A Review of Fluidic Oscillator Development and Application for Flow Control

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A Review of Fluidic Oscillator Development and Application for Flow Control

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This review provides a detailed discussion of the historical development of fluidic oscillators and their application to flow control. Fluidic oscillators were initially developed in the 1960's for a variety of applications, and have seen resurgent interest for their suitability for modern flow control applications. The devices produce an oscillating jet of fluid over a wide fan angle and have no moving parts, making them an attractive actuator concept. This review aims to highlight the most important historical papers of relevance to modern fluidic oscillator development. The reviewed works will extend from the early 1960's to the most recent investigations, with a focus on the fundamental operating mechanisms of fluidic oscillators. The authors present this review as a short synopsis of fluidic oscillators for flow control, while a more comprehensive review will be submitted for archival publication in the near future.

I. Introduction

FLUIDIC oscillators (also known as sweeping jets) are the subject of recent interest within the aerodynamic community for use as flow control actuators. The devices produce an oscillating jet at high frequency, yet have no moving parts. The exact nature of the oscillations is due to various fluid instabilities within the device that govern characteristics of the emanating jet, such as frequency and spread angle. The attractive features of fluidic oscillators for flow control are their characteristics of unsteady blowing, wide range of operating frequency, and the distributed nature of momentum addition. The emerging interest in these devices within the aerospace community has spurred resurgent development of fluidic oscillators as flow control actuators, and innovative application of them to flow control problems such as separation control, jet thrust vectoring, and cavity tone suppression.

Much of this recent work, however, is divorced from the deep, foundational work done in fluidics starting over half a century ago. Moreover, there are very few reviews on the subject: Campagnuolo and Lee [9], [10] presented a review of several types of fluidic oscillators applied to missile control systems; Fletcher and Woods [26] reviewed fluidic oscillators for temperature sensing; and Raghu [58] recently presented a review of fluidic oscillators, mostly focusing on contemporary development and application. Therefore, the aim of this review is to survey much of the forgotten literature, coursing from the early development of fluidics to the most recent efforts in fluidic oscillator development. We focus our review on the historical development of fluidic oscillators, but also provide an overview of recent applications of fluidic oscillators to modern separation control problems.

II. Basic Operating Principles and Device Classification

We begin the review with a brief synopsis of the known operating principles of the fluidic oscillator. There are actually two primary categories of fluidic oscillators; thus, we also provide a classification scheme for the various

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devices. Subsequent sections will delve into greater detail regarding the governing physical principles that were illuminated over time.

A fluidic oscillator produces a pulsing or sweeping jet at its output, the motion of which is driven by the inherent instabilities of flow within the device. If no diverters are installed in the exit, the jet produced by the fluidic oscillator exhibits a sweeping motion similar to that shown in Figure 1. The frequency of this pulsing or oscillation is dependent upon the geometry of the device, and usually the flow rate through the device (e.g., see Figure 2).

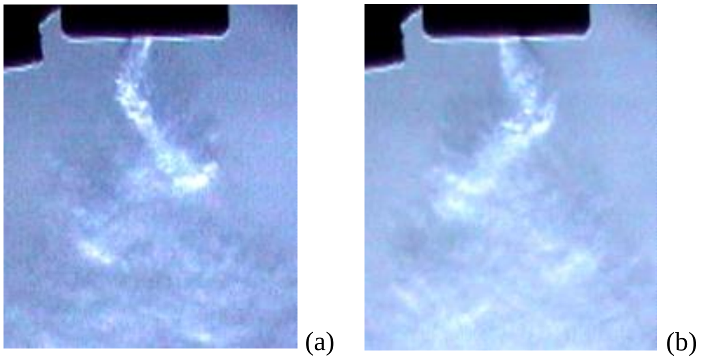

Figure 1: Typical external flowfield of a fluidic oscillator (flow from top to bottom) at two phase positions separated by 180°. In this case, the fluidic oscillator was operated with a dense gas and visualized with schlieren imaging (from Gregory *et al*. [34]).

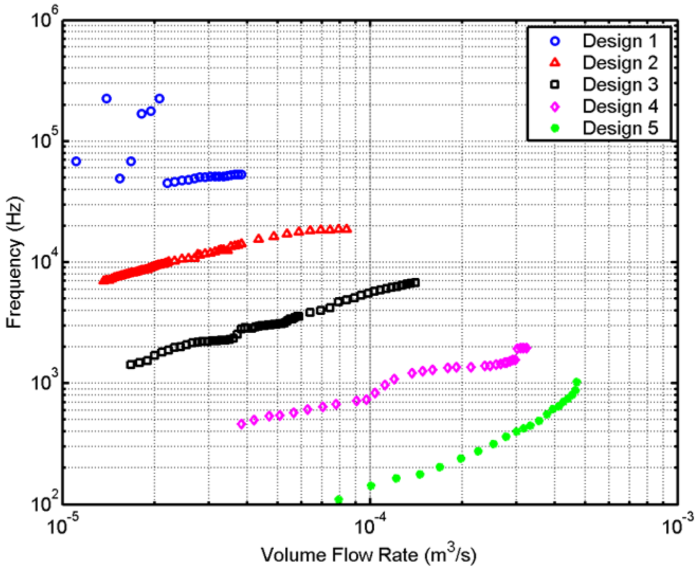

Figure 2: Frequency dependence on flow rate and oscillator scale for a typical fluidic oscillator. The scale of each device is varied by a factor of two, with design 1 being the smallest (from Tomac and Gregory [81]).

One characteristic of all fluidic oscillators is that there must be some type of feedback mechanism to drive the oscillations. The categories of fluidic oscillators that we define here are based on a differentiation of the various internal mechanisms that drive the oscillations. For the purposes of this review, we consider two primary types of oscillators: wall attachment and jet interaction. (There are other types of so-called fluidic oscillators that are discussed elsewhere – e.g., Campagnuolo and Lee [9], [10] also discuss the edgetone oscillator and the vortex oscillator, which are not discussed here.) The two primary types of fluidic oscillators are wall-attachment devices and jet-interaction oscillators.

1. Wall-Attachment Fluidic Oscillators

Wall-attachment fluidic oscillators operate based on the mechanism of a bi-stable attachment of a jet to adjacent attachment walls. Two canonical examples of the wall-attachment oscillator are shown in Figure 3. The power jet (defined as the primary flow through the main nozzle at the upstream end of the device) will attach to one of the two side walls inside the device, due to the Coanda effect (to be discussed in section III.A.2). Due to the presence of the jet on that wall, there will be a change in pressure and mass flow through the control nozzles depicted on either side of the power jet (the exact source of this disturbance depends on the sub-type of wall-attachment oscillator). This transverse disturbance ultimately causes the primary jet to detach from the original side wall and attach to the opposite side wall. This process completes a half-cycle of the oscillation; due to the symmetry of the device, the jet will oscillate between the two side walls in a periodic manner.

As illustrated in Figure 3, there are two sub-categories of wall-attachment fluidic oscillator: the ‘sonic oscillator’, first presented by Spyropoulos [72], and the ‘relaxation oscillator’, with an example presented here from Gaylord and Carter [28]. The sonic oscillator typically operates by the propagation of compression and expansion waves at acoustic speed through the feedback tube that connects the two control nozzles (Figure 3(a)). When the power jet attaches to the right wall, entrainment of the jet serves to lower the local pressure at the right control nozzle due to the limited volume available for entrainment. This reduction in pressure produces an expansion wave that propagates through the feedback tube. Simultaneously, as soon as the jet attaches the right wall, the pressure at the left outlet (ambient) acts on the left control nozzle. This sudden increase in pressure produces a compression wave in the feedback tube, starting from the left control nozzle. When the disturbances propagate through the tube and reach the opposite side control ports, the jet switches between attachment walls. Thus, the interconnected control ports set up a self-sustaining oscillation of the power jet between the two attachment walls.

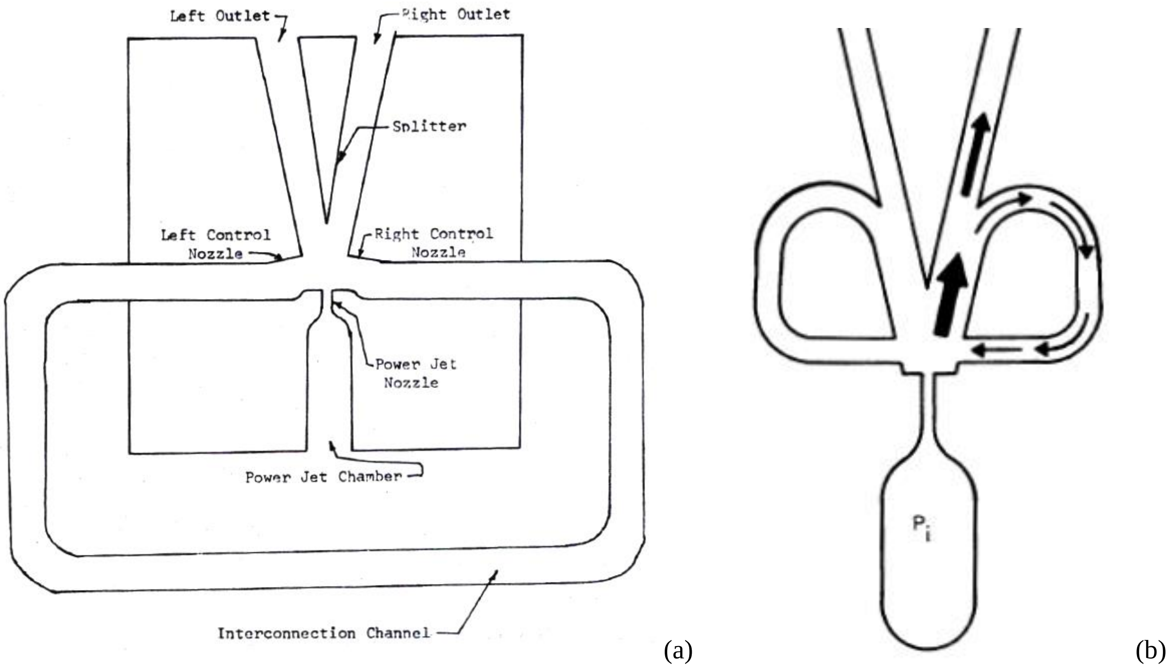

Figure 3: Illustration of the basic configuration of wall-attachment fluidic oscillators: (a) sonic oscillator (from Spyropoulos [72]) and (b) relaxation oscillator (from Gaylord and Carter [28]). The primary flow direction is from bottom to top in both cases.

The oscillation mechanism of the ‘relaxation’ oscillator (Figure 3(b)) is similar, but the source of disturbance is different. In this case, when the power jet attaches to the right wall, a portion of that jet is redirected down the right feedback tube to the right control nozzle. At this location, the mass flow is injected in a transverse direction and enlarges the separation bubble that exists between the power nozzle and the attachment wall. The mass flux into the separation bubble serves to enlarge the bubble and extend the separation point downstream. Simultaneously, entrainment on the left side of the jet lowers the pressure on the left side relative to the right. At a certain point, the jet completely detaches from the right wall and there is a sufficient pressure gradient to quickly draw the jet over to the left attachment wall. Again, due to the symmetry of the device, the process is repeated in succession to create self-sustained oscillations.

2. Jet-Interaction Fluidic Oscillators

The other primary category of fluidic oscillator is the jet-interaction type. These devices take on a much wider range of configurations, but the basic principle is the unsteady interaction of a jet or jets within a cavity that lead to an unsteady external jet. The jet-interaction category could also be defined as devices that lack any attachment walls, such that bi-stable attachment is *not* a relevant mechanism. While there are no attachment walls, there are still internal feedback paths that drive the instability. The physical configurations can be deceptively simple, yet the internal interactions quite complex. For example, Tomac and Gregory [81]-[83] studied an oscillator with two jets injected into a dome-shaped mixing chamber. There are complex interactions of jet bifurcation, vorticity generation, and vortex growth and interaction between the jets and side walls that take place.

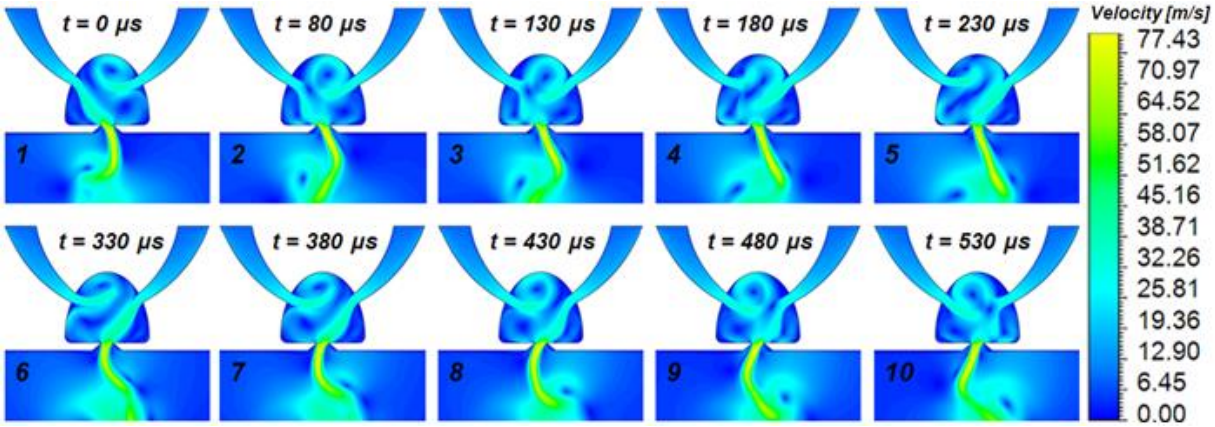

Figure 4: Two-dimensional CFD results of a jet-interaction fluidic oscillator internal and external flow (from Tomac and Gregory [81]).

3. Flow Control

Fluidic oscillators can be operated with a wide range of supply fluids, including water. In fact, the most common everyday use of fluidic oscillators is as windshield washer fluid nozzles. The oscillator produces a wider (time-averaged) distribution of mass relative to a steady jet. Use of fluidic oscillators instead of steady jets ultimately reduces wear on windshield wiper blades due to improved surface area wetting. The same characteristics with air as the working fluid make fluidic oscillators an attractive flow control actuator: they offer high frequency, no moving parts, and distributed momentum addition. Their use as flow control actuators has been discussed in reviews by Raman and Cain [60], Cattafesta and Sheplak [11], and Raghu [58].

III. Historical Development

Fluidic devices originated in the late 1950's and early 1960's as flow-based logic circuits that were implemented as a robust alternative to the then-embryonic transistor. The concept of wall-attachment of a jet due to the Coanda effect led to fluidic amplifiers, where a bi-stable primary jet would attach to one of two adjacent side walls. The jet could be switched between the two stable attachment conditions by application of a low-momentum control input. Since the high-momentum primary jet was switched by a low-momentum control jet, these devices were used as robust switching logic devices. Based on these concepts, the fluidic oscillator was first developed in the mid-1960's by connecting the control ports to form a self-oscillating device. One of the key advantages of fluidics technology was their robustness and fault-tolerance in a wide range of operating conditions. Good overviews of the field of fluidics are provided by Kirshner [44], [45].

A suitable review on fluidic oscillators must include at least a passing reference to the etymology of the device's name. The term 'fluidic' is commonly used in several ways that are distinct from the meaning of the term when applied to the field of fluidics. 'Fluidic' is an extremely popular technical term in the context of microfluidics, which may be defined as "the behavior, precise control and manipulation of fluids that are geometrically constrained to a small, typically sub-millimeter, scale" (Wikipedia). Within the aerospace community, 'fluidic' is often used as a generic adjective with a rough definition of 'fluid-like' or 'involving fluid.' This imprecise term, often used in phrases such as "fluidic injection" or "fluidic actuation", has been used to describe any form of flow control from steady blowing to pulsed blowing with electromechanical valves to synthetic jets, and has been used to differentiate between active and passive actuation. These two senses of the word 'fluidic' are not the focus of this review.

Here, the word 'fluidic' has a specific meaning based on the early technical origins of fluidic oscillators. The word was defined as a concatenation of 'fluid' and 'logic', being an apt technical descriptor of the early work with fluid logic devices and circuits, where the fluid dynamics emulated (and even physically replaced) electronic circuits. It is this 'fluid-logic' sense of the word that is the focus of this paper. One early synonym for 'fluidic' was 'flueric,' the origin of which is unclear, but has apparently been used as a synonym. Thus, a small portion of the literature cited here refers to 'flueric oscillators' (e.g., Schmidlin and Rakowsky [65]). An emergent synonym for the fluidic oscillator is 'sweeping jet,' which is an appropriate (but not all-encompassing) description of the external flow of fluidic oscillators. However, this term neglects reference to the historical basis of the fluidic oscillator, is ambiguous relative to the internal fluid mechanics of the devices, and does not include devices that provide a pulsed (instead of sweeping) output. Our survey of the literature indicates that the predominant term in historical and contemporary usage is 'fluidic oscillator.' Thus, we suggest that usage of this term be emphasized in publications that use the devices as described in Section II. Searches of the literature for publications beyond what is presented here should include the search terms 'fluidic oscillator,' 'fluid oscillator,' 'flueric oscillator,' and 'sweeping jet.' These terms should encompass most of the published literature on this topic. Unfortunately, however, the term 'fluidic' will also result in many search results that are not germane to the field of fluidic oscillators.

A. Fundamental Fluid Dynamics

This section provides a synopsis of the fundamental fluid dynamics topics that are relevant to fluidic oscillators. These basic research findings must serve as the foundation for subsequent modeling and development work. The key areas are jet flows and wall attachment of jets (i.e., the Coanda effect).

1. *Jet Flows*

The basic principles of jet flows are fundamental to the operation of fluidic oscillators. The jet within a fluidic oscillator may be considered two-dimensional, with an aspect ratio sufficiently high to ignore viscous effects of the upper and lower bounding walls (however, this is not always the case – see Dohta *et al.* [24]). Both laminar and turbulent jets must be considered, depending on the scale of the device. The velocity distributions, given by the similarity solutions of Prandtl and Schlichting, prove useful for understanding the internal jets. Olson provided a discussion of analytical techniques for jet flows in fluidic devices [55]. Kirshner provided a good foundational discussion of jet flows, set within the context of fluidics [46]. Kirshner [44], Kirshner & Katz [47], and Foster & Parker [27] also have chapters on jet flows. Gutmark & Wygnanski [37] provide data sets and analysis on turbulent jet flows, including statistics on the turbulent jet profile. Amitay & Cohen [1] studied the stability of plane wall jets subjected to blowing or suction, which has relevance to the stability characteristics of the primary jet with feedback flow providing suction and blowing in the transverse direction through the control ports.

2. *Coanda Effect*

Attachment of an open jet to an adjacent wall is the primary physical mechanism of the Coanda effect. This process occurs because the turbulent jet entrains surrounding fluid due to viscosity. With an adjacent bounding wall, the flow of entrained fluid is restricted, which lowers the static pressure between the wall and the jet. This lower pressure draws the jet towards the adjacent wall. As the jet moves closer to the wall, entrainment is further restricted, the pressure drops further, and jet deflection is increased until the jet is attached to the wall. In the attached condition, there is a cross-stream pressure gradient from ambient to the lower pressure at the attachment wall. This pressure gradient is balanced by the centrifugal force acting on the curved jet. The jet will remain attached to the adjacent wall as long as there is not an adverse pressure gradient along the wall sufficiently strong to induce separation. The necessary detachment pressure gradient will be determined by the angle and curvature of the attachment wall.

While Coanda did not offer any scientific writing on the topic of wall attachment, there are numerous technical papers on the subject. Warren provided some early, cursory discussion on the Coanda effect [86]. Kadosch offered some early reviews and technical discussions on the Coanda effect within the context of fluidic devices [41], [42]. In another review on the Coanda effect, Chang provided a good assessment of the contemporary investigations [14]. A helpful distinction was drawn between separation and detachment, in the context of wall attachment devices: the term 'separation' retained its traditional definition as the point along the wall where the velocity profile first exhibits reversed flow, while 'detachment' refers to the condition when the jet direction departs from the orientation of the wall (the jet leaving the wall). Englar further discusses the Coanda effect, particularly in the context of circulation control [25]. Kijkowski reported an analytical study of the boundary layer equations applied to a Coanda wall jet, determining that the curvature on the wall (for not too small radius of curvature) does not have an impact on the shape of the self-similar boundary layer profiles of a wall jet [43].

There have been quite a number of fundamental studies of wall jets and jet attachment to an adjacent wall. Stratford's early work studied separation of flows subjected to adverse pressure gradients [73], [74]. Glauert provided an early, seminal paper on wall jets [29]. Bourque and Newman performed a joint analytical and numerical study on the re-attachment of a jet to an adjacent inclined wall [7]. Sawyer also studied two-dimensional jet flows adjacent to a wall, including the effects of jet curvature which are critical for fluidic devices [62], [63]. Horovitz provided analytical models of turbulent free jets in the proximity of a wall, and began to include features such as control flows for fluidics applications [39], [40]. These are the critical, foundational papers that are often cited in the fluidics literature and form the basis for many subsequent models.

B. Wall Attachment Fluidic Amplifiers and Fluidic Oscillators

1. Early Development

The first known report of a fluidic oscillator is Warren's patent application from 1962 [87]. Surprisingly, Warren's work consisted of many of the basic features of fluidic oscillators that are discussed here: both wall attachment and jet-interaction geometries, and variable volume on the feedback lines to control oscillation characteristics.

The first known published scholarly work on the fluidic oscillator is that of Spyropoulos [72], where the device was referred to as a 'sonic oscillator.' This terminology was employed due to inferences regarding the feedback mechanisms that drove the oscillations. Spyropoulos proposed that the oscillation frequency in a bi-stable fluidic oscillator was determined by the switching time (t_s) and the wave propagation speed in the feedback tube (t_c):

$$f_{osc} = \left(2t_s + 2t_c\right)^{-1}. \tag{1}$$

Based on observations of compression and expansion waves travelling through the feedback tube, the wave propagation speed was found to be close to the speed of sound. For a wide range of feedback tube lengths and power nozzle supply pressures, the oscillation frequency exhibited a linear dependency on feedback tube length – an indication that the switching time (t_s) was negligible relative to the acoustic wave speed for that oscillator. Fairly good agreement with theory was found across a wide range of feedback tube lengths (two orders of magnitude). Tubes of varying diameter were also evaluated, with smaller diameter tubes having lower oscillation frequencies. Spyropoulos attributed this to a change in the switching time, although the smaller-diameter tubes could have had a lower wave propagation speed due to viscous effects. Spyropoulos also showed that the oscillation frequency generally increased with flow rate through the power nozzle, although Eq. (1) does not account for this effect. This behavior was also attributed to longer switching time at the lower flow rates, but other studies have suggested that the propagation speed through the feedback tube at lower primary flow rates is less than the acoustic velocity [76] and that multiple wave reflections within the feedback tube may be necessary to build up sufficient pressure for jet switching [38].

2. Switching Mechanisms

The switching time of wall-attachment fluid amplifiers was a topic of intense interest in the early development of fluid amplifiers. This has direct relevance to the operation mechanisms of fluidic oscillators, since the jet is switching attachment walls twice per cycle. If the oscillation frequency is high enough, then t_s is no longer negligible relative to t_c in Eq. (1). The switching process can be decomposed into three segments: dwell at one wall, detachment, and reattachment [88]. The switching process involves the addition of control flow to enlarge the separation bubble until the jet separates and fully detaches from the wall.

Lush [49] performed an extensive study in the jet switching process through analysis and experimentation. The key characteristics of switching were defined by the temporal evolution of the separation bubble between the jet and the wall. A control volume encompassed by the walls and the jet reattachment line defined the recirculation bubble, with a certain amount of recirculating flow required to satisfy jet entrainment in the stable condition. If control flow is added, the recirculation bubble enlarges, extending the wall attachment point further downstream. At a certain level of control flow addition, the bubble growth becomes unstable (growing unbounded), the jet completely detaches from the wall, and switches to the opposite wall. Goto and Drzewiecki [31] built upon Lush's model by considering blockage of output ports, and the impact of a splitter plate. Their comparisons with experimental data (e.g., see Figure 5) improved upon Lush's predictions, and offered good agreement. It is clear that there is a certain control port threshold pressure that is required for switching. The higher the applied pressure, the faster the jet will switch to the opposite attachment wall.

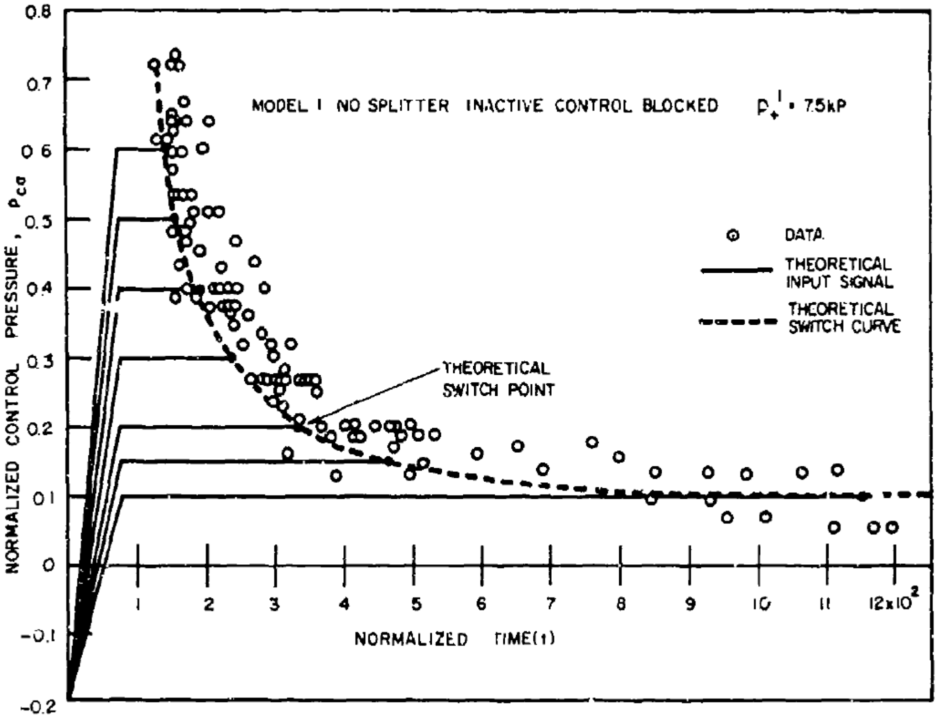

Figure 5: Comparison of theoretical switching model with experimental data (from Goto and Drzewiecki [31]).

3. Supersonic Fluidic Oscillators

There is substantial interest in the development and implementation of fluidic oscillators with supersonic flow at the exit of the device (e.g., for jet thrust vectoring). Even though a recent review has implied that "there are no direct measurements of supersonic sweeping jets or pulsed jets exiting from fluidic oscillators," [58] there are a number of investigations with supersonic fluidic amplifiers and oscillators that serve as a basis for further work in this area. One of the challenges associated with a supersonic oscillator is that the expansion of the flow inside the device will tend to cause the jet to simultaneously attach to both adjacent attachment walls with no resulting oscillations. Thus, pressure ratios must be carefully controlled in order to maintain a suitably wide operating range. Furthermore, external load on the output of a supersonic fluidic device can produce complex interactions within the device as the pressure ratio is adjusted, internal flow characteristics change, and disturbances propagate upstream in the subsonic boundary layers (which are critical to the switching process).

In early work on supersonic flow in bistable fluid amplifiers, Booth [6] briefly discussed operation of the bistable amplifier at pressure ratios high enough for supersonic flow, and studied the stability of the internal jet to varying external loads. Thompson [80] provided analytical relations for determining the location of boundary layer separation for a supersonic flow over a two-dimensional divergent wall. Thompson [79], [80] also suggested the implementation of a "boundary layer discontinuity" in order to break the feedback path between the external conditions and the jet separation characteristics, which occurs through the subsonic boundary layer. Bavagnoli [3] found that the switching time increased with supply pressure (on the order of a few ms), recorded the control pressure necessary for switching under various conditions, and determine the pressure recovery factor (ratio of output pressure to input plenum pressure) of the device. Campagnuolo and Holmes [8] developed a three-stage amplifier driven by a relaxation fluidic oscillator that produced proportional thrust control for rocket guidance. Based on the pressure ratios involved, the exit velocity of the final stage of the amplifier was supersonic, oscillating at rates exceeding 100 Hz. This system was able to provide over 80 lbs of thrust for control.

McGeachy and Chow [50]-[53] developed a supersonic fluidic oscillator that injected control flow tangential to the primary jet (versus the usual configuration of cross-stream control flow injection), where control flow was entrained by the primary jet. They found that the oscillation frequency of a supersonic fluidic oscillator depended strongly on the volume of the interaction chamber, and also on the supply fluid stagnation pressure and the feedback port opening area. The relative pressures at various locations within the mixing chamber and feedback channels were found to be critical descriptors of the oscillation time scale and mechanisms. They also applied quasi-steady analysis to the supersonic oscillator to estimate the mass flow rates of the feedback tubes and the primary jet under various operating states.

Raman *et al*. [59] also published work related to the extension of a 'flip-flop' jet nozzle to supersonic flows. Raman *et al*.'s oscillator was based on that of Viets [84], and was specifically developed for shear layer excitation in flow control applications. Their device operated as a supersonic flapping jet at frequencies over 300 Hz. Oscillations ceased when the pressure ratio was high enough that the internal jet expanded sufficiently to attach to both side walls.

Gokoglu *et al*. [30] performed a computational investigation of the internal flow of a fluidic oscillator operating at supersonic conditions. Their 2D simulations were able to match the experimentally-measured oscillation frequencies across a wide range of pressure ratios for both air and helium. They were able to verify the existence of supersonic flow at the exit, with the computations revealing the complex inner interactions of vortical structures with the feedback channels and exit nozzle that lead to the oscillations. Most recently, Seele *et al*. [69] reported schlieren images that clearly showed supersonic flow at the exit of a fluidic oscillator.

4. *Recent Fluidic Oscillator Characterization and Development*

There have been a number of recent investigations into the development and characterization of fluidic oscillators. A small selection of these studies are only briefly mentioned here, since this review focuses on the historical development of fluidic oscillators. Gregory *et al*. [34] characterized the external flow of a micro fluidic oscillator, which involved very low flow rates (1 liter per minute), a small exit orifice (325 μm), and very high frequency (~20 kHz). Wasserman *et al*. [88] used an innovative three-dimensional velocimetry technique to study the internal switching process of a wall-attachment (sonic) oscillator. Bobusch *et al*. [5] also did a PIV study with water as the working fluid, and revealed that several regions of trapped vorticity were key drivers of the oscillation process. Arwatz *et al*. [2] developed an actuator that combined the advantages of suction and blowing by merging an ejector with a fluidic oscillator.

In an effort to decouple the oscillation frequency from the flow rate, several studies have used hybrid devices with moving parts. Gregory *et al*. [35] used a piezoelectric bender to drive the switching process, while Culley [18] used a range of pressure input devices such as solenoid valves. Koklu and Melton [48] also used solenoid valves to drive the oscillation frequency for phase-locked PIV studies. Gregory *et al*. [33] also used plasma actuators in the control ports to force switching independent of flow rate. Tesar *et al*. [77] recently developed a fluidic oscillator that uses a Helmholtz resonator on one control port, with only the length of the resonator driving the oscillation frequency.

C. Jet Interaction Fluidic Oscillators

Fluidic oscillators can be designed without feedback channels based on the interaction of one jet with the walls of a confined geometry or two jets with each other and with the walls of a confined geometry. In these oscillators, vortices created between the jet and the boundaries of the confined geometry play a key role in forming the feedback loop without physical boundaries. Jet interaction and resultant vortices as the feedback loops govern the oscillation characteristics of this type of fluidic oscillators.

It is a known phenomenon since 1970s that the two opposed colliding jets lead to the self-sustained oscillations if certain parameters such as the jet velocities and the distance between two jets are properly selected. One of the earliest examples of a jet interaction fluidic oscillator is that of Schmidlin and Rakowsky [65]. They created oscillations by feeding a shallow cylindrical cavity with a jet from the side of the device, oriented towards the center of the cylinder. Flow was allowed to escape the cavity through orifices at the top and bottom of the cylinder. Through a coupled analytical and experimental investigation, they found that the jet excited the natural resonant modes of the cylindrical cavity, with accurate predictions of the frequency and phasing relationship of internal pressures in the cavity. While it is not clearly documented in their paper, it is presumed that the output of the upper and lower orifices was pulsatile. Another early investigation into jet interaction behavior was provided by Nomoto *et al.* [54] in which experimental observations and analytical approaches were used. They reported the existence of an impingement surface which is very sensitive to disturbances, and even internal fluctuations of the jet itself in the absence of external disturbances can cause instabilities of the impingement surface which can lead to self-excited oscillations. Denschikov *et al.* [19], [20] experimentally investigated the collision of two identically submerged and opposed water jets by coloring the jets with ink in a water tank. The ink-colored water jets were ejected from two nozzles and impinge at the center of the water tank. They reported that in the case of a single jet, the jet is always stable (i.e., not oscillating); however, when a second jet is present and impinges against the other jet, at first a stagnant region forms and afterwards both jets start deflecting each other to opposite directions in an oscillatory manner. Furthermore, the ends of these jets are twisted and create vortices at these regions.

The self-sustained oscillations created by the two colliding jets lead to the design of fluidic oscillators that form a feedback mechanism without any physical boundaries. This type of fluidic oscillator was patented by Raghu [57] and is shown in Figure 6. The main difference between this type and the traditional wall attachment-type fluidic oscillator is the lack of feedback channels, which are instead replaced by interactions between two jets and the vortical flow patterns created by these jets in an interaction chamber.

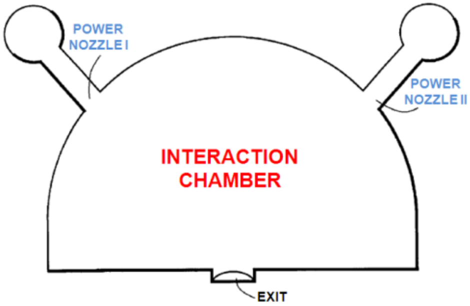

Figure 6. Feedback-free fluidic oscillator design of Raghu.

The principles of operation of feedback-free fluidic oscillators are known; however, the details of the highly unsteady internal flow physics of the device are not [11]. Gregory *et al.* [32] used pressure sensitive paint and dyed water to visualize the internal flow field of the feedback-free fluidic oscillator. They reported that the pairs of counter-rotating vortices created by the colliding jets drive the oscillations of the shear layer and these are responsible for the oscillatory flow field. Bidadi *et al.* [4] used numerical approaches and experimental visualizations to extract the operation characteristics of the feedback-free fluidic oscillator by using water as the supply fluid. Their CFD results indicated the importance of the vortices created by the interacting jets. However, Tomac and Gregory [81] used a refractive index-matched Particle Image Velocimetry (PIV) technique to extract the internal flow field of the feedback-free fluidic oscillator and provide more detailed experimental results to explain the oscillation mechanism of the device. They reported three separate flow regions with different mechanisms of oscillation depending on the flow rate and Reynolds number (*Re*), where *Re* was defined based on exit jet velocity and exit nozzle width. These regions were reported to be: low flow rate, transition, and high flow rate regions. Tomac and Gregory [83] further investigated the details of the internal flow field of the feedback-free fluidic oscillator by using index matched PIV technique in the low flow rate region. Figure 7 shows the internal flow field of the oscillator at low flow rate region from this study. In this figure, the velocity magnitude and vorticity contours inside the oscillator are shown at phase angles of 0°, 90°, and 180°. At phase angle of 0°, three vortices (a small dome shown with white arrow and two side vortices) can be clearly observed. As seen in the streamlines a big portion of lower jet coalesces with the upper jet making it more energetic than itself. At this point the core of the upper jet is connected to the exiting jet while the lower jet's right shear layer is twisted downwards feeding the lower side vortex. For phase angle of 90°, the dome vortex has reached the upper jet and started bifurcating it. The white arrow shows the saddle point that indicates the bifurcation process is taking place. And finally for the phase angle of 180°, a small dome vortex is being created by the upper jet this time while some of its portion still coalesces with the lower jet and helps the lower jet to keep its core connection with the exiting jet. The similar operation mechanism was reported to be responsible for the other half of the oscillation. Note that vorticity contours indicate the sign and strength of the vortices created in the oscillator. Furthermore, the increase of vorticity of negative sign observed over the walls (as shown with the white arrow in the vorticity contour of phase angle of 0°) was due to the interactions of the vortices with the oscillator walls. It was concluded that the oscillation created with the feedback-free fluidic oscillator is complex combination of vortex growth, vorticity generation, viscous effects, jet interactions and bifurcations, and interaction with the jets and side walls.

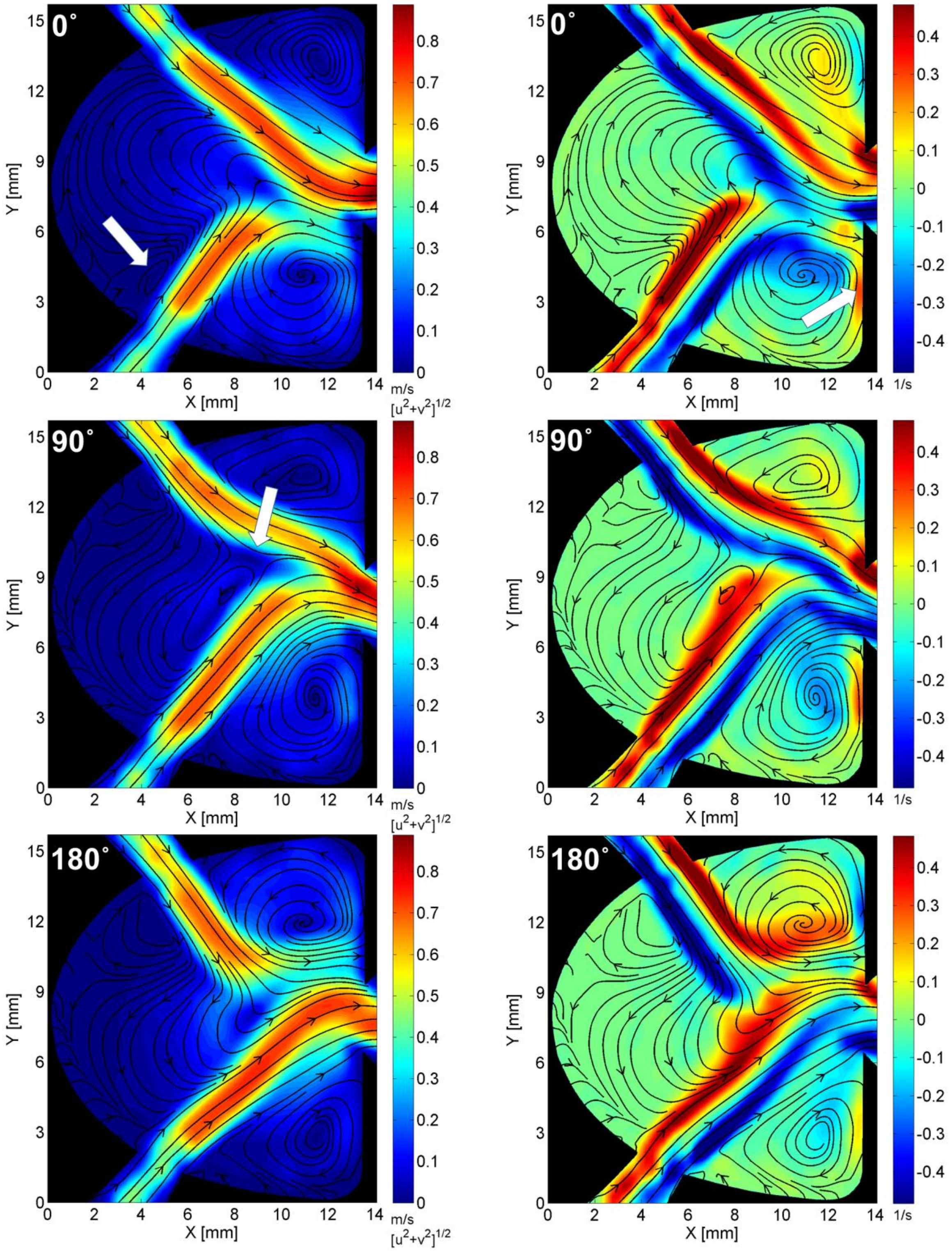

Figure 7. Velocity magnitude (left column) and vorticity (right column) contours of the internal flow field of the feedback-free oscillator in the low flow rate region (from Tomac and Gregory [82]).

IV. Separation Control Applications

Fluidic oscillators are useful devices to prevent, delay or promote the separation depending on the problem and can increase the aerodynamic performance of various designs. Oscillators have been used as sweeping jets, excitation actuators and vorticity generators.

Woszidlo *et al*. [89]-[91] used fluidic oscillators as sweeping jet actuators in their parametric study to control the flow over a generic multiple flap airfoil for various flap sizes, flap deflection angles up to 45° and various flow conditions. For all flap sizes, an actuator spacing range was recommended based on the ratio of the oscillating jet velocity to the freestream velocity for the most effective and efficient separation control. The best control performance, in terms of actuation location, was obtained close to the leading edge of the flap; however, actuation from the flap shoulder exhibited inconsistent flow control. Use of larger flap sizes yielded higher lift values when the flow was kept attached with the help of sweeping jets but required momentum input had to be increased accordingly. Nevertheless, the drag was almost independent of flap deflection angle if the flow was maintained fully attached over the flap; it was recommended that the momentum input and/or the flap deflection angle shouldn't be increased if the required lift is obtained. It was also reported that the effect of various other parameters such as jet size, oscillator frequency, actuator supply fluid properties, wing sweep angle, curvature, pressure gradient effects, boundary layer thickness, freestream unsteadiness should also be investigated.

DeSalvo *et al*. [21]-[23] used fluidic oscillators as sweeping jets to obtain attached flow over a flap at high flap deflection angles. Three arrays of fluidic oscillators operated at 6 kHz corresponding to reduced frequency on the order of 100-150 were used to manipulate the vorticity concentrations. Activating all three arrays of fluidic oscillators resulted in $\Delta C_L = 1.29$, while single array of oscillators produced $\Delta C_L = 1.24$. With the actuators activated flow turned toward the flap surface and attached to the surface. Furthermore, expanded and bifurcating nozzles were also used as flow control actuators. Results showed that expanding jet configuration performed the best with $\Delta C_L = 1.42$ at deflection angle of 40° and angle of attack (α) of 4°. Their finding suggests that spanwise oscillation does not necessarily contribute to the lift and that the momentum distribution of the actuating jet is the main cause of the gain achieved with the actuators creating expanding jets (i.e., fluidic oscillators and expanding nozzles).

Phillips and Wygnanski [56] investigated use of a fluidic oscillator sweeping jet array as an active flow control actuator on a NACA 0021 model with a 30% chord length flap. The actuation, activated in static cases, caused lift to increase as high as two times the baseline case for small angle of attack ($\alpha \approx 0°$ for $\delta = 20°$) and flow remained attached on the flap surface for a wider range of incidence angles. For dynamic baseline case, where the measurements were done without actuation during the deflection motion of the flap, dynamic stall vortex (DSV) was found to form on the flap, increasing both lift and drag as long as it was on the flap surface. However, dynamic cases with actuation seemed to avert the creation of DSV and separation, thus increasing lift, reducing drag substantially for certain momentum coefficients. Furthermore, a large difference in pitching moment suggested that the actuation method might be used to augment the effectiveness of the control surface.

Tewes *et al*. [78] used fluidic oscillators as sweeping jet actuators to control the separation on a super-critical airfoil based on lambda-shaped wing model. Actuators were located on the outer flap of the λ-shaped wing with two different alignments. Free-stream direction aligned fluidic actuators provided in 32% lift increase and actuators aligned parallel to the leading-edge provided 38.5% lift increase. Active flow control with fluidic oscillators improved the wing performance significantly while the orientation of the actuators was observed to be a critical factor for the efficiency of the flow control method.

Seele *et al*. [67] used a spanwise line of evenly distributed discrete bi-stable fluidic oscillators to delay separation on a V-22 airfoil model with a flap, semi-span V-22 wing/nacelle combination and 1/10-scale full-span powered V-22 model. Fluidic oscillators were used as sweeping jets and the results indicated substantial drag reduction and lift enhancement for all three test models. Up to 60% increase in lift-to-drag ratio L/D was reported for V-22 wing/nacelle combination in which the actuators were acting on the wing only and 29% download force reduction for the powered tilt-rotor model. It was also discussed in the study that the sweeping jets behave as vortex generators (VGs) that enhance mixing rather than the jets that energize the boundary layer.

Seele *et al*. used fluidic oscillators as sweeping jets installed on a rudder surface [68] and a trailing edge of a vertical stabilizer close to rudder hinge [69]. Both studies targeted to improve the control authority of the rudder. These studies showed that the evenly distributed actuation by using fluidic oscillators is much more effective than actuation concentrated on particular regions as long as the oscillator jet velocities are at least three times larger than freestream velocity and remain subsonic. Actuation from the rudder surface rather than the trailing edge of vertical stabilizer was found to be more efficient and can provide approximately 50% improvement in the control authority. Depending on the *Re* number and momentum input Seele *et al*.[69] reported up to 50-70 % increase in side force which can allow smaller and lighter rudders.

Cerretelli *et al*. [13] used embedded fluidic oscillators as unsteady boundary layer injectors to control the flow over a DU96 airfoil representing typical wind turbine airfoil at full scale Re numbers from 2×10^6 to 4.8×10^6. Depending on the control parameters such as Re, actuation levels, state of airfoil surface (i.e., clean or rough surface), they reported lift increase up to 60%. They also observed decrease in the boundary layer thickness of the suction surface and the unsteadiness of the mean flow velocity. Furthermore, drag reduction was reported for all actuation levels in the stall area.

Choephel *et al*. [15] investigated the effect of fluidic oscillator control on aerodynamic performance of the S903 airfoil. The oscillators used in this study brought the higher momentum fluid into the boundary layer by increasing the entrainment and delayed the boundary layer separation for *Re* numbers ranging from 4×10^5 to 1×10^6.. Actuation caused an increase of 11.9% in maximum lift coefficient compared to baseline case at a *Re* number of 7×10^5. It was also reported that if the ratio of the oscillating jet velocity to the freestream velocity kept constant, then gain in maximum lift was almost constant as the *Re* number varied.

Gross and Fasel [36] studied the control of flow over S822 wind turbine airfoil numerically via pulsed vortex generators, plasma actuators, and fluidic oscillators at Re number of 1×10^5 and angle of attack of 5°. A laminar separation bubble was observed to form on the suction surface and it affected the turbine life and efficiency by increasing the drag and creating unsteady loading on the airfoil. An inviscid shear layer instability was observed in the study and the fluidic oscillators were operated at a frequency to excite this instability. They reported increase of more than four times in the lift-to-drag ratio even for low blowing ratios.

Culley *et al*. [16],[17] used steady and unsteady injection to reduce the separation at the suction surface of stator vanes by using embedded fluidic oscillators, and also siren valve driven slot-vane and hole-vane actuators. The fluidic oscillators were mainly evaluated in this investigation because they have no moving parts, they provide higher frequencies that generate smaller scale structures which result in lower amplitude lift fluctuations, and thus less structural load on airfoil. Three bi-stable fluidic oscillators used in the study were operated at a fixed frequency of 2100 Hz and the phase differences between oscillators were not controllable. The best performance was obtained with the slot vane actuator rather than the fluidic oscillator control and more effective coupling between the oscillator output and the vane surface is strongly recommended to obtain better performance with the fluidic oscillators.

Cerretelli and Kirtley [12] used fluidic oscillators to inhibit the boundary layer separation on a model diffuser in which the hump pressure gradient served as the suction surface of a stator vane and compared the results with that of optimal steady blowing. Both actuations fully attached the flow; however, the fluidic oscillator provided the same control effect by using 30% less power and reducing the injection momentum by 60%. As the blowing coefficient was increased progressively, size of the separation decreased and eventually separation vanished.

Ries *et al*. [61] performed numerical and some preliminary experimental studies on a feedback fluidic oscillator that is designed to be used for controlling the laminar separation bubble formation by exciting the instability modes of the flow at specific frequencies. The comparison was done with and without actuation at different frequencies, amplitudes, and Reynolds numbers. Characterization of such fluidic oscillator observed to be promising to control the laminar separation in LP turbines by providing required frequencies at a reasonable size.

Vukasinovic *et al*. [85] applied active flow control with fluidic oscillators to suppress separated flow and resultant large-scale unsteadiness over a rounded geometry in transonic regime for both pre-choked and choked flows. Upstream control targets the active pre-shocking of the flow upstream of the main shock and weakens the main shock. On the other hand, downstream control targets the suppression of strong velocity/density gradients in the shear layer upon incipient flow separation. Fluidic oscillators used in this study combine nonzero mass addition into the flow resulting high frequency vorticity generation and enhancement in mixing.

Anwartz *et al*. [2] added a suction mechanism to a fluidic oscillator making the resultant actuator capable of suction and oscillatory blowing simultaneously. This actuator is called suction and oscillatory blowing (SaOB) actuator. Schatzman *et al*. [64] used experimental and numerical techniques to investigate the control of the flow at the aft portion of an axisymmetric bluff body by using SaOB actuators at *Re* number range from 2×10^6 to 5×10^6. The control was achieved by amplifying the actuator generated small disturbances along the shear layer. Their results indicated that the drag reduction mechanism with the SaOB actuator is a combination of boundary layer suction, wall-jet momentum addition, shear layer excitation, thrust and streamwise vortices.

Seifert *et al*. [70],[71] also used the SaOB in their active flow control investigation. They control the flow behind a generic 2D truck model to increase the back pressure to reduce the drag and reported a net drag reduction of 10% on full-scale trucks is achievable with fluidic oscillator based SaOB actuators.

Taubert and Wygnanski [75] used seven different attached aft bodies together with the fluidic oscillators to reduce the drag on a semi-trailer truck model. Fluidic oscillators were located at the rear end of the trailer and expected to enhance the entrainment of the shear layer by creating streamwise vortices. However, contribution of the fluidic oscillators in drag reduction was reported to be minor and it was discussed that this might be due to orientation of the oscillators and oscillator interference with one another particularly at the corners.

V. Conclusion

This paper has provided a survey of the historical development and modern application of fluidic oscillators for flow control. There is a resurgence of interest in fluidic oscillators within the aeronautical flow control community, but little awareness of the historical development work that has been done. The basic working principles and characteristics of fluidic oscillators were presented, with a classification scheme of fluidic oscillators presented. Following this was a discussion of the basic fluid dynamic principles at work, including jet flows and the Coanda effect. Development of wall-attachment fluidic oscillators was discussed next, where the extensive literature (spanning over fifty years) on switching time and oscillation characteristics was surveyed. Supersonic fluidic oscillators and recent developments in fluidic oscillators were highlighted. Jet-interaction oscillators were then discussed, with a focus on the interaction mechanisms at work. The review presented here is still a work in progress; we intend to flesh out the discussion of key papers in more detail and add many relevant citations before submission for archival journal publication in the near future.

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