Multi-slotted synthetic jet actuator for flow control of separated flows

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Abstract A numerical and experimental characterization of an innovative multi-slotted synthetic jet issuing in a quiescent environment has been carried out. A Laser Doppler Vibrometer (LDV) has been employed to obtain the vibrational modes of the diaphragm for a wide range of frequencies, whereas Hot-wire measurements and Particle Image Velocimetry (PIV) have been used to study the external flow field. A dedicated Lumped Element Model (LEM) has been properly developed for the present actuator; the LEM has been calibrated on LDV and Hot-wire data, and has been used for the optimized design of the actuator for the control of a separated flow. The numerical characterization consists in direct numerical simulations of the flow field generated by the actuator, carried out with the OpenFOAM code. Simulations allowed to detect the vortical structures generated at the orifice exit, and analyze their motion while moving downstream. Interaction and convergence between adjacent jets in the far-field have been also investigated.
Keywords: Synthetic jet actuators, Particle Image Velocimetry, Direct Numerical Simulation

1 Introduction

Synthetic jet (SJ) actuators are currently used in many industrial or research applications. The opportunity to use a device producing a non-zero average momentum rate, with a null average mass flow rate during an operation cycle [1], is particularly attractive for active flow control systems, requiring reduced sizes and low weights. Several literature works are focused on these devices, which mainly aim at designing and characterizing them in a quiescent ambient, or at evaluating their effectiveness as flow control devices. Several experimental campaigns have been carried out with this purpose, using a wide range of experimental techniques. On the other hand, many computational studies have been performed, using RANS, LES [2] and DNS [3] techniques.

The first works on SJ devices focused on round or slotted actuators; three-dimensional edge effects in non-circular synthetic jets have been investigated only recently. Jet Reynolds, Stokes and Strouhal numbers and the aspect ratio of the exit orifice have a strong impact on jet development; their effects on the SJ behavior have been extensively studied. Moreover, the vortex motion in the external environment is strongly influenced by the initial shape of the vortices; an interesting feature of non-circular configurations is the axis switching, a periodic deformation of the vortex rings which leads to an apparent variation of the vortex orientation. Besides, the vortices could experience bifurcations and spanwise instabilities, that strongly influence the jet mixing. Recently there have been also a growing interest on multiple-orifice or multi-slot configurations [4, 5], since in many practical applications it is necessary to use such configurations to control flows on aerodynamic surfaces as wings and tails [4].

The scope of this work is to characterize an unconventional multi-slotted device, tracking the motion of the vortical structures from the exit of the actuator, and identifying the optimal configuration for the control of a separated flow. The frequency response of the actuator is also determined, in order to achieve the desired value of the exit velocity at the selected frequency.

2 Synthetic jet device

The SJ device is composed of a stainless steel sandwich structure: the top part, with dimensions of 261×70 mm^2, contains twelve slots; a flat rectangular ring is used to create a single cavity, under which three piezo-speakers are applied; the bottom part has been used to provide an additional structural support. In this way each diaphragm subtends four slots, thus forming three distinct groups of slots. A Sonitron SPS-8770-03 piezoelectric element, equipped with a multi-layer (polymer/metal) diaphragm embedded in a plastic support whose dimensions are 70×87 mm^2, was chosen as piezoelectric element. All couplings were made with a two-part epoxy adhesive. The slot is 1 mm wide, with a spanwise length of 15 mm, and a depth of 1 mm. The distance between two consecutive slots of the same group is 5 mm. The cavity depth is 2 mm. The device was electrically excited by a sine signal, generated through a multi-function instrument and then transmitted to a linear gain amplifier. A peak-to-peak voltage equal to 60 V_{pp} was chosen. The whole device is entirely homemade, with the exception of the diaphragm, which was already assembled.

3 Experimental characterization

To determine the frequency response of the actuator, a Laser Doppler Vibrometer (LDV) allowed the acquisition of vibrations of the diaphragm, by reconstructing the entire deflection for each vibrational mode. The frequency response in terms of exit velocity has been completed measuring the streamwise jet velocity by means of a hot-wire anemometer, equipped with a 5 μm diameter sensor. The probe was placed at the exit section of a central slot, with the wire parallel to the longer side of the slot. The frequency response, both in terms of jet velocity and diaphragm displacement amplitude, showed a peak next to the structural resonance frequency (250 Hz), that has been chosen as a reference condition for the subsequent analysis.

The experimental data (hot-wire and LDV) have been used to calibrate a proper Lumped Element Model (LEM). Only a single row of slots has been considered, relying on the fact that multi-slotted actuators, with symmetric configuration and a notable distance between the nozzles, can be considered as divided in sub-volumes, each of them operating with its own pressure and orifice velocity.

The final step of the characterization has been a time-resolved PIV investigation, which allowed to obtain the velocity field in the middle plane of the device. The analysis was conducted by means of a high-speed camera, with a sampling frequency of 7500 Hz, thus obtaining 30 phase-averaged velocity data. The centerline velocity at the orifice exit was finally compared with the hot-wire measurements.

4 Numerical characterization

Direct numerical simulations have been performed in order to characterize the vortex motion in the external environment and to achieve the best configuration for flow control. The simulations, that fully include the actuator geometry, have been performed using OpenFOAM code. The numerical setup took advantage from the experimental results: the shape of the diaphragm deformation (mimicked by a time-periodic inlet condition at the unperturbed position of the diaphragm) resembles the experimental leading vibrational mode, whereas its amplitude has been obtained from PIV data. The phase-averaged velocity fields allowed to follow the vortex motion, recognizing the instability mechanisms and the axis switching. Proper Orthogonal Decomposition has been used to shed light on the interaction and the coalescence between adjacent jets.

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