



Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Particle image velocimetry measurement of an instability wave over a porous wall in a duct with flow

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ARTICLE INFO

Article history:

Received 31 March 2016

Received in revised form

22 September 2016

Accepted 26 September 2016

Handling Editor: R.E. Musafir

Keywords:

Duct aeroacoustics

Porous liner

Hydrodynamic mode

ABSTRACT

The flow in a rectangular channel lined with a porous material and acoustically excited with an upstream loudspeaker has been investigated using particle image velocimetry. The measurements are phase-locked to the loudspeaker signal so that the phase-averaged velocity in the lined section is obtained during an excitation period. Most features of the phase-averaged velocity field in the lined section are found to be well described from the sum of three single duct modes: the hydrodynamic instability wave, a standing wave and an acoustic wave. The hydrodynamic instability wave travels at half the mean flow velocity, and its structure shows differences to the case of a locally reacting liner. The relative phase lag between the hydrodynamic and acoustic waves at the liner end dictates the interference between both waves, giving rise to the oscillations of the acoustical transmission coefficient as a function of the frequency. A detachment of the instability wave from the porous wall is observed in the vicinity of the liner downstream edge, together with the separation of the mean vorticity core.

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1. Introduction

In many industrial applications where noise propagates through pipes and ducts, acoustic treatments are used to reduce the sound transmitted to the surroundings. To diminish the energy losses in the mean flow, the acoustic treatments are located in the walls of flow ducts and they are called acoustic liners. There exist two families of liners. The first family includes the locally reacting liners, i.e. liners that are locally equivalent to an acoustic impedance. They are efficient tonal noise attenuators and are widely used in aero-engines [1]. The second family includes porous liners, which are non-locally reacting. They are effective broadband noise attenuators [2] and are commonly used in the air conditioning and ventilation systems, as well as in exhaust systems for gas turbines or IC-engines.

There is an important effect of flow on the performance of locally reacting and porous liners. The interaction of the boundary layer with the lined wall changes the modal structure existing in absence of flow [3–6]. Rienstra [5] showed theoretically that there can exist “strange modes” in a flow pipe with a locally reacting liner. These modes can be divided into acoustic and hydrodynamic surface modes, and their number and stability character depends on the liner impedance, as well as the flow Mach number. It was also shown that for a certain range of impedances, at least one hydrodynamic mode was unstable.

Previous experimental investigations have revealed a peak of the transmission coefficient around the resonance frequency of locally reacting liners, with the peak frequency and level depending on the flow Mach number [7–9]. Alongside

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with the transmission coefficient peak, a static pressure drop along the lined section was detected. These results were attributed to the presence of an unstable hydrodynamic mode over the liner. Marx et al. [10] studied experimentally a low resistance liner using particle image velocimetry (PIV) and laser Doppler velocimetry (LDV). A linear, convectively unstable mode was directly observed in the lined section, and its wavelength, phase velocity, amplification and wall-normal eigenfunctions were obtained.

The case of flow ducts lined with a porous material is also of fundamental and practical interest. A porous liner is not locally reacting, and the acoustic fields inside and outside the porous material cannot be decoupled. They both need to be calculated simultaneously [11,12]. Aurégan and Singh [13] investigated experimentally the acoustic properties of a homogeneous porous liner in a flow duct. They observed oscillations of the transmission coefficient in a wide range of frequencies. The transmission coefficient was decomposed into a 'hydrodynamic' contribution, responsible for the oscillations, and an 'acoustic' contribution, similar to the transmission coefficient without flow. These two contributions were associated with an hydrodynamic wave and an acoustic wave, respectively. The oscillations of the transmission coefficient were then hypothesised to be due to the interference between the hydrodynamic and acoustic waves at the downstream liner section. This picture differs from the locally reacting liner case, where acoustic resonance plays a crucial role in the instability mechanism.

The current work aims at further investigating the unstable mode over a porous liner with grazing flow. PIV has been used to measure the velocity field in the lined section. This way the complete spatial structure of the waves present can be observed. This will lead to a better modelling, which will improve its prediction and prevention in applications.

A preliminary version of this study was presented as a conference paper [14]. The current version contains additional results and extended discussions. In particular, proper orthogonal decomposition has been used to 'clean' the measured velocity fields, an analysis of the mean vorticity has highlighted new features of the mean velocity field, the velocity signals in time have been analysed, further results and discussion concerning the detachment of the instability wave have been included, and finally, the impact of the instability wave to the turbulent field has been assessed. For completeness, some figures from [14] are presented in the current paper.

In Section 2 the experimental rig and the measuring technique are presented, together with results from microphone measurements. Section 3 describes the phase-locking technique, and the procedure followed to split the velocity field into mean, phase-averaged and turbulent components. In Section 4 the results are presented and discussed.

2. Experimental setup

2.1. Duct rig

The rig used consists of a rectangular duct composed of an upstream segment of dimensions 8 cm (width) $\times$ 3 cm (height) and a downstream segment containing the test section, with dimensions 8 cm (width) $\times$ 2 cm (height). Both are united by a 0.2 m long convergent. The downstream duct segment is 0.6 m long, and has an anechoic termination. The lined wall is located at the centre of the test section. It spans the entire channel width and has a length of 8 cm. The test section has two rectangular windows, one on the opposite wall to the liner and another at a side wall. The former lets the laser sheet pass through, illuminating the entire lined section, and the latter allows the light reflected to reach the camera. The flow through the duct was generated with a fan providing a mean centreline velocity up to about 100 m/s. The incoming sound is generated by a loudspeaker fixed in the upstream duct segment, at 1.5 m from the test section. The sound level at the entrance of the test section was 143 dB, in order to maximise the signal-to-noise ratio. The same rig was used by Marx et al. [10], and it is sketched in Fig. 1.

2.2. Porous liner

The porous material consists of a rigid metallic foam (RECEMAT, NC4753.05 nickel-chromium alloy), which is the same used by [13]. The parameters of the porous material in the fluid equivalent model [15] were determined to be: porosity $\Phi = 0.99$, tortuosity $\alpha_\infty = 1.17$, viscous length $\Lambda = 1 \times 10^{-4}$ m, thermal length $\Lambda' = 2.4 \times 10^{-4}$ m, and resistivity $\sigma = 6.9 \times 10^3$ kg m $^{-3}$ s $^{-1}$. The 25 mm depth cavity was filled with five plates of thickness 5 mm each, rigidly assembled to

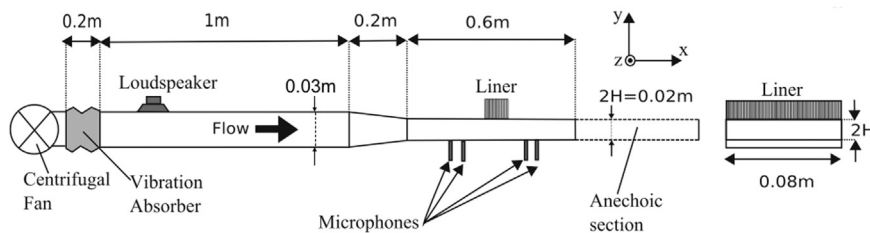


Fig. 1. Experimental setup [10].

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