actuators

Editorial

Advances in Flow Control by Means of Synthetic Jet Actuators

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1. Introduction

The need for flow control is widely recognized in various fields of technological applications such as fluid dynamics, atomization, heat transfer, and others. The common goal to be achieved is the maximization of the performance of the engineering systems in the design phase, both for the purposes of safety and the reduction of energy consumption. A class of modern active control actuators is clustered under the common term of synthetic jets (SJ), meaning that the jet is directly synthesized within the fluid to be controlled without the use of any traditional pumping device [1,2].

Literature includes a very large number of works focused on this technology, aiming at either characterizing the device's performance, including the frequency response and the energy conversion efficiency, e.g., [3,4], or investigating their effectiveness in a particular environment, among many others [5,6]. Valuable applications refer not only in the strict sense to the flow control (influencing the separation point or manipulating the turbulence), but also to heat transfer from heated surfaces [7,8], mixing enhancement [9], under water propulsion [10]. A lot of experimental campaigns were successfully conducted on these actuators, using a great variety of experimental techniques, [11,12]. On the other hand, many computational studies have been also carried out, ranging from the early two-dimensional RANS techniques [13], to three-dimensional DNS [14–16] and LES [17] computations, in both quiescent environments and crossflow conditions.

Nowadays the basic operating principles of these devices are quite consolidated; nonetheless, the continuous development of innovative actuators requires further investigations of the working principles and the basic mechanisms of interaction of a synthetic jet with an incoming crossflow. As a matter of fact, the huge bulk of the current ongoing research is devoted to various applications for flow control, addressing specific needs and issues. To highlight the impact of the current Special Issue, the present editorial article has the aim of presenting modern lines of research, trying to understand the current developments and the last applications of these devices. To achieve this goal, a bunch of very recent contributions published in the last two years have been considered below.

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2. Results and Discussion

Analyzing the recent literature contributions, it emerges that synthetic jet devices have two main fields of application:

- flow control on aerodynamic surfaces;
- cooling of heated areas.

The first field, probably, is the most studied; indeed, the ability to produce a null average mass flow rate (during an operation cycle), with a non-zero average momentum rate, makes these devices suitable for this kind of application. Moreover, synthetic jets have received great interest in recent years as an effective cooling technique: in the impinging configuration, they can improve the heat sinks thermal performance, enabling 20–40% more heat to be dissipated with respect to fans steady flows [18].

Besides these two specific topics, different research groups on the one hand developed new technologies to generate synthetic jets, on the other one they focused on their evolution in quiescent and crossflow conditions.

2.1. Design Aspects

A SJ is an electromechanical device composed of a small closed cavity connected to the external environment through a slot or an orifice. Its working principle is based on a subsequent alternation of over- and under-pressures within the cavity which causes the formation of a train of vortices and so a turbulent jet downstream of the orifice. The pressure variations are usually related to cavity volume changes achieved by means of loudspeakers or piezoelectric elements, or they can be due also to electrical discharges between electrodes embedded in the cavity (in the case of plasma SJ actuators). The characteristics of the jet depend on the actuator geometry, the actuation frequency and eventually by the energy discharged in the cavity in each cycle.

Besides the classic configuration (one orifice for cavity), several innovative arrangements have been proposed. In particular, a coaxial synthetic jet, in which two cavities (each of one equipped with a diaphragm) are arranged coaxially with 0° orientation angle, was presented in [19]; while, double piezoelectric synthetic jet micropump was illustrated in [20]. Furthermore, plasma synthetic jets were studied with different insulating materials [21], varying the thermal conductivity, the throat length and the discharge duration.

In early activities, the investigation on SJ actuators has favored the single-orifice configuration compared to the multiple-orifice one, both because of the high velocity outputs required in some applications, and due to the difficulty of predicting the behavior of the actuator in more complex configurations [22]. Two-orifice devices were applied to study the fluid–structure interaction [23], and to identify the minimum spacing avoiding any vortex interaction, [24]. Very recently, an analytical approach, based on the fluid dynamic behavior argued by means of numerical simulations, was introduced to obtain simple relationships for the resonance frequencies of twin-orifices, [25], and a novel definition of the flow main regions, represented by the near field, where two distinct jets converge, and the far field, where a unique jet is detected, was presented in [26]. A multi-orifice actuator, coupling a piezo-driven synthetic jet with another constant-volume square cavity, was discussed in [27]. An alternative configuration to the double-orifice, consists of two adjacent cavities, sharing the same diaphragm, but with two emitting slots, [28]; these devices show higher velocities and a double characteristic frequency compared with the single configuration, with additional vectoring characteristics.

2.2. Flow Control Applications

Synthetic jet actuators have been proven to be effective flow control devices, thanks to their characteristic high velocities, low weight and moderate power consumptions. Their application includes drag reduction, wake control, mitigation of blade structural vibrations, suppression or reduction of separation zones on aerodynamic surfaces, induction of turbulence, and many others.

The ability to control a flow is strictly related to the interaction of the synthetic jet with the incoming boundary layer. In this framework, a very important parameter to control the flow is the momentum coefficient, which represents the ratio of the momentum of the jet to that of the cross-flow within the region of the jet. A universal scaling for the trajectory of synthetic jets in cross-flow was obtained in [29] for a single-slot configuration and then the analysis was extended to the twin slotted jets in [30].

The reduction of separated regions over an airfoil is currently the most studied configuration for SJ devices. Recently, the actuators authority to suppress the flow separation has been tested on a EPPLER555 wing with an aileron deflection angle of 3°–9° [31], on a NACA0015 for different angles of attack [32], on a SD7003 airfoil in post-stall conditions [33], and on a large-sweep wing considering an array of dual SJ actuators [34]. The interaction of an actuators array with a massively separated flow was explored experimentally over a cantilevered, swept, tapered model having a deflected control surface [35]; furthermore, the effect of the pulse modulation close to the natural shedding frequency of a separated flow was investigated in [36]. Another typical flow configuration studied in this framework is represented by the back-facing ramp with a specific slant angle [37]; whereas the extension to supersonic flows is carried out by means of plasma synthetic jet technology [38,39]. Finally, very recently Palumbo et al. [40] analyzed the role of a synthetic jet actuator in inducing turbulence in a boundary layer crossflow.

Other relevant studies regard the active control of a continuous jet issuing from a long pipe nozzle by means of a concentrically placed annular synthetic jet [41], a drag-reduction method in a turbulent channel [42], the control of the flow around a cylinder in crossflow with a square section geometry [43] and equipped with a leeward porous coating [44]. A feedback control for suppressing horizontal (lateral) wake bimodality of a square-back Ahmed body [45], and for alleviating the aerodynamic side-force fluctuations on a canonical high-rise building immersed in an atmospheric boundary layer [46], should be highlighted as well.

In more modern research the flow control is increasingly based on machine learning, enabling efficient nonlinear active flow control. The use of artificial neural networks, coupled with reinforcement methods, allowed the achievement of autonomous learning of complex tasks. Deep reinforcement learning algorithms have been implemented to discover efficient control schemes to reduce the drag of a cylinder in laminar flow conditions [47], to suppress vortex shedding behind circular [48,49] and elliptical [50] cylinders, and to control the flow over a NACA0012 airfoil under weak turbulent condition [51].

2.3. Heat Transfer Enhancement

Impinging synthetic jets are also widely adopted as cooling devices, being more effective in cooling a heated surface than steady jets at the same Reynolds number. Therefore, most of the works focus on the development of new configurations (often with multiple orifices) to maximize the cooling capacity of the devices.

The flow characteristics and the unsteady heat transfer of synthetic jets impinging on a heated plate were recently studied in a noncircular five orifices and multiple axisymmetric orifices configurations in [52–54], respectively; while a novel liquid cooling active heat dissipation device based on a dual synthetic jets actuator was presented in [55]. Moreover, synthetic jets were also used to manipulate the flow behavior behind the surface-mounted square rib for heat transfer enhancement [56].

Other interesting SJ impinging applications regard the investigation of the vortex impingement mechanisms onto a porous wall [57], and the influence of sphere diameter and Reynolds number on synthetic jet vortex rings impinging on a spherical wall [58].

2.4. Summary of Contributions

Table 1 reports a list of the major numerical and experimental applications in the field.

Table 1. Major literature works.

	Numerical	Experimental
Design aspects		
Innovative configurations	[19]	[20,21]
Multi-orifice actuators	[26]	[27,28]
Flow control applications		
SJ interaction with a boundary layer	[40]	[29,30]
Airfoil and wing configurations	[31,33,34]	[32,35,36]
Back-facing ramp model	[37]	
Supersonic flows	[39]	[38]
Control of a continuous jet		[41]
Drag-reduction method	[42]	
Flow behind cylinders	[43,44]	
Deep reinforcement learning	[47–51]	
Other applications	[45,46]	
Impinging applications		
Heat transfer enhancement	[55]	[52–54,56]
Porous and spherical walls	[57,58]	

3. Conclusions

The updated bibliographic collection reported in this Editorial, commenting on the relevant outcomes of the works presented in this Special Issue, has highlighted the most studied aspects and applications regarding synthetic jet actuators.

Nowadays, the continuous progress of the experimental measurements and the increase of computational powers have produced high-resolution data, allowing further investigations both on the basic aspects and on the interaction mechanisms of synthetic jets with a crossflow.

Most of the research is focusing on flow control applications, evaluating the variation in the topology of the flow field and aerodynamic forces on surfaces, and on heat transfer problems, trying to enhance the cooling effect of the devices. However, several innovative applications are currently under evaluation, proving the worth of these devices in the fluid dynamics community.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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