Applied Acoustics 82 (2014) 45–52

Contents lists available at ScienceDirect

Applied Acoustics

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

Prediction model of flow duct constriction noise

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ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 11 February 2014
Accepted 3 March 2014
Available online 29 March 2014

Keywords:
Flow noise
Noise prediction
RANS

ABSTRACT

The scaling law for aerodynamic dipole type of sound from constrictions in low speed flow ducts by Nelson and Morfey is revisited. A summary of earlier published results using this scaling law is presented together with some new data. Based on this, an effort to find a general scaling law for the sound power for components with both distinct and non-distinct flow separation points are made. Special care is taken to apply the same scaling to all data based on the pressure drop. Results from both rectangular and circular ducts, duct flow velocities from 2 to 120 m/s and sound power measurements made both in ducts and in reverberation chambers are presented. The computed sound power represents the downstream source output in a reflection free duct. In particular for the low frequency plane wave range strong reflections from e.g. openings can affect the sound power output. This is handled by reformulating the Nelson and Morfey model in the form of an active acoustic 2-port. The pressure loss information needed for the semi-empirical scaling law can be gained from CFD simulations. A method using Reynold Average Navier Stokes (RANS) simulations is presented, where the required mesh quality is evaluated and estimation of the dipole source strength via the use of the pressure drop is compared to using the turbulent kinetic energy.

1. Introduction

Accurate determination of flow generated noise from constrictions in low speed ducts can be done by measurements. Assuming broad-band sound generation with no distinct harmonics in the spectrum, i.e., excluding non-linear aeroacoustic phenomena such as whistling, the measurements can be done using standard methods for sound power [1]. In low Mach number confined flows separation at a constriction corresponds to a compact dipole source due to an unsteady force acting on the fluid. An alternative to experiments is to simulate the broad band sound generation using Computational Fluid Dynamics (CFD). However such system require a complex simulation, e.g. full compressible Large Eddy Simulation (LES), and is still a significant challenge not useful for everyday engineering practice. The need is often to predict an approximate level of the flow noise for a particular case, avoiding spending the time to make the measurement or conduct the full simulation analysis.

As shown by Nelson and Morfey [1], using a generalized spectrum, the flow noise generation in low speed flow ducts can, if the effect of incoming turbulence is neglected by assuming a homogeneous inflow, be approximated from the component pressure drop. The pressure drop or the equivalent pressure loss coefficient can be obtained from standard measurements or possibly from relatively fast CFD models such as Reynold Average Navier Stokes (RANS) simulations.

A reduction of energy consumption in todays society is in great focus and the pressure drop is closely related to energy losses in the system. Since it is already used in the product development process, e.g. for ventilation products, the use of pressure drop is suitable as an model input. By determining a set of spectra for different constriction geometries, having either a distinct point of flow separation e.g. orifices, or a non-distinct, e.g. dampers or bends, a generalized model for noise prediction would be available. This paper intends to review previously published measurement data applying the same scaling to all the data in order to see common trends in the dimensionless noise spectra. Furthermore, the possibility to use a CFD approach to estimate the dipole strength of a duct component is addressed.

Iudin initiated the concept of noise prediction from air duct elements creating flow separation in 1955 [2], but Nelson and Morfey

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http://dx.doi.org/10.1016/j.apacoust.2014.03.001
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are normally cited as having created the foundation for the more recent work on the subject by their publication from 1981 [1]. They were inspired by the work on flow spoilers by Gordon [3,4]. But also by the work on the correlation between the noise radiation and the fluctuating forces on flow spoilers by Heller and Widnall [5]. The Nelson and Morfey 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. In Ref. [1] the steady state drag force was determined by measurements of the component pressure drop and the duct area. The model was verified via measurements in a rectangular flow duct connected to a reverberation chamber. Test objects were a number of strip spoilers and some orifice type geometries created as inverted strip spoilers in rectangular ducts. As detailed below over the years a number of papers based on Nelson and Morfeys scaling model have been published.

Oldham and Ukpoho [6] continued the work determining the component open area ratio and characteristics dimensions (vena contracta) from the measured pressure drop. This new definition enables components with more complex geometries to be scaled. Oldham et al. also extended the model to include circular ducts. Measurements were conducted on circular dampers at different angles and circular orifices with different diameters. Waddington and Oldham [7] measured the spectra for mitred bends in rectangular ducts and Oldham and Waddington [8] investigated the similarity when altering the air velocity and duct dimensions of different types of bends.

Gijrath et al. [9] analyzed a number of bends by estimating the generated sound power from measurements of the sound pressure level in a duct. Effects of rounding inner and outer corners of the bends were also investigate together with an analysis of the Mach number dependency. Nygård [10] introduced the concept of 2-ports, to handle wave interaction effects in the plane wave range, and compared the simulation results from a 2-port simulation code to measurement results. Different bend geometries were analyzed and also the interaction of two bends with a defined in-between distance was measured. Two bends were concluded as independent sources if the in-between distance was at least 8 duct diameters. An in-duct measurement setup similar to the one by Gijrath et al. [9] was used.

Allam and Åbom [11] continued the use of 2-ports and investigated an orifice geometry by induct measurements comparing the up and downstream side. Both passive, scattering properties, as well as active, noise generating, properties were determined in the plane wave range using a method proposed by Lavrentjev et al. [12]. It can be noted that the data in Ref. [11] unlike all other reported data gives a complete aeroacoustic description of the orifice. The data is measured so that in principle all boundary effects are eliminated, thereby representing the correct up- and downstream sound power in an infinite duct. The interaction of two orifices at a varied in-between distance was also investigated and the sources were concluded independent at an in-between distance of at least 7 duct diameters. Ducret [13] investigated the sound generation for bends in tailpipe applications. Noise generation and scaling laws for different bend radius were analyzed. Measurements in a reverberation chamber were conducted using ducts with 1–5 diameters of duct length after the bends. Tailpipe diffusers were analyzed using different diffuser angles.

Mak et al. [14] measured strip spoilers with similar geometries to the ones in [1] but for lower Strouhal numbers. A second and a third strip spoiler were introduced and the flow noise was predicted by determining the drag forces and their phase relationship together with the coherence function of the noise sources. In a series of papers Mak et al. [15–17] also investigated the possibility to gain the dipole force information from CFD simulations. In the model developed, the averaged turbulent kinetic energy was used instead of the pressure drop directly as dipole input data. Reynolds Average Navier Stokes (RANS) simulations gave the averaged turbulent kinetic energy in each node of the calculation mesh and a relationship between the drag force and the total turbulent kinetic energy in selected nodes was used in combination with a reference spectrum to create the dipole input data. Also in a recent work Mak et al. [18] has applied Large-Eddy Simulations (LES) to estimate the fluctuating dipole.

Besides the work following [1], general guidelines and reference spectra for air conditioning systems can be found in e.g. ASHREA Handbook for HVAC Applications [19] or VDI 2081 Noise generation and noise reduction in air-conditioning systems [20]. These provide references to publications of measurement data for noise generation in e.g. ducts [21] and by duct elements [22]. Ingard et al. [22] did e.g. measurements on a rectangular damper at different angles a case which will be included in the review below.

The paper is divided into three sections. The first part defines the generalized description of the model including source and radiation characteristics together with system interaction properties in the plane wave region. The second part reviews measurement data for orifice, bend and damper geometries using the described model intending a reference spectrum generalization. Finally the third part compares two CFD approaches using RANS simulations analyzing mesh and turbulence model dependency.

2. Model for generalized predictions of flow noise

In this section a model based on the dipole forces of the flow noise source in combination with an acoustic radiation resistance for an infinite duct is described. Essentially the model is the same as the originally presented by Nelson and Morfey [1] but written in a form which better highlights the physical concepts involved. The original model [1] represents a power based approach not suited for the low frequency plane wave range. For the plane wave range the model for in duct constrictions is better expressed in the form of 2-ports [10] as presented in Section 2.3.

2.1. Source model

There are two main assumptions for the source model of Nelson and Morfey [1]. First low Mach numbers and a compact source or point is assumed. Secondly only dipole sound sources related to the flow separation and unsteady forces produced along the duct axis are included. This implies the sound pressure up or downstream of the flow separation to be the product of a force, F, and a function describing the radiation properties. The sound power in a frequency band, e.g., 1/3 octave, generated in one direction of the duct can then, in the frequency domain, be described by

$$W_D = R(He)|S_{FF}(St)|^2 \tag{1}$$

where S_{FF} is the force autospectrum as a function of a Strouhal number (St) and R is the radiation resistance for an infinite duct as a function of the duct Helmholtz number (He). Assuming that the force autospectrum can be split into a mean force $\overline{F}$ part and a source strength spectrum part K^2, the sound power can, when constants are included into R, be written as

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

Note that the mean force is frequency independent. In [1], the mean force is defined for flow separation at a certain known point or cross section. This force can be related to the pressure drop over the element and the duct area A, as

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