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Contribution to the Understanding of Flow Interactions Between Multiple Synthetic Jets

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Introduction

THE application of synthetic jet actuators (SJAs) for controlling flow behavior is gaining widespread acceptance. The vast majority of the work is being conducted in the area of aerospace, with the objective of modifying and manipulating separated flows over lifting surfaces. The fundamental physics of the flow generated by an SJA has been investigated experimentally by Smith and Glezer,[1] whereas numerical studies were conducted by Rizetta et al.[2]

In its most basic form, the SJA is a cavity that is bounded by an oscillating diaphragm on the bottom, whereas the top is covered by a rigid plate containing an orifice. Oscillations of the diaphragm cause the fluid to be alternately drawn into and expelled from the cavity in such a way that the net mass flow is zero. However, from the viewpoint of momentum or vorticity production, the effects of an SJA's operation are not neutral. A train of vortex rings, rolled up on the edge of the orifice, is formed, and it propagates outward from the orifice plate. Time-averaged velocity profiles in planes parallel to the orifice plate show a qualitative similarity with a steady jet, which explains the name "synthetic jet."

Early work on applications of SJAs was carried out by Smith et al.,[3] who utilized synthetic jets on a NACA airfoil and subsequently achieved a delay in the angle of stall from 5 to 18 deg. Wood et al.[4] reported a delay of the separation line associated with the flow past a circular cylinder. More recent work by Amitay and Glezer[5] showed that it is possible to manipulate the global aerodynamic forces on a thick airfoil, at high angles of attack, by deploying an array of SJAs with pulse-modulated actuation.

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Although the flow structures and flow behavior arising from isolated SJA devices seem to be well understood, in both the quiescent and crossflow conditions, the interaction between multiple synthetic jets has not been addressed with a sufficient level of detail. This problem is not trivial, and to date there are no design guidelines available as to the optimum spacing between the synthetic jets in an array for producing a desired aerodynamic effect. Moreover, application of synthetic jets on swept wings may lead to vortex trains interference and, thus, to combining or canceling the vorticity generated by the neighboring orifices. Further complications may arise if one wishes to modulate the relative phase lags between the excitation of devices forming an array.

This Note presents some preliminary flow visualizations that aim to explain the fundamental nature of such interactions between a pair of synthetic jets. The photographs of resulting smoke, ink, and surface flow visualizations are presented, and a discussion focused on explaining the flow phenomena is provided, together with suggestions for future research.

Experimental Setup

The experiments were conducted in three different situations: in still air inside a quiescent chamber, in the laminar crossflow of a water tunnel, and in a turbulent boundary layer in a wind tunnel. The setup for quiescent experiments was similar to that reported by Wood et al.[4] and consisted of a 50-mm-diam model of an SJA driven by an electromagnetic shaker at a frequency of 50 Hz. A number of orifice plates could be attached, each having two holes of diameter either 3.5 or 5 mm and a relative spacing between the holes of 6, 7, 8, 9, 10, 13, 16, and 20 mm. The exit velocity of the fluid was controlled by the level of excitation of the shaker and, for the results presented here, this was 5 m s^{-1}. Smoke was generated using a heated wire suspended inside the actuator cavity, along with mineral oil. A transverse cross section of the flow was visualized by a laser sheet obtained from a 5-W continuous argon ion laser.

The experiments in the laminar crossflow were conducted in a 10×14 in. water tunnel with a freestream velocity variable between 2 and 20 cm s^{-1}. A 100-mm shaker driven model of an SJA was mounted on a flat plate, which was submerged in the flow, and the same range of orifices was used. A food dye was used for visualizations, and two video cameras provided orthogonal views of the flow. The orifice plates could be rotated to vary the orifices' yaw angle relative to the freestream flow. The results presented here correspond to the diaphragm excitation frequency of 5 Hz, an exit velocity from the orifices of 8.5 cm s^{-1}, and a freestream velocity of 6.6 cm s^{-1}.

Finally, the experiments in the zero pressure gradient turbulent boundary layer were conducted in a 0.5×0.5 m low-speed wind tunnel operated at 32 m s^{-1}. Two small SJAs, similar to those described by Wood et al.[4] and Crook,[6] were mounted flush on a 0.5-m wide flat-plate airfoil, mounted in the tunnel center. The orifice diameters were 1 mm, whereas the spacing between orifices was 6 or 8 mm. The pair of SJAs were mounted within a metal disk, which could be rotated, allowing for variation in the yaw angle. The actuators were driven at a frequency of 1900 Hz, with the peak exit velocity from the orifice of 20 m s^{-1}. Surface visualizations of the flow were obtained by coating the airfoil with a mixture of kerosene and luminous paint and taking photographs with a digital camera.

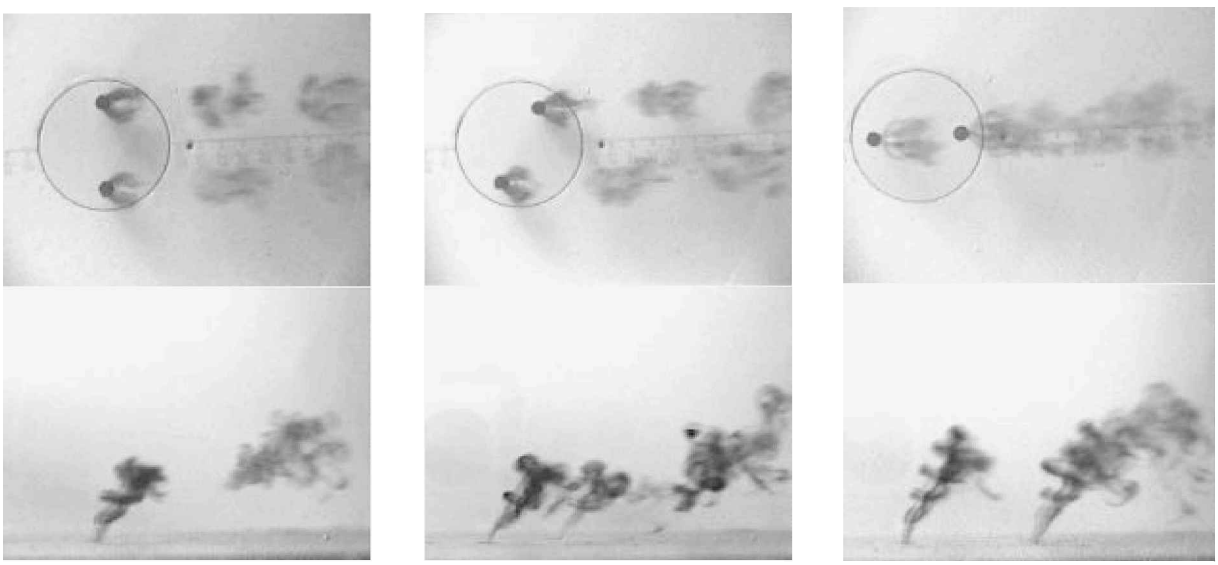
Results and Discussion

Figure 1 shows the flow visualizations obtained for a pair of synthetic jets in quiescent conditions. The orifice plate is on the left in each of Figs. 1a–1c. The vortex structures are traveling from left to right. The only variable in the images shown in Fig. 1 is the spacing between orifices. Figures 1a–1c show that there are three types of interactions between synthetic jets.

For sufficiently large orifice spacing, the vortex rings from adjacent orifices seem to propagate unaffected by one another (Fig. 1a). When the distance between orifices is reduced (Fig. 1b), the roll up of the near side of each vortex ring, that is, the part of a ring nearest to an adjacent ring, gives rise to an induced velocity, acting on the opposite ring. This is a likely explanation for why the rings from

a) b) c)

Fig. 1 Interaction between two adjacent synthetic jets in quiescent conditions. Spacing between orifices varies: a) 20, b) 8, and c) 6 mm; excitation frequency is 50 Hz, exit velocity 5 m s^{-1}, and diameter of orifices 3.5 mm in all cases.



a) b) c)

Fig. 2 Vortex patterns produced by adjacent synthetic jets in a laminar crossflow with yaw angle to freestream direction varying: a) 90, b) 60, and c) 0 deg; excitation frequency 5 Hz, exit velocity 8.5 cm s^{-1}, freestream velocity 6.6 cm s^{-1}, spacing between orifices 20 mm, and orifice diameter 3.5 mm in all cases.

adjacent jets alter their trajectory and move toward each other. The closer the rings come together, the stronger the interaction. That the parts of each vortex ring that interact are counter-rotating would imply that there must be some vorticity cancellation as the structures collide. Finally, for orifices very close together (Fig. 1c), notice an almost immediate interaction between the two slugs of fluid leaving the orifices as they try to roll up and form distinct vortex rings. The result of this is what appears to be a single, large vortex ring, which then propagates away from the orifices. Whether this type of ring interaction causes vorticity destruction and cancellation, or simply a redistribution of the vorticity, is unclear. Quantitative data would be needed to clarify this.

Figure 2 shows the results of flow visualizations conducted in the laminar crossflow of the water tunnel. For each of Figs. 2a–2c, there are two types of photographs shown, a top view (so that the rings would travel perpendicularly out of the page if no crossflow were present) and a side view (where the rings are perpendicular to the page), with the orifice plate at the bottom of the image. The flow is moving from left to right in each of Figs. 2a–2c. In Fig. 2, the variable of interest is the angle of yaw between the twin-orifice arrangement and the freestream. (That is, 0 deg corresponds to the orifices parallel to the crossflow and 90 deg to the orifices perpendicular to the crossflow.)

As expected, the side images show that the ejected vortex rings and, hence, the jet, are skewed in the downstream direction. The top views show that, when the orifices are aligned perpendicular to the crossflow (Fig. 2a), the situation is similar to that in still air (Fig. 1a), apart from the vortex rings being convected along with the crossflow, as well as propagating out of the surface. In this case, as for the still air experiments, the spacing between orifices is one key factor in causing the jets to interact. (This feature is not shown in Fig. 2.) However, for a set spacing, as the yaw angle decreases, the interactions between rings also change. The example shown in Fig. 2b corresponds to the yaw angle of 60 deg. Interestingly, in this situation, the structures exiting the orifices are, in essence, out of phase by 180 deg. Finally, at a 0-deg yaw angle (Fig. 2c), an interesting phenomenon is observed, whereby the front ring of a given pair of rings is ejected from its orifice just in time to merge with the trailing ring of the preceding pair of rings. Experiments such as these show that a combined use of orifice spacing and yaw angle could be used to engineer a desired phase lag and degree of vortex interaction to suit particular flow control needs.

Figure 3 shows some examples of surface flow visualizations obtained from the wind-tunnel tests of SJAs located in a zero pressure gradient turbulent boundary layer. These, of course, are not an ideal way of investigating the three-dimensional nature of the vortex structures. Note that they can only show time-averaged features of the flow. However, given the preliminary nature of the investigation and well-known difficulties in smoke visualizations at high speeds, the two-dimensional "footprints" can provide some useful clues about the flow physics.

In Figs. 3a–3d, the flow is from left to right. The images, taken looking down onto the plate, show how consecutive vortex rings are swept downstream by the crossflow, forming what are essentially, in a time-averaged sense, long vortex tubes. (Although in reality, close to the orifices, there still must be a discrete substructure of individual

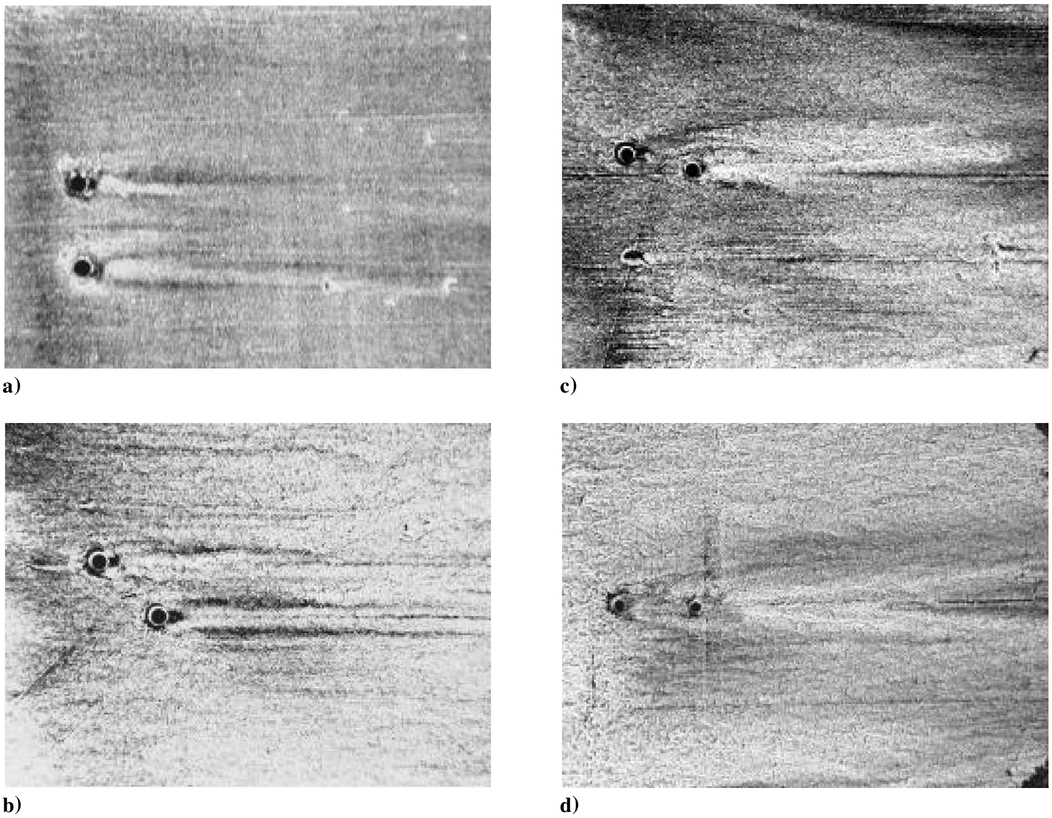


Fig. 3 **Surface flow visualizations produced by adjacent synthetic jets in a turbulent crossflow, where yaw angle to freestream direction varies: a) 90, b) 45, c) 15, and d) 0 deg; excitation frequency 1.9 KHz, exit velocity 20 m s^{-1}, freestream velocity 32 m s^{-1}, spacing between orifices 8 mm, and orifice diameter 1 mm in all cases.**

vortices.) The dark patches running parallel to the crossflow are the regions where the paint has been swept away by the highest skin friction. These correspond to the location of the vortex tubes. For the first two images (Figs. 3a and 3b), the limiting factor for vortex interaction seems to be the orifice spacing. In these cases the spacing is too large to allow interaction. For the yaw angle of 15 deg (Fig. 3c), a small lateral offset of the two orifices, caused by the orifice orientation, resulted in the upper vortex tube of the lower orifice interacting with the lower tube of the upper orifice. Because these two tubes are counter-rotating, they are liable to interact in a destructive manner. This leaves only the outer two tubes that are, in essence, very similar to the tubes that would be produced from a single, but wider, orifice. Finally, Fig. 3d shows the orifices aligned with the crossflow. In this case, it is most likely that the rear orifice produces a counter-rotating pair of vortex tubes that interacts in a constructive way with the pair of counter-rotating tubes from the orifice in front. There will be no obvious vorticity destruction, and a strong possibility exists that the various tubes will combine in a way that would see a stronger, more coherent vortical structure produced. To verify this, it would be necessary to examine how far downstream the structures persist and whether it is appreciably longer than for a single orifice.

Conclusions

A preliminary study of flow interactions between a pair of synthetic jets has been conducted, and a number of interesting phenomena have been observed. It has been shown that, to produce a single coherent synthetic jet from each actuator in an array, there is a minimum spacing between actuators that needs to be observed. Furthermore, the experiments in the crossflow conditions have shown that the combined effects of the yaw angle and the orifice spacing could either reduce or enhance the amount of coherent vorticity present in the flow. Finally, it is believed that a careful selection of these two parameters could be used to design a desired phase differencing for flow control strategies of the future. This may be important from the viewpoint of imposing excitation frequencies on a shear layer for control purposes, where mechanisms could be devised for varying the available excitation spectra, using multiple orifices.

To explore these ideas, further work is required. This should include a detailed parametric study, especially in the crossflow conditions, to ascertain the effects of diaphragm excitation levels and frequency on the minimum distance between SJAs in an array. The unsteady characteristics and excitation spectra of the three-dimensional structures generated within the turbulent boundary-layer arrangement should be explored using advanced techniques such as with a laser Doppler anemometer or with phase-locked particle image velocimetry. Finally, there is a large scope for investigating how the geometrical arrangement of multiple orifices could affect the spectra of the coherent structures introduced into a shear layer during the control of the separated flows.

Acknowledgments

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