



Numerical Studies of an Array of Fluidic Diverter Actuators for Flow Control

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Abstract

In this paper, we study the effect of boundary conditions on the behavior of an array of uniformly-spaced fluidic diverters with an ultimate goal to passively control their output phase. This understanding will aid in the development of advanced designs of actuators for flow control applications in turbomachinery. Computations show that a potential design is capable of generating synchronous outputs for various inlet boundary conditions if the flow inside the array is initiated from quiescence. However, when the array operation is originally asynchronous, several approaches investigated numerically demonstrate that re-synchronization of the actuators in the array is not practical since it is very sensitive to asymmetric perturbations and imperfections. Experimental verification of the insights obtained from the present study is currently being pursued.

1.0 Introduction

Applications of flow control require some type of actuation mechanism. The efficiency of the actuator is a function of the magnitude of the energy transferred to the problematic flow and its spatial extent and direction. The objective is typically not to alter the flow field directly because of the excessive energy requirement, but to leverage or redistribute the freestream energy by introducing small but controlled perturbations at the most receptive location in the flow field to achieve the desired effect. The ability of the flow control actuator to focus the control action in such a *localized* space and bring about *global* effects in the flow field is perhaps the most important characteristic of effective flow control technologies.

An ideal actuator must develop *sufficient* control authority at a location which requires *minimum* control authority. It must maximize benefit but minimize complexity, size, weight, power, and cost while maintaining reliability. Robust actuators that can function over a range from subsonic to supersonic conditions are needed. Enhanced understanding of their operation will enable improved and customized designs for particular flow control applications. Therefore, the specific implementation of an actuation mechanism and its ancillary support structure requires assessment of benefit versus penalty at the system level.

The application of fluidic control devices to cut UAV costs and maintenance by using air jets has recently been reported (Ref. 1). However, the system level assessment remains a challenge for internal flow control applications in turbomachinery (Refs. 2 and 3). Enhanced effectiveness and efficiency of turbine cooling schemes resulting in reductions of required coolant flows, but with minimal penalties in the overall system-level efficiency, are important design goals in the development of advanced turbine engines. Higher turbine inlet temperatures for better efficiencies lead to increased mechanical stress and environmental durability issues on the materials for turbines. Hence, efficient rotor and stator blade cooling is a critical technology need. Active closed-loop control to optimize for the best performance for the entire flight envelope is needed to meet the mass flow constraints for cooling.

Fluidic diverters, as described in this paper and in References 4 to 6, are actively controlled actuators which inject fluid into the freestream in an unsteady, periodic manner. While the devices require a source of pressurized fluid, they have no moving parts, add little to no weight, and require no external power for operation. Furthermore, the devices can be scaled over a great extent in terms of size, periodic frequency, and flow rate. Their increasing usage in real applications has been reported more recently, as in such examples of (a) enhancing significantly the performance of a single-element high-lift airfoil by employing a spanwise array of fluidic oscillator jets (Ref. 7), and (b) reducing the drag and increasing the lift substantially of a V-22 airfoil with and without deflected trailing-edge flaps and a semi-span V-22 wing/nacelle combination (Ref. 8). The active control of separation and lift enhancement by arrays of sweeping jets distributed along the span of single- or multiple-flap airfoils have also been recently investigated (Refs. 9 to 11). For applications of fluidic oscillators in commercial products like wind turbine blades, encouraging results are reported for both lift increase and drag reduction (Ref. 12). In all these cases, the fluidic actuators in the array oscillate in an asynchronous mode (random phase). To our knowledge, there has been no study so far of synchronous sweeping jets or diverter arrays for flow control applications.

In this paper, we examine some internal flow and operational characteristics of an array of uniformly-spaced fluidic diverter actuators with a goal to control their output phase for flow control applications in turbomachinery, whether for synchronous output, which may be desired for more efficient turbine film cooling, or controlled asynchronous output, which may be utilized for enhanced mixing in combustors. This work is an extension of our earlier work on a single diverter demonstrated to be capable of generating exit flow velocities ranging from subsonic to supersonic (Refs. 13 and 14). The present effort is specifically to achieve the synchronization of these diverter arrays while still retaining the principal advantage of “no moving parts” that are characteristic of such fluidic devices.

2.0 An Array of Fluidic Diverter Actuators

The operation principles of generic fluidic diverter actuators are described in the literature (Refs. 4 to 6). A jet created at the end of a converging section steers to one side of a central chamber and attaches to the wall in this region due to the Coanda effect (Refs. 15 and 16), the tendency of a fluid jet to stay attached to an adjacent curved surface. A part of the momentum or the pressure pulse is transmitted back through the feedback channel in the central region, which switches the jet attachment from one side to the other side of the chamber. Thus, the jet of fluid is diverted alternately into the two outlets provided at the exit.

The frequency characteristics of the actuator greatly depend on the design of the internal geometry of the wall-attachment region and the feedback channels. Fluidic oscillators typically have linear flow rate versus frequency characteristics. Pulse frequencies from 1 to 10 kHz have been obtained with meso-scale (nozzle sizes in the range of 0.2 to 1 mm) fluidic actuators with very low mass flow rates (of the order of 0.05 to 0.5 gm/s).

As an example of the concept of flow separation control using such an array of fluidic actuators in a stator vane, pulsing jets with sufficient authority (velocity amplitude ratio $u/U \sim 1$, where u is the exit velocity from the actuator and U is the freestream velocity) slightly ahead of the separation line leverage the high momentum freestream flow to cause reattachment of the separated flow on the suction-side surface. The reattachment will minimize the wake downstream of the stator vane under off-design conditions and reduce losses (Ref. 17). This enables higher vane loading, which can result in lower solidity, i.e., fewer vanes per stage, or even a reduced number of stages to achieve the same pressure rise in the compressor.

Fluidic diverters and sweeping jets can be designed in a compact array suitable for small footprints. Not only do pulsed and sweeping jets reduce mass flow rates relative to steady jets but have also been demonstrated to be more effective in many flow control applications. A schematic of implementing such a concept by embedding arrays of fluidic diverter actuators in a turbine blade is shown in Figure 1.

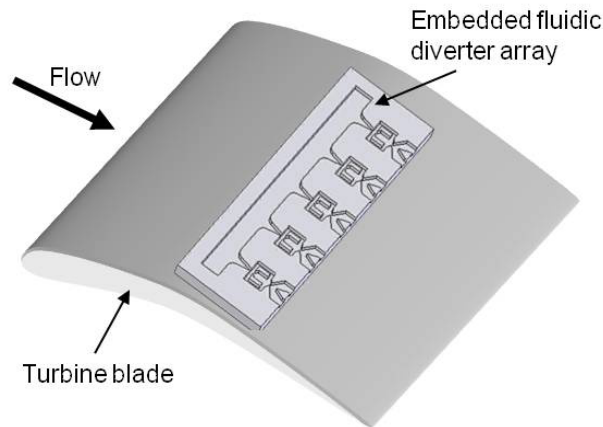


Figure 1.—Concept of embedded fluidic diverter arrays in a turbine blade.

Film cooling holes are typically used in gas turbine engines to cool the high pressure turbine vanes and blades using relatively cool air bled from the high pressure compressor. The standard practice is to use steady-flow jets issuing through round holes or (shaped) holes with expanded exits (Ref. 18). Fluidic diverters offer the opportunity to spread these film cooling jets in the transverse direction, allowing for more economical use of precious cooling air and a reduction in engine cycle losses associated with the coolant air bleed from the compressor. In this case, the fluidic diverters are not meant to control the aerodynamics of the boundary layer, but to more effectively lay down a layer of cool air near the blade surface.

Sweeping jets provide a better coverage on the surface compared to the steady straight jets, as demonstrated by comparative temperature distributions visualized using a liquid-crystal technique (Ref. 10). Note that, besides the potential of sweeping jets to increase film cooling effectiveness, unsteady flow inside the fluidic elements can also increase the heat transfer *inside* the blade passages as an additional benefit.

3.0 Motivation and Objectives

This study is motivated by the need to develop robust and efficient actuators for flow control applications in turbomachinery. When fluidic diverter actuators are used in an array, both synchronizing the outputs of individual diverters at will and breaking their synchronicity at controlled or prescribed levels of phase differences are challenging. It is envisioned that, for certain flow control and turbine film cooling applications, an array of synchronized actuators would be more effective than asynchronous ones.

The specific objective of this paper is to understand the internal flow structure and oscillation mechanisms in an array of uniformly-spaced fluidic diverter actuators by a time-dependent numerical analysis so that effective methods can be developed to synchronize their flow output without sacrificing the principal advantage of requiring only a pressure source and having “no moving parts,” which are characteristics of these fluidic diverters. The coupled velocity, temperature and pressure fields are calculated, and the self-induced oscillatory behavior of the flow is successfully predicted. Several approaches are tried computationally for synchronization. This understanding will aid in the development of efficient fluidic actuators with minimum pressure losses and advanced designs for effective surface coverage. Our previous studies (Refs. 13 and 14) of a single fluidic diverter demonstrated that its operation can be extended from subsonic to supersonic exit velocities for Mach numbers (Ma) up to 2.5. This study focuses on an example case with a supply-to-ambient pressure ratio of 1.064, corresponding to an isentropic air flow $Ma = 0.3$. The extension of the methodology developed for synchronization to arrays operating at other Mach numbers is straightforward.

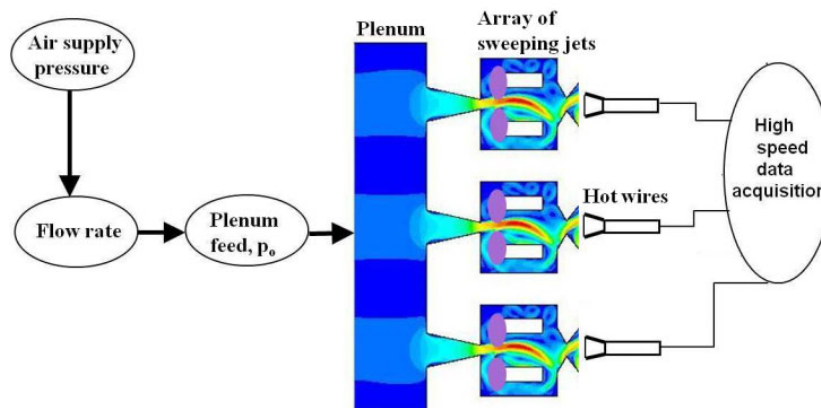


Figure 2.—A simple schematic of the experimental setup.

4.0 Experimental Measurements

Accompanying experiments are performed to validate the approach developed by our numerical modeling effort to synchronize an array of fluidic actuators. A more detailed description of the experimental setup and measurement techniques are given in Reference 19. A simpler schematic of the experimental setup involving an array of sweeping jets is shown in Figure 2. Some portions of the fluidic device are camouflaged due to the commercially sensitive nature of the information, but the physics of the phenomena and the results of computations discussed below can easily be followed without any sacrifice.

In order to determine the frequency and synchronicity of flow oscillations and to monitor the state of the gas flow through the jets, we use hot wires (exaggerated in size in the figure) positioned at the approximate centers of the device's outlets. Note that for supersonic flows, microphones are more practical as compared to the more fragile hot wires (Ref. 14). The reported frequencies are stated with respect to each jet. The gas supply pressure and its corresponding flow rate and jet oscillation frequencies are recorded via a high-speed data acquisition system.

Oscillation frequencies are found to be insensitive to whether the tests are conducted by keeping the gas supply pressure constant or by performing a blow-down of the initially filled supply. This is expected since the characteristic times of oscillations frequencies are much smaller than the response times of oscillations to the change in source pressure for the blow-down rates we employ; i.e., for the blow-down cases, the oscillation frequencies are practically measured at successively smaller “constant” supply pressures. The measured gas supply pressure is obtained very near to the plenum, within three inches, and is assumed to have negligible pressure drop before entering the device inlet.

For the experiments of this study, air is used as the supply gas, although helium was also tried in past experiments to study the effects of gas thermal properties and sonic speed.

5.0 Numerical Model

The numerical investigation uses the standard commercial CFD software FLUENT 6. The computational domain is two-dimensional (2-D) and is expanded from a single fluidic diverter used in our previous studies to an array of three diverters connected by a plenum with various prescribed boundary conditions, as shown in Figure 3. The outlets of the diverters are assumed to open to the ambient environment at 1 atm (p_∞) and 298 K (T_∞). The diverter-to-diverter separation distance is chosen such that the nearest outlet-to-outlet distance between two neighboring diverters in the array is the same as that of the left-to-right outlet of a given diverter. This would result in an array of outlets which are uniformly spaced spanwise on the surface of an airfoil.

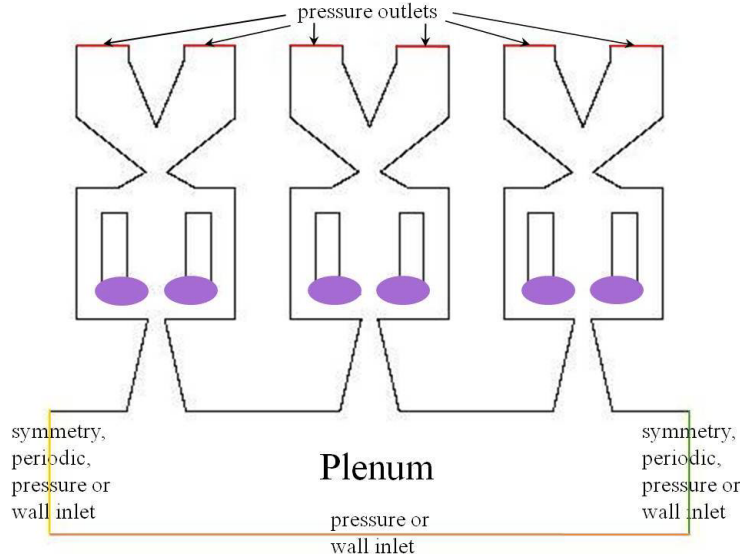


Figure 3.—A schematic of the 2-D computational domain and the types of applied inlet boundary conditions.

5.1 Boundary Conditions

Various types of inlet boundary conditions are applied around the periphery of the plenum to represent different flow situations. Although only three diverters are shown in Figure 3, the actual number of diverters encompassed by the model in the array varies depending on the type of inlet boundary conditions applied. If both the left and right sides of the plenum are taken to be wall boundary conditions, then only three diverters are indeed modeled with a pressure inlet boundary condition at the bottom of the plenum. If periodic boundary conditions are used on the left and right sides of the plenum with a pressure inlet boundary condition at the bottom, then the array is treated as infinitely long with infinite number of diverters and the model results reflect the behavior for the central three diverters. Symmetry boundary conditions on both sides of the plenum yield similar solutions as the ones obtained by periodic boundary conditions for this geometric application. If a wall boundary condition is used on one side of the plenum and a symmetry boundary condition is used on the opposite side with a pressure inlet boundary condition at the bottom of the plenum, then the model results reflect the behavior of the last three diverters at one end of an array. Another geometric variation of the array tried in our modeling is where the left and right sides of the plenum are taken as pressure inlet boundary conditions with a wall boundary condition at the bottom of the plenum. These various cases are conveniently labeled as “left-bottom-right” inlet boundary conditions applied during the computations in order to differentiate the different conditions. For example, a figure labeled as “symmetry-pressure-wall” refers to the results obtained from the model using the symmetry boundary condition on the left side of the plenum, pressure inlet at the bottom of the plenum, and wall boundary condition on the right side of the plenum.

Under isentropic conditions, the ratios of the supply temperature (T_o) and pressure (p_o) at the inlet to the respective flow exit temperature and pressure at the outlet are related to the Mach number (Ma) as follows:

$$T_o/T_\infty = 1 + (\gamma - 1)/2 \cdot Ma^2 \quad (1)$$

$$p_o/p_\infty = [1 + (\gamma - 1)/2 \cdot Ma^2]^{1/(\gamma-1)} \quad (2)$$

where γ is the ratio of the specific heat at constant pressure to specific heat at constant volume. For the computations in this study, if a pressure boundary condition is applied at an inlet, then the supply pressure is taken at a constant value of 1.064 atm, which corresponds to $Ma = 0.3$ at the exit assuming the flow

expansion of air ($\gamma = 1.4$) is isentropic under the prevailing conditions. The supply temperature at the inlet and the internal walls are assumed to be at the constant ambient temperature of 298 K.

A detailed description of the physical models including turbulence, spatial and temporal resolutions, and solution algorithms used in our computations is given in our previous studies (Refs. 13 and 14). Self-induced oscillatory behavior of the flow in each of the fluidic diverters in an array is successfully predicted for all the cases studied here.

6.0 Discussion of Results

As mentioned in Section 3.0, in order to investigate flow fields in different geometries with different number of fluidic diverters in an array, various types of inlet boundary conditions are applied around the periphery of the plenum connecting the diverters. The following cases are considered: (a) symmetry-pressure-symmetry inlet boundary conditions and (b) periodic-pressure-periodic inlet boundary conditions, both representing infinitely long array of diverters with similar geometries, (c) symmetry-pressure-wall inlet boundary conditions representing the right end of an array of six diverters, (d) wall-pressure-wall inlet boundary conditions representing an array of only three diverters, and (e) pressure-wall-pressure inlet boundary conditions representing a situation in which the bottom of the plenum is a solid wall and the gas pressure is supplied symmetrically from both sides of the plenum connecting three diverters in order to sustain the flow.

At the beginning of the calculations, the flow is initiated from rest by the supply pressure applied at the prescribed sides of the plenum depending on which one of the aforementioned five cases is being considered. As the flow starts to make its first pass through the plenum and diverters, capturing the flow acceleration and the transient development of pressure and temperature fields within the array accurately are crucial. Correct determination of the start-delay time of oscillations is one measure of how well numerical accuracy is sustained during this evolution period.

6.1 Start-Delay Times

In our previous study of a single fluidic diverter for subsonic flows, the start-delay time of oscillations for $Ma = 0.3$ was determined to be 2.2 ms (Ref. 13). Here, also for $Ma = 0.3$ but for arrays, the start-delay times of oscillations determined by our computations are given in Table 1. For the previous single fluidic diverter case, the computational domain did not include a plenum and the beginning of the converging nozzle originating from the plenum was used as the inlet boundary condition. Note that oscillations start at about the same time consistent with the single diverter, and all three diverters in the array start simultaneously. The pressure-wall-pressure case is the only exception, where the left and right diverters start at the same time but in different directions and earlier than the central diverter. It is also noteworthy that the oscillation frequencies obtained from our computations for all of the cases reported in the table are around 775 Hz and are the same as the previously validated case for a single diverter by experimental measurements.

TABLE 1.—START-DELAY TIME OF OSCILLATIONS FOR
DIFFERENT CASES WITH VARIOUS INLET
BOUNDARY CONDITIONS

Case	Start-delay time of oscillations, ms
Symmetry-pressure-symmetry	2.1 for all three diverters
Periodic-pressure-periodic	2.2 for all three diverters
Symmetry-pressure-wall	2.0 for all three diverters
Wall-pressure-wall	2.2 for all three diverters
Pressure-wall-pressure	1.7 for left and right diverter 2.2 for center diverter
Single diverter	2.2

6.2 Boundary Conditions for Synchronized Output

The flow fields of all five cases starting from quiescent original conditions are examined after the establishment of full oscillations by taking a snapshot for each case at exactly 10 ms after the initiation of the flow at the inlet. The prevailing velocity magnitudes are shown in Figure 4. The remarkable observation is the similarity among the first four cases, (a) to (d), for which a pressure inlet boundary condition is used at the bottom of the plenum. For all four cases, the diverters start their oscillations simultaneously and remain synchronized. The individual diverters in the array are decoupled from one another for their given separation distance and plenum height. Under these circumstances, the type of boundary conditions applied to the two opposing sides of the plenum does not matter much and leads to a synchronized operation. This finding is significant and provides clues for approaches to be taken in order to successfully synchronize an initially asynchronous array of diverters.

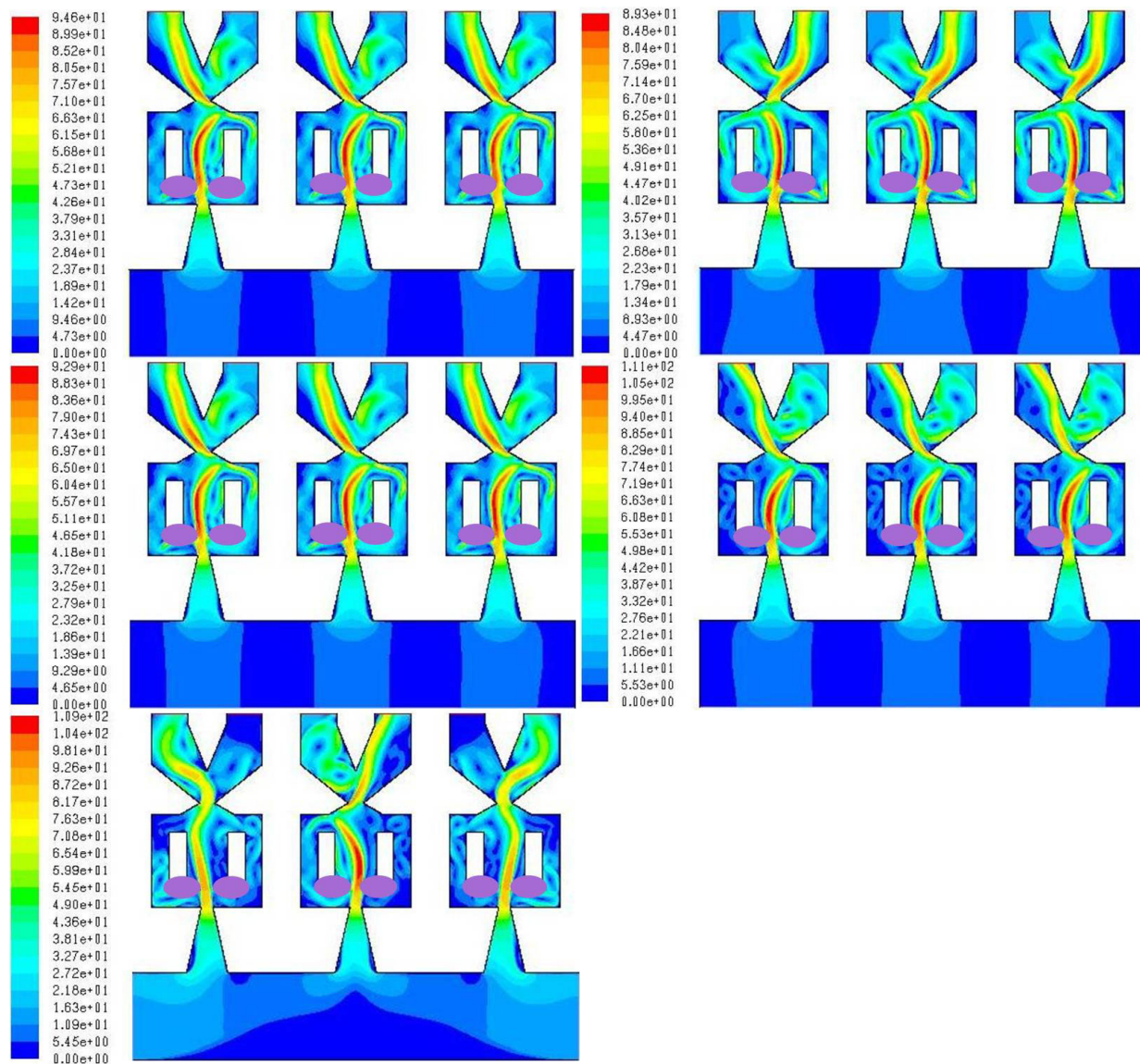


Figure 4.—Snapshots of velocity magnitude (m/s) taken at 10 ms for various plenum inlet boundary conditions: (a) symmetry-pressure-symmetry, (b) periodic-pressure-periodic, (c) symmetry-pressure-wall, (d) wall-pressure-wall, and (e) pressure-wall-pressure.

The velocity magnitude field shown in Figure 4(e) for the pressure-wall-pressure case depicts that the left and right diverters are out of synch by a phase difference of 180° and the central diverter is not in synch with either of them. This boundary condition scenario indicates an inherent difficulty in being able to synchronize such an array with the given geometric setup for inlet flow. Therefore, the pressure-wall-pressure case is not included for the subsequent synchronization attempts presented below.

6.3 Switching from Synchronous to Asynchronous Mode

Since cases (a) to (d) synchronize from the beginning and our objective is to develop approaches to synchronize arrays that are originally asynchronous, a deliberate action is taken to break the synchronicity for these cases. For that purpose, a pressure pulse is applied at the plenum bottom inlet but only to its central one-third portion for a period of 1 ms. During this time, the inlet pressure along this bottom central one-third strip is increased to 1.387 atm, corresponding to an isentropic Mach number of 0.7, while the remaining two one-third sections of the inlet on each side of the central pulse section are kept at the original level of 1.064 atm. The disruption created at the end of this pressure pulse at 11 ms is shown in Figure 5 for the wall-pressure-wall boundary condition case as an example. Similar disruptions breaking synchronous behavior are also created for the other three cases.

Immediately after completing the application of the pulse, the entire inlet pressure at the bottom of the plenum is brought back down to the original 1.064 atm level at 11 ms. The computations are carried on for another 9 ms to ascertain that the deliberate pressure pulse was sufficient to break the synchronicity and that the diverters remained asynchronous. This was confirmed by examining the velocity magnitude fields at 20 ms. Indeed, all four cases, each with a pressure inlet boundary condition at the bottom of the plenum, developed asynchronous flow fields and resulted in outputs that are out of synch. Figure 6 shows the flow field at 20 ms for the symmetry-pressure-symmetry case as representative of other three cases.

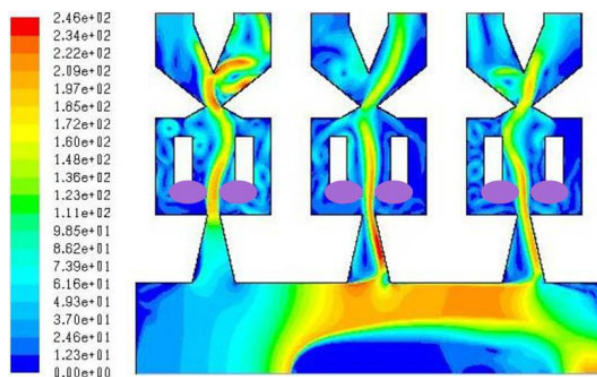


Figure 5.—A velocity magnitude (m/s) snapshot at 11 ms for wall-pressure-wall boundary condition case right after completion of asymmetric pressure pulse.

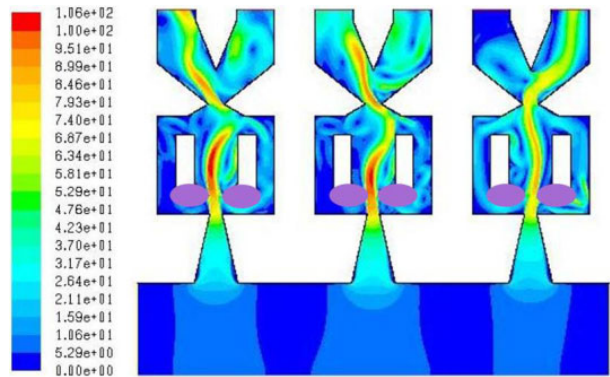


Figure 6.—A velocity magnitude (m/s) snapshot at 20 ms for symmetry-pressure-symmetry boundary condition case showing that synchronicity is broken.

6.4 Asynchronous to Synchronous Oscillations

The various approaches taken to synchronize the output starting with an asynchronous mode are described below.

6.4.1 Method 1: Choking the Array by Pressure Pulsing

The first approach is to increase the pressure at the inlet to a sufficiently high level for a period of time in order to choke the converging nozzle of each diverter in the array. The idea is to briefly isolate the upstream from the downstream of the nozzle location to see if this isolation erases the memory of oscillations such that when the choking is released the flow might reestablish the originally synchronized oscillations.

For this purpose, the inlet pressure is increased at 20 ms to 3.671 atm corresponding to an isentropic Mach number of 1.5. This pressure pulse is applied for a period of 1 ms. During this time, the flow in the central section and outlets of the diverters becomes supersonic. Special attention is given to maintain numerical accuracy by allowing sufficient temporal resolution and employing solution-adaptive dynamic grid refinement based on local pressure gradients in order to accurately capture and resolve the shocks (Ref. 14). The solution algorithm is also accordingly adjusted to allow a more robust convergence scheme (Ref. 20).

For all cases, choking increases the oscillation frequency as expected, depending on the magnitude of the applied pressure to create supersonic flows. It seems that choking also preserves the initial asynchronous behavior since all diverters feel the effect simultaneously. In order to avoid redundancy, the symmetry-pressure-symmetry case is presented in Figure 7 as representative of other similar cases. We observe that at 21 ms, right after the completion of the choking pressure pulse, the original asynchronous flow directions present in each diverter at the start of the choking pressure pulse are frozen. When the choking pressure is subsequently relaxed at 21 ms back to the original level of 1.064 atm for the entire inlet at the bottom of the plenum, there is a very brief period of flow reversal inside the diverters and the plenum, after which the flow adjusts itself to the forward direction and establishes the regular oscillatory motion. The computations are carried on for another 9 ms until 30 ms to ascertain that the flow does not show any sign of recovering from its asynchronous behavior (Fig. 8).

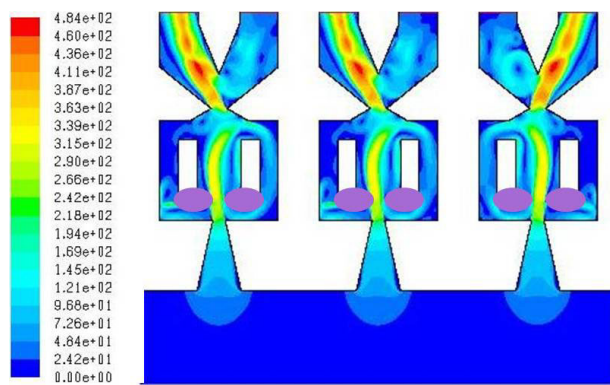


Figure 7.—A velocity magnitude (m/s) snapshot at 21 ms for symmetry-pressure-symmetry boundary condition case right after completion of choking pressure pulse.

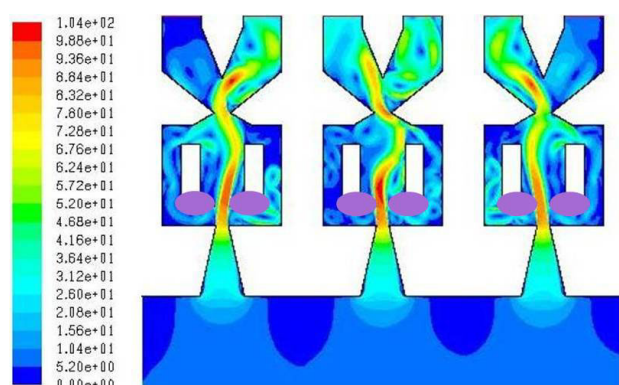


Figure 8.—A velocity magnitude (m/s) snapshot at 30 ms for symmetry-pressure-symmetry boundary condition case showing that choking does not sync the array.

6.4.2 Method 2: Relaxing the Flow by Depressurization

The second approach is in a way opposite to the first approach of choking. Depressurizing the inlet by bringing the source gas pressure down to the outlet pressure level would eliminate the driving force for flow through the diverters and slow down the existing gas motion inside them by viscous dissipation. Here, the hypothesis is that if the depressurization is long enough for the remaining flow disturbances inside the diverter to decay to a weak enough level, then re-pressurizing the inlet would re-start the flow with a momentum high enough to sweep the remnants of disturbances and establish synchronized oscillations, just like it does at the beginning when the inside of the diverters are at rest. Naturally, the question is what is a long enough time for flow disturbances to decay, or equivalently, what is a weak enough flow disturbance to get wiped out completely by the re-started flow through the diverters without influencing the initiation of synchronized oscillations.

The inlet depressurization is applied at 11 ms to all four cases whose synchronicity have been broken right after a 1-ms-long asymmetric pressure pulse. At present, computations with depressurization have progressed for another 49 to 60 ms during which there has been no pressure differential between the array inlet and outlets. Figure 9 shows the decayed velocity magnitudes at 60 ms for the representative case of symmetry-pressure-symmetry inlet boundary condition. The velocities in the central region of the array are reduced by nearly three orders of magnitude to 5 to 15 cm/s from its initial Mach 0.3 level of about 100 m/s before the application of depressurization. At this point, we re-pressurize the inlet to its original value of 1.064 atm across the entire bottom of the plenum and the flow through the diverters is re-initiated. The oscillations are re-established in a few milliseconds. A snapshot of the velocity magnitude at 65 ms for the representative case of periodic-pressure-periodic inlet boundary condition is shown in Figure 10 and demonstrates that synchronization of the oscillations in the array is not attained after the re-start. Needless to say, re-starts after shorter depressurization periods have also failed to synchronize the array output. Unfortunately, computations with longer periods of depressurization could not be completed at the time of submission of this paper. However, the evidence from our computations starting from quiescent initial conditions, as depicted in Figure 4(a) to (d), imply that synchronization should eventually be accomplished by longer depressurization periods which would asymptotically decay the fluid motion inside the array to quiescence.

An outcome of this numerical experiment is the lesson that the ability to synchronize the array is highly dependent on the level of initial disturbances. In fact, even for the initial computations shown in Figure 4, one realizes that extreme care should be given to minimize numerical inaccuracies to be able to obtain a synchronous output of the array. The sensitivity of synchronous results to seemingly minor imperfections, geometric or numerical, indicates that a robust synchronous operation of this array by simply manipulating the inlet boundary conditions is not practical.

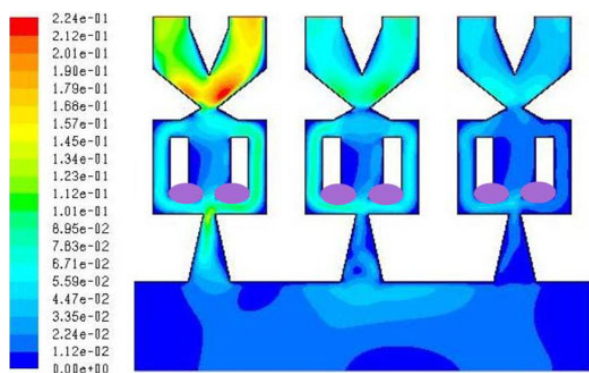


Figure 9.—A velocity magnitude (m/s) snapshot at 60 ms for symmetry-pressure-symmetry boundary condition case showing velocity decay after depressurization.

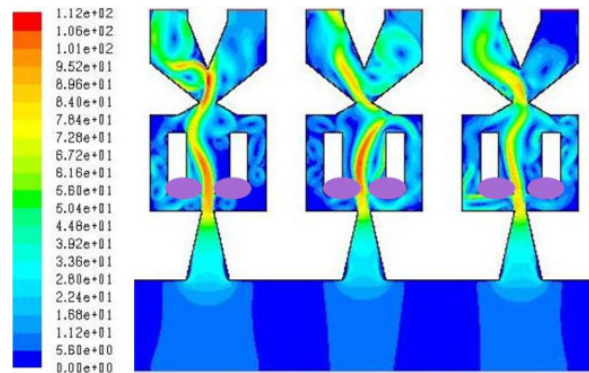


Figure 10.—A velocity magnitude (m/s) snapshot at 65 ms for periodic-pressure-periodic boundary condition case showing that the array is not synched after re-start.

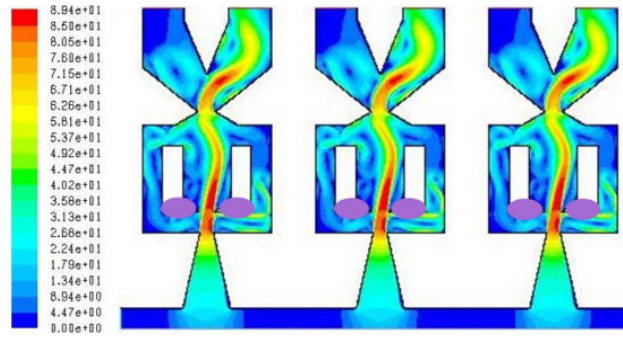


Figure 11.—A velocity magnitude (m/s) snapshot at 10 ms for periodic-pressure-periodic boundary condition.

6.4.3 Method 3: Coupling Diverters by Reducing Plenum Height

The next approach is an attempt to couple the diverters based on the hypothesis that the diverters would feel their respective pressure pulses produced by their axial oscillations through a thinner plenum and this coupling would eventually steer the diverters towards synchronization as a state of minimum energy. For that purpose, the plenum height is shortened so that the plenum would become a conduit relaying the pressure and velocity information among the diverters. Based on the velocity magnitude fields obtained in the cases studied above, the plenum height is reduced to one-fifth of its original value.

Previous computations with various inlet boundary conditions (a) to (d) are repeated with this thinner plenum. The velocity magnitude field at 10 ms, this time for the representative case of periodic-pressure-periodic inlet boundary condition, is shown in Figure 11. First, it is duly noted that this array is also capable of generating a synchronous output if started from a quiescent initial condition. However, for the given uniform spacing between the diverters, the anticipated coupling is not accomplished via the use of a thinner plenum. The diverters still behave individually and their synchronous output is sensitively dependent on the numerical accuracy of the computational scheme. For example, if grid adaption is not employed in the time-dependent computations, then accumulating numerical errors lead to artificial flow instabilities inside individual diverters, resulting in varying oscillation delay times for each diverter, and hence, create an asynchronous output of the array.

The same procedure as Method 2 described above is applied to the thinner plenum cases as well in an attempt to re-synchronize the array. Similarly, the synchronicity of the array is broken by an asymmetric pressure pulse applied at 10 ms for a period of 1 ms, and the depressurization is started at 11 ms and continued until 60 ms. As shown in Figure 12 for the representative case of periodic-pressure-periodic inlet boundary condition, the velocities in the central region of the array have decayed to similar levels as those of the taller plenum cases discussed above, but re-starting the flow has not produced a synchronous array for this case either, as shown in Figure 13 at 65 ms for the representative case of periodic-pressure-periodic inlet boundary condition. These observations apply to all cases regardless of the various inlet boundary conditions, indicating again the fragility of the array to sustain or re-establish a synchronous output.

It should be cautioned that snapshots of flow fields after re-pressurization can coincidentally look synchronous and be misleading. If, for example, the delay time for the initiation of oscillations among the individual diverters in the array is apart by approximately one period of oscillation, then these initial phase differences would lead to subsequent oscillations which appear to be synchronous. It is, therefore, very important to correctly capture when the oscillations of individual diverters re-start after the re-pressurization of the array. Observing the animations of how the flow develops inside the entire array during the initiation of oscillations is also very useful for not being misled by frozen snapshots of synchronous flow fields. While generating a synchronous array is the objective, how this synchronicity is obtained is quite relevant for understanding the fragility of the system, and hence, the ultimate reliability of its operation.

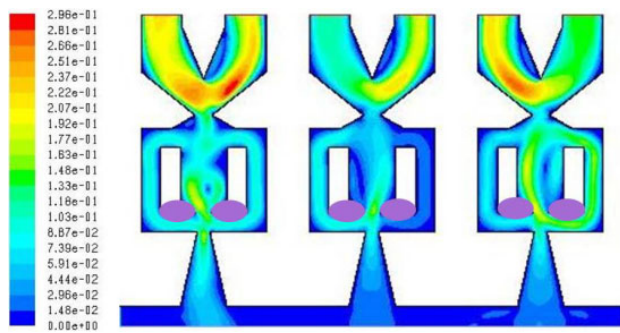


Figure 12.—A velocity magnitude (m/s) snapshot at 60 ms for periodic-pressure-periodic boundary condition case showing velocity decay after depressurization.

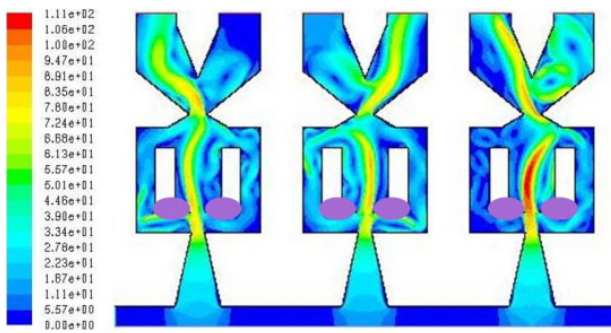


Figure 13.—A velocity magnitude (m/s) snapshot at 65 ms for periodic-pressure-periodic boundary condition case showing velocity decay after depressurization.

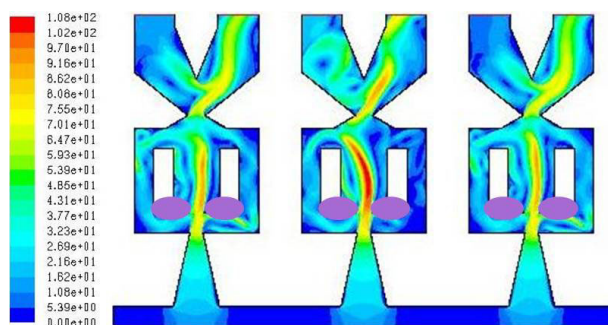


Figure 14.—A velocity magnitude (m/s) snapshot at 65 ms for wall-pressure-wall boundary condition case showing velocity decay after depressurization.

An example of how a synchronous-looking flow field can be obtained by simply varying the inlet boundary conditions for the thin plenum case from periodic-pressure-periodic (Fig. 13) to wall-pressure-wall is shown in Figure 14 by a snapshot of the velocity field taken at 65 ms. It is, however, determined that this fortuitous behavior is a result of the different initiation times of oscillations of individual diverters after re-pressurization.

Even though our initial computations have been successful in generating synchronous outputs from an originally quiescent array, further evidence has indicated that, once its synchronicity is broken, subsequent synchronization of this array only by manipulating the inlet boundary conditions is not practically possible due to its small tolerance to imperfections. Indeed, our preliminary experiments, using an array of sweeping jets manufactured by the guidance given by our computations, have not been able to obtain synchronous outputs from hot wire measurements. Further elaboration for more careful experiments is not deemed to be warranted at this time.

7.0 Conclusions

It is envisioned that for certain flow control and film turbine film cooling applications an array of synchronized actuators would be more effective than asynchronous actuators towards satisfying the need to develop robust and efficient actuators. Our time-dependent computational model reveals the internal flow structure and oscillation mechanisms in an array of uniformly-spaced fluidic diverter actuators under various inlet boundary conditions. The coupled velocity, temperature and pressure fields are calculated, and the self-induced oscillatory behavior of the flow is successfully predicted. This understanding is

utilized to develop effective methods and operational procedures for synchronizing their flow output. It is determined that a potential design is capable of generating synchronous outputs for various inlet boundary conditions if the flow inside the array is initiated from quiescence. However, when the array operation is originally asynchronous, several approaches proposed and tried computationally have shown that re-synchronization of the actuators is not practical since this particular array is very sensitive to asymmetric perturbations and imperfections.

Our next step would be to translate these observations into practical methods of obtaining synchronous or phase-controlled asynchronous arrays of pulsing or sweeping jets. The computational model is a productive and efficient tool to investigate the operation and design optimization of arrays of synchronized fluidic diverters and similar unsteady fluidic actuators.

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14. ABSTRACT In this paper, we study the effect of boundary conditions on the behavior of an array of uniformly-spaced fluidic diverters with an ultimate goal to passively control their output phase. This understanding will aid in the development of advanced designs of actuators for flow control applications in turbomachinery. Computations show that a potential design is capable of generating synchronous outputs for various inlet boundary conditions if the flow inside the array is initiated from quiescence. However, when the array operation is originally asynchronous, several approaches investigated numerically demonstrate that re-synchronization of the actuators in the array is not practical since it is very sensitive to asymmetric perturbations and imperfections. Experimental verification of the insights obtained from the present study is currently being pursued.					
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