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Concurrent identification of aero-acoustic scattering and noise sources at a flow duct singularity in low Mach number flow

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ABSTRACT

A numerical method to concurrently characterize both aeroacoustic scattering and noise sources at a duct singularity is presented. This approach combines Large Eddy Simulation (LES) with techniques of System Identification (SI): In a first step, a highly resolved LES with external broadband acoustic excitation is carried out. Subsequently, time series data extracted from the LES are post-processed by means of SI to model both acoustic propagation and noise generation.

The present work studies the aero-acoustic characteristics of an orifice placed in a duct at low flow Mach numbers with the "LES-SI" method. Parametric SI based on the Box–Jenkins mathematical structure is employed, with a prediction error approach that utilizes correlation analysis of the output residuals to avoid overfitting. Uncertainties of model parameters due to the finite length of times series are quantified in terms of confidence intervals. Numerical results for acoustic scattering matrices and power spectral densities of broad-band noise are validated against experimental measurements over a wide range of frequencies below the cut-off frequency of the duct.

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1. Introduction

Duct flow singularities, such as constrictions, valves or orifices, are used in a variety of applications. Such ducted elements may generate intense broadband noise, which is usually undesired. Furthermore, if a proper acoustic feedback between the singularity and the duct system is established, self-sustained tonal acoustic oscillations [1,2] known as "whistling" may develop. These phenomena yield high pressure fluctuations which, if not properly damped, may generate mechanical failures in the pipe system. The development of proper methodologies to predict, model and control noise generation and acoustic scattering by duct singularities is therefore of significant importance.

Low order acoustic network models [3] are frequently used to study acoustic propagation and dissipation in duct systems. This modelling strategy decomposes the system under study into discrete acoustic elements, also known as "multi-ports" [4–6]. The so-called "acoustic scattering matrix" of a multi-port characterizes transmission and reflection of incoming sound, i.e. the passive acoustic properties of the element. Noise generation, considered as an active property, may be described mathematically by means of a "noise vector" [4].

Holmberg et al. [6] assess experimentally both passive and active acoustic properties of a mixer plate placed in a duct. The analysis consists of two-steps: First, the acoustic scattering of the element and the reflection at the boundaries (duct

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open ends) of the test rigs are evaluated by means of multiple external harmonic acoustic excitations. The noise sources are subsequently quantified by aero-acoustic measurements without external sources and by taking into account the influence of reflections and of the acoustic propagation in the test rig. An alternative experimental approach to characterize the acoustic properties of a duct singularity was proposed by Paschereit et al. [7], who assess the scattering properties and the noise source by using three independent acoustic states. Two independent states, acquired by exciting the configuration at the two terminations, respectively, are used to measure the acoustic scattering matrix. A third independent acoustic state, which is realized by exciting the test rig concurrently at both duct ends, allows to determine the noise source vector. This approach is preferable in situations where low reflection coefficients at the terminations of the test rig are difficult to implement.

Experimental measurements can yield a reliable characterization of the acoustic properties of a duct singularity when carried out with great care and expertise. However, the costs of test rigs, diagnostic apparatus and measurement campaigns can be considerable. Moreover, the experimental assessment of large and complex installations is often not feasible. To overcome these problems, analytical and numerical approaches are adopted. Analytical models yield a basic characterization of the acoustic scattering of simple duct elements – see e.g. [8] for an area expansion or [9] for an orifice – and for a restricted range of operating flow conditions. However, when more complex geometries and flow fields are considered, the analytical approach is unfeasible.

Numerical methods are more flexible and allow to take into account a wide range of configurations and operating conditions. The simulation of the acoustic propagation and dissipation in ducted flows is often based on Linearized Euler Equations (LEE) [10] or Linearized Navier–Stokes Equations (LNSE) [11,12]. These numerical approaches afford a good prediction of the acoustic scattering and of the interaction of an incident acoustic wave with the shear layer developed at the singularity. However, the linearization around a steady flow condition does not capture the interactions between the turbulence and the acoustic waves and the so-called scattering of sound by turbulence. Moreover, broad-band noise generated by turbulent fluctuations cannot be assessed by means of linearized methods.

Indeed, noise generated by turbulence-boundary interactions is usually characterized numerically by means of the so-called Curle's analogy [13], or Ffowcs-Williams Hawking's analogy [14] in case of moving noise sources. These acoustic analogies are extensions of the well known analogy of Lighthill [15] for configurations where solid boundaries are significant. Unsteady turbulent fluctuations act as quadrupole sources of the acoustic field, whereas the flow-boundary interactions act as a dipole source of sound. However, the computation of the related Green's functions is not always simple and the application to closed domains (such as duct systems) is not straightforward.

O'Reilly et al. [16] have explored a straightforward method for the numerical assessment of the acoustic characteristics of an orifice in a duct. The flow field and the acoustic properties of the element were determined by acoustically exciting a high-order Direct Numerical Simulation (DNS) of the filtered, compressible Navier–Stokes equations. The excitation imposed was a “sum-of-sine-waves” signal [16] of different discrete frequencies. The acoustic scattering matrix was subsequently assessed by measuring the acoustic response of the system at those frequencies. Good predictions of the acoustic transmission and reflection coefficients in a quiescent medium were achieved. However, the acoustic scattering in the presence of flow was not captured correctly. In this case, the prediction of the passive properties of the element were “contaminated with flow generated sound” [16].

To the authors' knowledge a reliable numerical approach to characterize both acoustic scattering and noise sources of duct singularities is still missing. To achieve this goal, a method based on an improvement of the established LES-SI approach [17,18] is proposed. The LES-SI approach consists of a combination of Large Eddy Simulation and System Identification techniques. In a first step, an acoustically excited Large Eddy Simulation is carried out. Subsequently acoustic data series extracted from the computational domain are post-processed by means of System Identification (SI) techniques to identify the acoustic properties of the duct singularity. In contrast to a linearized method based on LEEs or LNSEs, the use of highly resolved compressible LES allows to simulate the small turbulent structures responsible for noise generation. Moreover, LES should make it possible to capture explicitly important interactions between the turbulent flow field and an incident acoustic perturbation, yielding a more complete representation of acoustic scattering.

The LES-SI method has been used to identify the acoustic scattering matrix of different duct singularities such as an area-expansion [18], a T-junction [19] or an orifice [20]. In the present work we employ LES-SI to *concurrently* identify both the scattering matrix and the noise source vector of a duct element with merely a single LES run. In an earlier study [21], the present authors already extended the established SI technique, based on correlation analysis, to model the noise sources. A new parametric SI approach based on the Box–Jenkins model structure [22–25] and a prediction error method [22–25] was introduced. However, in this earlier study [21], the noise model identified exhibited a dependency on the imposed acoustic excitation. In the present study, the parametric SI approach is revised and extensively analysed. The proper choice of a parametrization is discussed on the basis of *residual analysis*, the *uncertainty* of model parameters resulting from time series of finite length is quantified.

The parametric LES-SI approach is applied to concurrently identify the acoustic scattering matrix and the noise sources generated by turbulence of an orifice placed in a duct. This configuration has been experimentally studied by Testud et al. [26,27]. The choice of the geometry is not crucial, since the method can be applied to a wide range of configurations and duct singularities. The analysis is performed assuming anechoic terminations. No acoustic feedback due to reflections at the boundaries is considered. Therefore, the noise sources are only due to the instabilities of the turbulent shear layer developed

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