^2(1 + (3\pi/4k)(a+b)/A)}{12\pi\rho_0 c_0}, \quad k > k_0 \tag{7}$$

where ρ_0 is the density of air, c_0 the speed of sound in air, a and b the dimensions of a rectangular duct, r the radius of a circular duct and k_0 the duct cut on wavenumber determined e.g. as presented in Ref. [2]. Eqs. (5)–(7) will still be used with the new mean force definition proposed in this work.

[1] Error in Ref. [2] for Eq. (1) which is corrected here.