EFFECTS OF A SYNTHETIC JET ACTUATOR ON THE DELAY OF SEPARATION IN A BOUNDARY LAYER

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Abstract. *This work has as a fundamental objective the study of the effects of synthetic jet actuators on the flow of the boundary layer developed on a flat plate. The aim here is to obtain computational data that indicates how this effect may be used as a means of flow control, describing the dynamics of the synthetic jet in the presence of external flow. The present paper uses a Direct Numerical Simulation (DNS). The incompressible Navier-Stokes equations are written in vorticity-velocity formulation. The spatial derivatives are discretized with a sixth order compact finite differences scheme. The Poisson equation for the normal velocity component is solved by an iterative Line Successive Over Relaxation Method and uses a multigrid Full Approximation Scheme to accelerate the convergence. The results of simulations with different values of frequency, amplitude and slot length were verified through a temporal Fourier analysis. The results shows that the best combination of the parameters of a synthetic jet actuator can be achieved but demands a wide number of numerical simulations for a specific case.*

Keywords: *synthetic jet, delay of separation, boundary layer stability, active flow control, laminar flow transition.*

1. Introduction

Several studies demonstrate that flow control can be used to delay the separation of a boundary layer. Experimental works has been done to demonstrate and evaluate drag reduction techniques that have definite possibilities of influencing, for instance, the project of an aircraft. The passive means are the forms of operation that do not interact dynamically with the flow, and the active means act in a dynamic way in order to modify with the flow synthetic jet actuators have been used as active flow control technique. Several experiments have demonstrated that, using this technique, it is possible to achieve separation delay of a boundary layer in flows over airfoils.

The development of jets with zero liquid flow mass was the result of several investigations that employed several experimental and computational methods. Both methods, experimental and computational, are used in a complementary way. The experimental data provides not only the physical base for the study, but also a database, against which the computational data may be tested. The validated computational model may be used to examine details of the flow that are hard to find experimentally.

The synthetic jet actuator may be considered an attractive device for future use for several reasons. The device is made-up by a cavity with a movable membrane connected to an orifice; it may be manufactured in small dimensions. It is of simple construction that it does not depend on micro machining. With the above-mentioned attributes, it is easy to manufacture the actuators and to modify their geometric parameters. Also, they operate with zero net mass flow, that is, they synthesize a jet from the flow field an external source of fluid. Thus, no piping system is necessary for the actuator, which greatly simplifies the installation.

The membrane oscillation is able to modify the flow in the cavity of the actuator of the synthetic jet and to influence the boundary layer flow. The effects produced by the synthetic jet actuator depend on the parameters of the jet and of the orifice. There exists an effect of the external flow over the flow inside the cavity, however this will not be taken into account in the present study.

The present work is divided as follows: next section presents a description of the first works realized with synthetic jet actuators, as well as the evolution of this device of active flow control and their advantages in relation to other control techniques; in section 3, the numerical method adopted here is described; in the subsequent section the numerical results are presented where is shown the effects produced by the synthetic jet in a boundary layer; and finally, the last section presents the conclusions obtained with the numerical simulations.

2. Flow control with a synthetic jet actuator

2.1. The evolution of the synthetic jet actuators in the flow control

One of the first studies using of synthetic jet actuators in active flow control were done by Smith and Glezer (1994). This device when applied in a flow field, results in exclusive effects that are not possible with suction or blowing means in a fixed or pulsed process. Synthetic jets with low numbers Reynolds similar to the devices used in recent studies of flow control have been studied extensively, both experimentally and numerically. The synthetic jet appeared as one of the most useful devices of active flow control, with a potential application. Some of these techniques are seen in studies that include transition control in Lorkowski et al. (1997); separation delay, Sinha and Pal (1993); effective vortex control, Roos (1997); vectorial propulsion of jet motors, Smith and Glezer (1997); mixture upgrading for active control of separation, Davis and Glezer (1999) and turbulence in boundary layers, Crook et al. (1999). At this time, of all the flow control actuators being studied, most of these studies are addressed to the use of synthetic jets actuator.

The use of acoustic excitement for separation control was investigated by Huang et al. (1987) and Hsiao et al. (1990), which used a cavity addressed acoustically inside of an airfoil to excite the boundary layer through a small located rectangular slot close of the leading edge of the airfoil. Both studies used a resonant level of pressure on the slot to gage the control receiver. The work of Huang et al. (1987) was limited for the frequency of vibration of the airfoil, with a scaling for the frequency about $f \cong 110$ Hz. Hsiao et al. (1990) investigated a wide strip of performance of frequencies up to $f \cong 5000$ Hz. These works reached an increment of 40% in the lift coefficient in attack angles poststall. Bremhorst and Hollis (1990) accomplished a study with flow control being executed through the use of steady and pulsed jets.

Rizzetta et al. (1998) included the cavity flow as part of direct numerical simulations of synthetic jet flow and verified that significant differences arise when the flow of the cavity is neglected. Udaykumar et al. (1999) developed a method that allows simulation of unstable incompressible viscous flow with mobile boundary. The fundamental advantage of this method for the flow is that the whole geometry of the synthetic jet besides the diaphragm oscillating is modeled in a stationary Cartesian mesh. Carpenter et al. (1998) employed a velocity-vorticity method to compute the entire flow. They ignored viscous effects and found that after an initial estimate, the velocity in the centerline of the flow underwent softened oscillations. The interaction of synthetic jets with a traverse flow can lead to a modification in the aerodynamic shape of blunt bodies and, in that way, gives a way for control of flow separation. This idea was used by Amitay et al. (1997) in a flow over a circular cylinder. Depending on the azimutal position of the jets, a new aerodynamic profile of the cylinder was evident as the increase of pressure at the base and a distribution of asymmetrical pressure grew around of the cylinder.

Synthetic jets have recently been used for several applications of flow control, including controlling transition, delaying separation and effecting vortex control. However, there have been just some investigations of their operations. Smith and Glezer (1998) noticed that synthetic jets, generated using rectangular plane slots, exhibit a standing vortex near the exit of the slot. This was explained as being due to turbulent dissipation of the vortex cores. They also noted that self-similar in the flow is established closer to the slot than for a steady jet. This can be verified in works with acoustic streaming, where this phenomenon appears when sound waves induce unidirectional flow, and it typically has a very weak effect unless the sound waves are attenuated in some way. For synthetic jets, the reduction is provided by the slot and also through viscous dissipation. However, the synthetic jet flow is not just induced by the acoustic streaming, but also for the movement of a membrane. Kral et al. (1997) performed numerical simulations of synthetic jet flow, neglecting the cavity, to be in better agreement with the data Smith and Glezer (1997), when the flow was assumed to be completely turbulent. Cain et al. (1998) extended this work including the compressibility effects. They verified that as the jet Mach number increased, the acoustic waves induced by the jet became much stronger.

There are today efforts to study numerically the flow field within the actuator cavity, as well as of it exterior, by obtaining solutions to the unsteady compressible Navier-Stokes equations Rizzetta et al. (1998). This is accomplished for the interior flow by use of an overset deforming zonal grid system. Solutions for the external jet flow field are considered in both two and three spatial dimensions using a high order implicit compact finite difference scheme. The computational procedure is summarized, details of the calculations are presented, and the accuracy of the numerical results is assessed via grid resolution and time step size studies. Characteristics of the resultant flow fields are elucidated, and comparison is made with experimental data.

2.2. The mechanism of the synthetic jet performance

The synthetic jet actuator consists of a membrane located at the base of a small cavity with an orifice in the opposite face to that of the membrane. The membrane is forced to oscillate through electrical, magnetical or mechanical means. In the flow field created by the synthetic jet actuator, during a single cycle of operation, a succession of important events occur that may be observed. In a single oscillation cycle, the orifice expels fluid as the membrane moves upward, as shown in the figure 1. When the volume of the cavity decreases, the synthetic jet is in the expulsion cycle. During this interval of time, fluid begins to flow outside from the cavity through the orifice. This induces a vortex ring at the extremity of the orifice due to the separation of the flow. A boundary layer grows on the walls of the orifice.

This boundary layer separates at the extremity of the orifice. The layer free from recently formed shearing moves as a vortex ring or, depending on the geometry of the orifice, as a pair of vortexes. The vortex ring moves in an outward direction, under its own pulse.

After the vortex ring moves a certain distance from the surface, the volume of the cavity begins to expand, it is the begin of a suction cycle. When the membrane moves down, air from outside is sucked into the cavity. The vortex ring continues moving further away from the extension of exit of the actuator. Fluid is being extracted from the atmosphere to fill the volume of the cavity that expands. If the vortex ring is at a certain distance from the orifice, the fluid entraining into the cavity will not influence it. Once the volume of the cavity reached the maximum, the cycle is ready to begin again. This cycle is repeated: ring formation, ring translation, suction-countless times in a sequence of 100 to 2000 times a second. In this way, on top of a single period of oscillation of the membrane, although there is zero net mass flow inside or outside of the cavity, the average transfer of momentum is not null. The flow produced, where a transfer of momentum occurs; is indeed a jet that was synthesized from the ambient fluid.

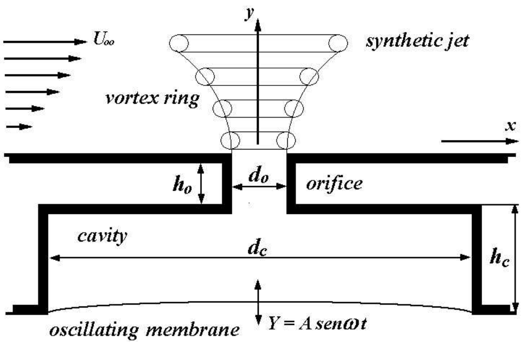

Figure 1. Operation of the synthetic jet actuator.

3. Numerical method:

The parameters varied in the present study are the amplitude, the frequency of oscillation of the disturbed flow, and the slot length, where the jet is introduced.

The following non-dimensionalization used was:

$$x=\frac{\bar{x}}{\bar{L}}\ ,\quad y=\frac{\bar{y}}{\bar{L}}\ ,\quad u=\frac{\bar{u}}{\bar{U}_\infty}\ ,\quad v=\frac{\bar{v}}{\bar{U}_\infty}\ ,\quad t=\bar{t}\frac{\bar{U}_\infty}{\bar{L}}\ ,\quad \mathrm{Re}=\frac{\bar{U}_\infty\bar{L}}{\bar{\nu}}, \tag{1}$$

where L is the reference length, U is the reference velocity and ν is the kinematic viscosity, and Re is the Reynolds numbers. The parameters adopted in the present study were: L = 0.05 m, U_∞ = 30 m/s and ν = 1.5 x 10^{-5} m^2/s, the resulting Reynolds number is Re = 1 x 10^5. The calculation domain extends from x_0 = 1.00 to x_{max} = 3.88 in the streamwise direction and y_0 = 0 to y_{max} = 0.096 in the wall normal direction.

The vorticity in the spanwise direction, denoted by ω_z, is given by:

$$\omega_z=\frac{\partial u}{\partial y}-\frac{\partial v}{\partial x} \tag{2}$$

The vorticity-velocity formulation was adopted in the numeric simulations realized here. Adopting vorticity as being the negative of the rotational of the velocity, the equation of vorticity transport can be obtained:

$$\frac{\partial\omega_z}{\partial t}=-\frac{\partial u\omega_z}{\partial x}-\frac{\partial v\omega_z}{\partial y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2\omega_z}{\partial x^2}+\frac{\partial^2\omega_z}{\partial y^2}\right) \tag{3}$$

The continuity equation for the incompressible two-dimensional flow simulated in this study is:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{4}$$

From the vorticity equation (3) and the continuity equation (4) a Poisson-type equation for the normal velocity component can be derived:

$$\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}=-\frac{\partial \omega_z}{\partial x} \tag{5}$$

The time integration was done with fourth order Runge-Kutta scheme, Ferziger and Peric (1997). The spatial derivatives were discretized using compact finite differences. A 6th order scheme is used for the interior points and a 5th order scheme is used at the boundaries. The details of the discretization scheme can be found in Souza et al (2005).

The unsteady computation starts from a steady state laminar solution. In the present study a Blasius solution was used as a base flow. To simulate the propagation of the synthetic jet in a boundary layer, we must introduce the jet in the computational field. In order to do that it is necessary to change the boundary conditions at the wall. The jet may be introduced at the wall, through a slot with blowing and suction with a certain frequency. The method adopted consists of introducing a slot at the wall ($i_1 < i < i_2$), where i_1 and i_2 are the first and the last point of the slot, respectively. The function used for the normal velocity v is:

$$\begin{aligned} &v(i,0,t)=f(x)_i\, A sin\beta\, t \qquad \text{para} \qquad i_1 \le i \le i_2 \\ &v(x,0,t)=0 \qquad \text{para} \qquad i<i_1 \quad \text{e} \quad i>i_2 \end{aligned} \tag{6}$$

The value of A is real constant that can be chosen to adjust the amplitude of the synthetic jet. The constant β is the dimensionless frequency. The function $f(x)_i$ adopted here is a function:

$$\begin{aligned} &f(x)_i = sin^3(\varepsilon) \\ &\text{where} \qquad \varepsilon=\frac{i_2-i}{i_2-i_1} \qquad , \qquad i_1 \le i \le i_2 \end{aligned} \tag{7}$$

Now we have a region at the wall where the normal velocity component is different from zero. The v velocity distribution at the wall is fixed at each time step according to equation (6). The vorticity calculation at this boundary also changes, because the second derivative of the v velocity in streamwise direction has a value in the disturbance strip region. This value can be evaluated from equation (6).

It was implemented a buffer domain, located near the outflow boundary in order to avoid reflections that could come from this boundary. The code used in the present study was validated beforehand in Direct Numerical Simulations of spatially disturbances propagation, the validation of the code is shown in Souza et al. (2005).

4. Results and discussion

The results of simulations with different frequency values, amplitude and slot length were verified through a temporal Fourier analysis. Through this analysis it is verified which is the best situation to delay the separation of the boundary layer. The total number of points in the streamwise and wall normal direction used in the simulations were 257 and 97, respectively. The distance between two consecutive points in the streamwise and wall normal directions were 0.01125 and 0.001, respectively. The time step used was 0.00393 given a CFL number of 0.35. Fourier temporal analysis of the flow interacting with a synthetic jet was done in the position x = 3.1375. The difference between the base flow (Blasius profile) and the distorted flow gives an idea of how the synthetic jet is changing the profile. The figures show below this difference for the streamwise velocity component. In these graphs the negative values corresponds to an increase in the values of the base flow and the other way round. Increasing the values of the streamwise velocity component near the wall can result in an increase in the derivative of this component in the wall normal direction. Increasing this value we believe that a separation can be postponed, since separation occurs at du/dy = 0.

4.1. Analysis of slot length

The figures below show the difference between the Blasius profile (base flow) and the profile of medium velocity u obtained through the Fourier analysis in the position x = 3.1375 in a normal direction to the wall. With this difference it can be inferred the influence of the slot dimension in the synthesized flow.

Figure 2 shows the results of the first case, where the size of the slot corresponds at the distance between point i_1 to point i_2. Three different values for i_2 (i_2=39 -> x = 0.4275, i_2=43 -> x = 0.4725 and i_2=51 -> x = 0.5625) were tested with a fixed value for i_1 (i_1=31 -> x = 0.3375). The amplitude was settled to A=2 in all cases. The frequency also remained constant, in this first case, corresponding to the value b=15. In this case, it can be observed that with the larger slot length tested, corresponding to the value i_2 =51, the best result was achieved.

In the second case, showed by figure 3, the same parameters of the first case were used, but the amplitude was increased to the value A=3 and the frequency was decreased to b=11. The figure 3 shows that for this case the best result was obtained with the smaller value of the slot, corresponding to the value i_2=39, opposite result than the obtained by the previous test case.

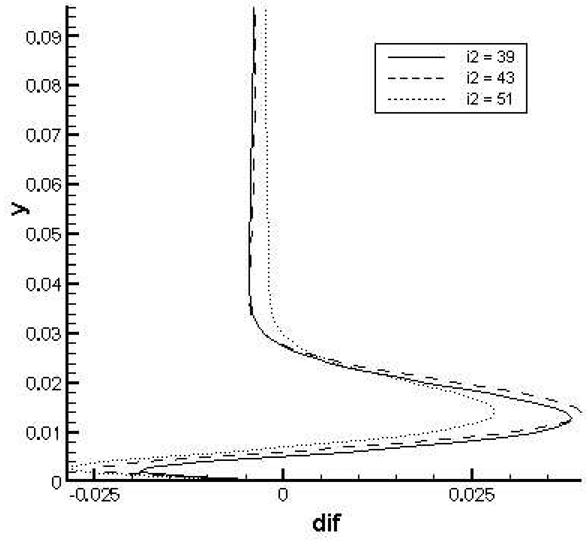

Figure 2. Temporal Fourier analysis with variation of the length slot for A=2 and b=15.

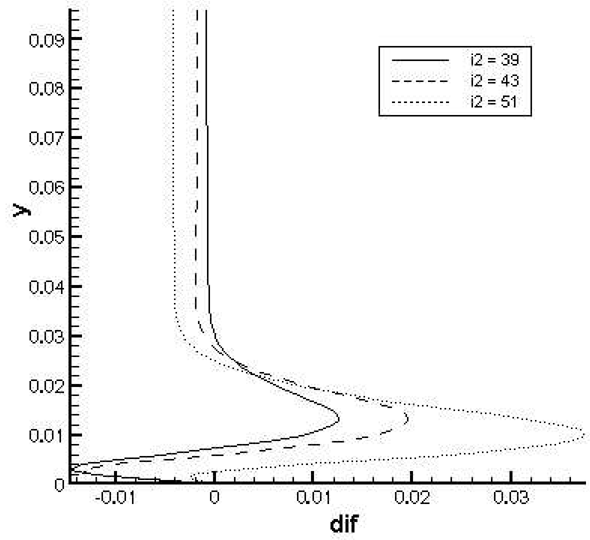

Figure 3. Temporal Fourier analysis with variation of the length slot for A=3 and b=11.

4.2. Analysis of frequency

The influence of the oscillation frequency of synthesized flow is analyzed in the two graphs below. In the simulations corresponding to the figure 4, five different values of frequency were adopted, corresponding to b (b=11, b=13, b=15, b=17, b=19).

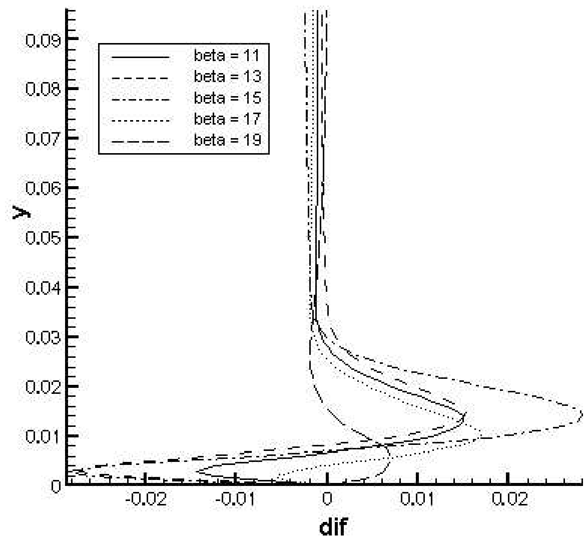

Figure 4. Temporal Fourier analysis with variation of frequency for A=2 and i_2=51.

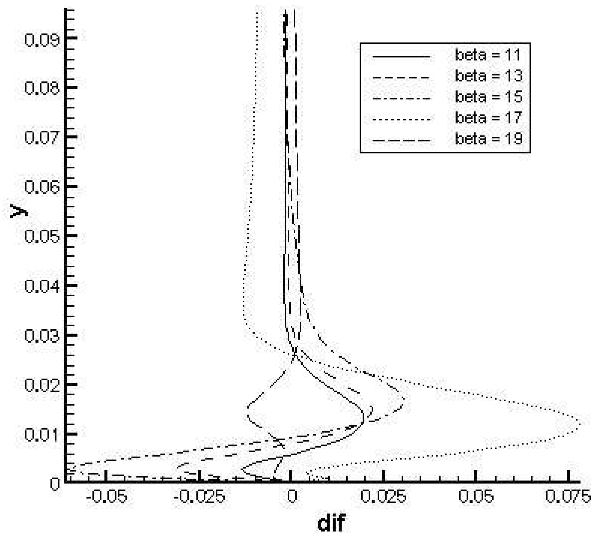

Figure 5. Temporal Fourier analysis with variation of frequency for A=3 and i_2=43.

In these simulations the size of the slot remained constant with values of i_1=31 and i_2=51. The amplitude was settled to A=2. In this case, it can be observed by the figure 4 that the value b=13, resulted in a larger increment for the velocity component u near the wall, if compared with other frequencies b.

In figure 5, the same parameters of previous simulations were adopted, but the amplitude was settled to the value A=3 and the slot length changed for i_1=31 and i_2=43. Figure 5 indicates that for this case the best result occurs for a value of frequency corresponding to b=15.

4.3. Analysis of amplitude

The influence of the amplitude of the synthesized flow was analyzed and the results are shown in the two graphs below. In these simulations four different values for the amplitude were adopted, corresponding to the value A (A=2, A=3, A=4, A=5). For both cases the slot length remained fixed with values for i_1=31 and i_2=43.

Figure 6 shows the results obtained for the frequency b=15. In this case, it can be observed that the value A=3 of the amplitude, produces a larger increment for the velocity component u, near the wall when compared with other amplitudes.

In the last case shown here, the frequency was settled to the value b=19. It can be inferred in figure 7 that for this case the largest increment for the velocity component u near the wall occurs for A=5, when compared with other results.

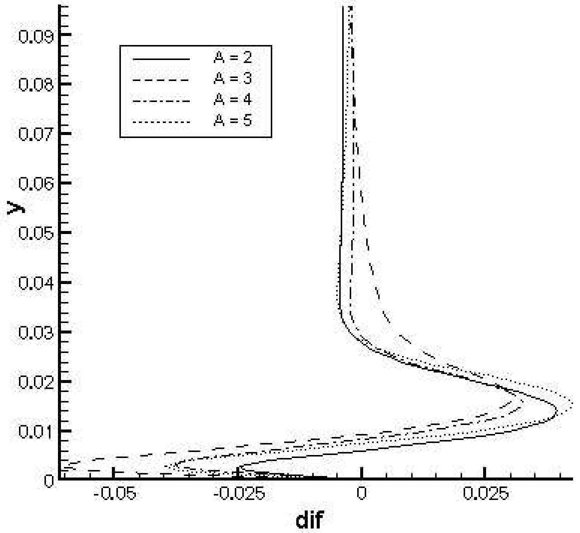

Figure 6. Temporal Fourier analysis with variation of amplitude for b=15 and i_2=43.

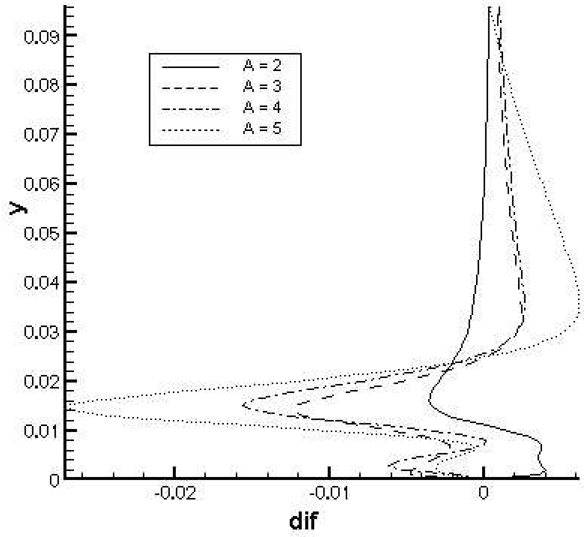

Figure 7. Temporal Fourier analysis with variation of amplitude for b=19 and i_2=43.

5. Conclusions

In the present work a numerical study of the influence of a synthetic jet in a boundary layer was performed. Different parameters were analyzed in the simulations. The results of simulations with different frequency, amplitude and slot length values were verified through a temporal Fourier analysis. Through this analysis it was verified which is the best situation to delay the separation of the boundary layer. Results of the numerical simulations showed that the introduction of the synthetic jet contributed to an increase of the velocity component u near the wall inside of the boundary layer. The flow oscillations introduced by the synthetic jet induced an acceleration of the flow near the surface of the flat plate. In some cases, for certain combinations of frequency, slot length and oscillation amplitude, larger increments of the velocity component u near the wall were observed. It was shown that is hard to achieve the best parameters (slot size, frequency and oscillation amplitude) since they are interconnected and dependent. The main conclusion in this work is that the best combination of the parameters of a synthetic jet actuator can be achieved but demands a wide number of numerical simulations for a specific case.

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