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Investigation of orifice aeroacoustics by means of multi-port methods

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ABSTRACT

Comprehensive methods to cascade active multi-ports, e.g., for acoustic network prediction, have until now only been available for plane waves. This paper presents procedures to combine multi-ports with an arbitrary number of considered duct modes. A multi-port method is used to extract complex mode amplitudes from experimental data of single and tandem in-duct orifice plates for Helmholtz numbers up to around 4 and, hence, beyond the cut-on of several higher order modes. The theory of connecting single multi-ports to linear cascades is derived for the passive properties (the scattering of the system) and the active properties (the source cross-spectrum matrix of the system). One scope of this paper is to investigate the influence of the hydrodynamic near field on the accuracy of both the passive and the active predictions in multi-port cascades. The scattering and the source cross-spectrum matrix of tandem orifice configurations is measured for three cases, namely, with a distance between the plates of 10 duct diameter, for which the downstream orifice is outside the jet of the upstream orifice, 4 duct diameter, and 2 duct diameter (both inside the jet). The results are compared with predictions from single orifice measurements. It is shown that the scattering is only sensitive to disturbed inflow in certain frequency ranges where coupling between the flow and sound field exists, whereas the source cross-spectrum matrix is very sensitive to disturbed inflow for all frequencies. An important part of the analysis is based on an eigenvalue analysis of the scattering matrix and the source cross-spectrum matrix to evaluate the potential of sound amplification and dominant source mechanisms.

1. Introduction

There is great interest in scattering and source data of aeroacoustic components in duct and pipe systems, and methods to extract this data are presented for example in Refs. [1–4]. The aeroacoustic properties are commonly described in terms of active two-port data for plane waves in ducts with single inlets and outlets as first mentioned by Cremer in Ref. [5] or multi-port data for higher order acoustic duct modes and systems of multiple inlets and outlets as proposed by Lavrentjev and Åbom in Ref. [6]. Using advanced post-processing methods, multi-port data can be determined from measurements and computations by mapping a set of eigensolutions ('acoustic duct modes') of a convective wave equation onto sufficiently sampled pressure fields [6,7]. This approach is advantageous for several reasons [8]. First, the gained acoustic field can be efficiently cleaned of hydrodynamic pressure fluctuations of the mean flow that often 'pollute' the data acquired in the

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turbulent boundary layers close to the duct walls. Second, the reflections of the test rig terminations in measurements or the test domain boundaries in computations can be determined by decomposing the sampled sound fields into upstream and downstream propagating acoustic modes. Such reflections can be subtracted from the sampled pressure signals, which results in source and scattering data that is independent of the test set-up. Multi-port data gained from different set-ups or with different methods, e.g., from both measurements and computations, can therefore be compared directly. The procedures to extract multi-port data have been discussed in the literature in detail: for experiments, e.g., in Refs. [9,8,10], and for numerics, among others, in [11–13]. In principle, sets of multi-port data can be utilized to predict the acoustic scattering (passive data) and sound generation (active data) in complex networks of aeroacoustic sources. However, even if the procedure is well established for the plane wave range using two-ports [14,15], applications for active multi-ports of arbitrary order are sparse. Bi et al. investigated a combined scattering matrix in non-uniform lined ducts without mean flow that was computed from analytical solutions of different liner segments [16]. Wang and Sun extended this work to non-uniform liners with mean flow [17]. The focus, however, was only on the passive properties, especially on the solution of a single uniform liner element. This paper derives equations to compute the combined scattering *and* source data for pairs of multi-ports in cascades and therefore allows a complete prediction of active multi-port data in such networks. Potentialities and limitations of the predictions are demonstrated by investigating installation effects (acoustic and hydrodynamic) at tandem orifice configurations with different separation distances between circular, single-hole orifice plates in low Mach-number flow ($M = 0.078$). As a first step, the scattering matrix and source cross-spectrum matrix of a single orifice plate are measured and the quality of the scattering data is evaluated using the error-analysis described in Ref. [4]. Subsequently, the derived network formulas are used to predict configurations of tandem plates, and the result is compared to measurements on similar systems.

Inside the unstable shear layers that evolve in the wake of orifice plates, the acoustic field can interact with the hydrodynamic field, resulting in sound amplification or damping. Those effects can be triggered by acoustic disturbances as well as turbulences impinging on the shear flow [18]. Changing inflow conditions may disturb the boundary layers inside the orifice plates and the shear layers in the wake of the orifice, thereby influencing the flow-acoustic interaction. Even though the process of amplification itself is non-linear, the potential of this amplification can be described with linear theory and is represented by the eigenvalues of the squared exergy matrix as derived in Ref. [19] and tested, for example, in Refs. [20,13]. In the present study, this theory is applied to the measured and predicted tandem configurations to uncover weaknesses in the capability to capture the acoustic-flow interactions in the passive part of the network model. This is furthermore the first time that the amplification potential is computed for higher order modes and in multi-port networks. In addition, the amplification potential is useful for analysing the sensitivity to installation effects for multi-ports in cascade.

The active part of the configurations is represented with source cross-spectrum matrices as described in Ref. [9] and tested, e.g., in Refs. [21,22]. One aspect that appears to have been overlooked in earlier work is that the source cross-spectrum matrix can be diagonalized due to the Hermitian character, and its eigenvalues may be interpreted as independent modal point sources. This paper analyzes the eigenvalues for the different test cases to gain insight into the source composition.

The paper is structured as follows: First, the multi-port theory and the needed scattering and source notation is introduced in Section 2. Second, the equations necessary to group multi-ports and combine them into networks are derived in Section 3. The measurement set-up, mainly adapted from Ref. [4], is introduced in Section 4, and the results are presented in Section 5. Section 5.1 shows the scattering prediction compared with measurements for the three tandem configurations. The source cross-spectrum matrix and plots of independent source mechanisms for the different test cases can be found in Section 5.2.

2. Representation of aeroacoustic sources as multi-ports

Aeroacoustic sources inside ducts can be modeled as acoustic multi-ports in terms of their sound transmission and reflection and their ability to create sound waves. Assuming linear and time invariant acoustic wave propagation, a linear system of equations can be formulated in the frequency domain

$$\mathbf{p}_{+} = \mathbf{S}\mathbf{p}_{-} + \mathbf{p}_{s+} . \tag{1}$$

The sound emitted by a duct component $\mathbf{p}_{+}$ equals the sum of scattered (incident) sound $\mathbf{S}\mathbf{p}_{-}$ and the sound created by the component itself $\mathbf{p}_{s+}$. Here, $\mathbf{S}$ is denoted as the scattering matrix (or passive part) and $\mathbf{p}_{s+}$ is the source (or active part). The reader should understand the quantities in Eq. (1) as vectors and matrices of propagating acoustic duct modes, e.g., $\mathbf{p}_{-}$ and $\mathbf{p}_{+}$ are vectors containing the complex acoustic modal pressure amplitudes propagating toward and outward from the component at a point at the multi-port inlet and outlet, respectively. A mode in this paper is denoted as an (m,n)-mode, where m is the circular and n is the radial mode order, but it is also ordered and numbered based on its cut-on frequencies as the i-th mode. The plane wave mode corresponds to the (0,0)-mode and has the order number $i = 0$. The scattering matrix and the source vector are characteristic properties of an aeroacoustic source and can be used to describe sound fields established inside a duct and pipe system. A full multi-port study is aimed at determining these characteristics, and there is a sizeable literature introducing procedures to gain scattering and source data from measurements and computations, e.g., Refs. [6,7,23] and more recently in Refs. [4,24,25,13].