Micromachined Jets for Manipulation of Macro Flows

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Abstract

This paper describes the successful fabrication and initial characterization of micromachined jets (microjets) fabricated for use in macro flow control and other applications. The microjets were fabricated using standard silicon micromachining techniques and consist of an orifice situated atop an actuator cavity which is bounded by a flexible membrane. Typical microjet orifice sizes range from 150-300 microns. Vibration of the membrane using either electrostatic or piezoelectric drive results in a nominally round turbulent air jet formed normal to the microjet orifice. An important feature of the jet is that it is formed without net mass injection by an oscillatory flow that is acoustically induced near the edge of the orifice. Initial characterization was performed using a miniature total pressure tube and a conventional miniature hot wire sensor. Microjets with velocities of 17 m/s and coherent to lengths exceeding 500 diameters were achieved. The microjet Reynolds number at a distance of 15 diameters is estimated at approximately 1400.

Introduction

While there is no question that one of the most important application areas for microactuators is the control of macro-events, these actuators usually generate insufficient force to directly realize control authority. Thus, some type of mechanical amplification is required. An attractive means for the amplification of the actuator output is its coupling to inherently unstable pressure or flow systems. If system operating points are carefully chosen, the relatively small forces generated by a microactuator can be used to create large disturbances in either static, pressure-balanced systems or in free- and wall-bounded shear flows. These concepts have been exploited for years in a number of static and dynamic macro systems such as pressure regulators and fluidic actuators, respectively. More recently Huff et al. [1] have demonstrated the adaptation of a pressure-balanced system to an electrostatically-actuated microvalve.

An example of flow control that illustrates a scaling hierarchy which can be adopted for microactuators is in the area of jet thrust vectoring. Recent experiments by Green and Glezer [2] have demonstrated the utility of millimeter-scale surface actuation for thrust vectoring of larger jets having characteristic length scales that are at least two orders of magnitude larger. Vectoring is accomplished by exploiting hydrodynamic instabilities of the macro-jets near the flow boundary such that the energy necessary for their manipulation is extracted from the mean flow and thus the power input to the actuators is of the order of several milliwatts [3-4]. The efficacy of this technique has been demonstrated in an air jet emanating from a rectangular orifice (7.62 x 1.27 cm) as shown in contour plots of the measured streamwise velocity component in the cross-stream plane (Figure 1a-1c). The unforced jet is shown in Figure 1a for reference. In Figure 1b, the jet is forced by and vectored away from the bottom actuators. Time-periodic vectoring is achieved when the input waveforms to the top and bottom actuators are modulated out of phase (Figure 1c). Recent jet vectoring experiments at Georgia Tech (Smith and Glezer, unpublished) in which the mechanical actuators were replaced with millimeter-scale zero mass flux surface jets have suggested the concept of cascaded control. Namely, that micromachined jet actuators (microjets) be used to manipulate millimeter-scale jets which, in turn, will control larger jets. Arrays of micromachined jets are particularly attractive for such applications because they can be individually addressed and phased. In this paper, we describe some design and fabrication concepts of micromachined jet actuators and include some preliminary measurements of their performance.

Jet Operation

In the present investigation a nominally round turbulent air jet is formed normal to an orifice in a flat plate. An important feature of the jet is that it is formed without net mass injection by an oscillatory flow that is acoustically induced near the edge of the orifice. As in larger-scale geometries (e.g., Ingard and Labate [5]) the jet is synthesized by a train of vortex rings. Each vortex is formed during the half cycle of the acoustic wavetrain when the orifice velocity is in the streamwise direction and is advected away from the plate under its self-induced velocity. The vortices are

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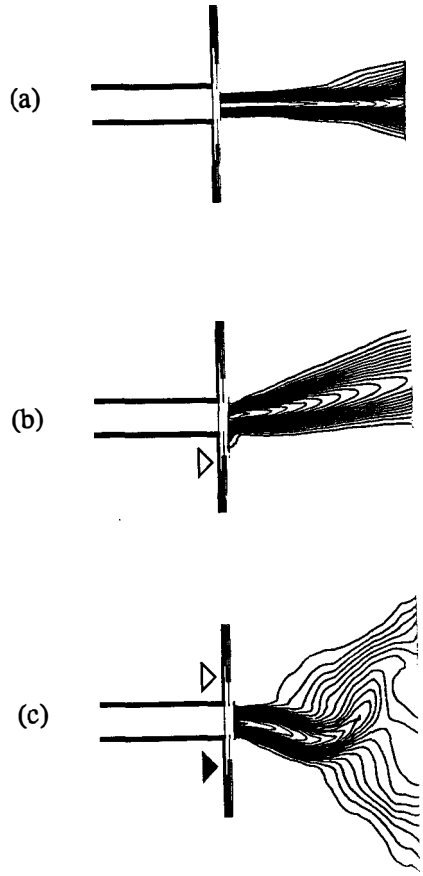


Figure 1 Measured contours of streamwise velocity for a rectangular air jet with dimensions 7.62 cm x 1.27 cm. (U_{exit} = 6.5 m/s).

formed at the excitation frequency and the jet is synthesized by their interaction downstream from the orifice. In the present work, the acoustic excitation is provided by a diaphragm that is mounted at the bottom of a sealed shallow cylindrical cavity under the orifice plate as described below.

Fabrication

A cross-section of the prototype microjet in shown in Figure 2. In this design, the orifice and actuator are incorporated into the same wafer. Both electrostatic and piezoelectric drive can be used in this configuration. Although only a single jet is shown in this configuration, extension of this concept to addressable arrays of microjets is straightforward and has been realized by us.

The microjet orifice and actuator hole were anisotropically etched in the wafer as pictured in Figure 3. Starting with a high resistivity two inch <100> silicon wafer that was polished on both sides, a layer of silicon dioxide 1 micron in thickness was formed using wet thermal oxidation. On the front side a 3000 Å layer of aluminum was deposited using DC sputtering. Photolithography was then used to pattern a square orifice hole in the aluminum. This hole was designed to be 265 microns on a side. Using the

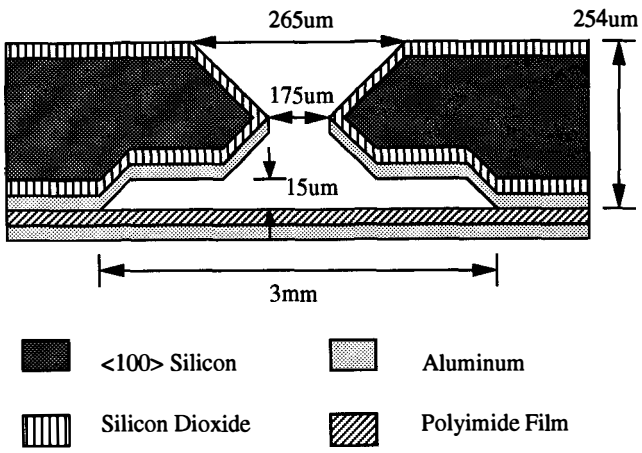


Figure 2 Cross-section of fabricated microjet.

patterned aluminum as a mask for infrared alignment, a matching orifice hole was created on the back side of the wafer using photolithography. Using the patterned silicon dioxide as an etch mask, the jet orifice was anisotropically etched using a 20% potassium hydroxide solution in water at 60 °C (Figure3b).

Photolithography was then used to pattern a square actuator hole in the back-side oxide 3 mm on a side (Figure 3c). This hole was anisotropically etched to a depth of 15 microns using a timed etch consisting of 20% potassium hydroxide in water at 50 °C (Figure 3d). The wafer was then re-oxidized using thermal oxidation such that a layer of 2500 Å of silicon dioxide was formed in the etched region. A layer of aluminum 3000 Å in thickness was then sputtered on the back side of the wafer to act as an electrode for electrostatic actuation. A layer of polyimide film was bonded to the back side of the wafer to form the flexible actuation diaphragm. This polyimide film was then coated with a layer of 3000 Å of aluminum using DC sputtering to provide the second electrode for electrostatic actuation (Figure 3e).

For electrostatic actuation, application of voltage between the diaphragm electrode and the electrode on the back side of the wafer was used to realize diaphragm actuation. Alternatively, a ground plane below the wafer could also be used for actuation; in this case, voltage is applied between the diaphragm electrode and the ground plane. For piezoelectric actuation, the back side of the wafer was fitted with non-vented standoffs and bonded to a commercial piezoelectric transducer. Vibration of the piezoelectric transducer caused pressure fluctuations in the transducer-actuator wafer cavity, thus realizing diaphragm actuation. Both electrostatic and piezoelectric actuation were successful in the creation of microjets. In the case of piezoelectric actuation, the jet output could be modified by the electrostatically actuatable diaphragm. In the jet measurements described below, piezoelectric actuation is used.

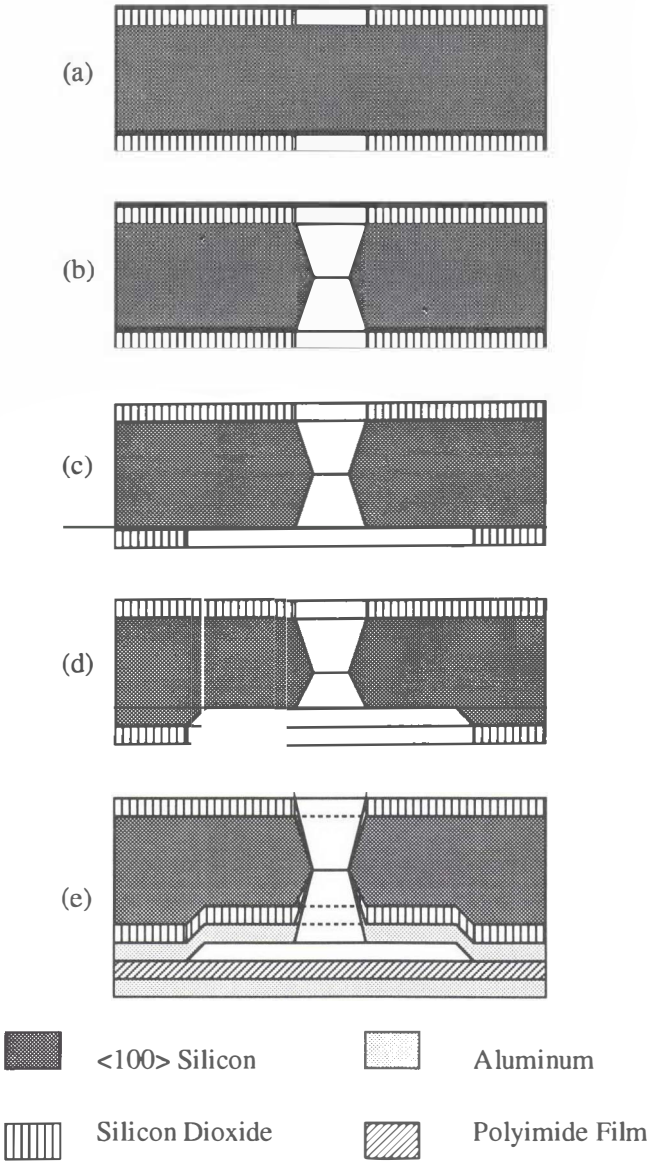


Figure 3 Microjet fabrication sequence.
a) Prior to etching orifice
b) After etching orifice
c) Prior to etching actuator cavity
d) After etching cavity
e) After membrane attachment and metallization

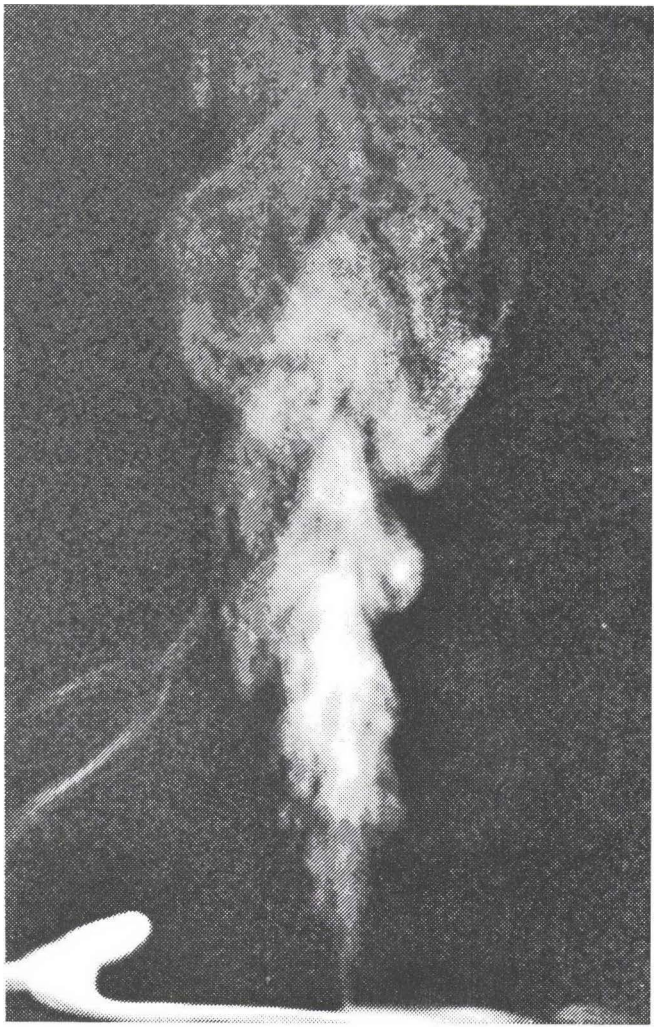


Figure 4 Smoke visualization of operational microjet.

Initial Measurement of the Jet Flow

In all experiments reported here, the piezoelectric driver is operated at its nominal 1.3 kHz resonance frequency in its first axisymmetric mode of vibration using a laboratory function generator and a high voltage (max. 120 Vrms) broad band DC amplifier (the present measurements were taken at an excitation level of 42 Vrms). Figure 4 is a smoke visualization photograph of the jet where the smoke is injected radially near the orifice edge. The field of view measures 89 mm in the streamwise (x) direction and thus corresponds to nearly 500 jet diameters. The jet appears to become turbulent at or near the orifice, and spreads almost linearly with streamwise distance. Large coherent vortical structures are apparent in the far field of the jet. The Reynolds number of the jet based on the centerline velocity and its width at x/D = 15 (see velocity profiles in Figure 5) is approximately 1400.

The streamwise velocity component was measured using a miniature total pressure tube having inner and outer diameters of 212 μm and 340 μm, respectively. Radial profiles of the time-averaged streamwise velocity were measured at x/D = 15, 25, and 35 using a three-axis traversing mechanism and are shown in Figure 5. Despite the obvious limitations in spatial resolution and sensor interference, these profiles suggest that the jet is reasonably symmetric about its centerline, and furthermore, when these profiles are plotted in the usual similarity coordinates (Figure 5b), they appear to collapse reasonably well on top of each other, suggesting that the jet is self-similar. The self-similarity of the flow is further supported by the linear decay of the centerline velocity with streamwise distance for x/D > 15 as shown in Figure 6 (a line with a slope of -1 is shown for reference). Measurements at x/D < 15 are included for reference as an indication of the the spatial limitations of the sensor.

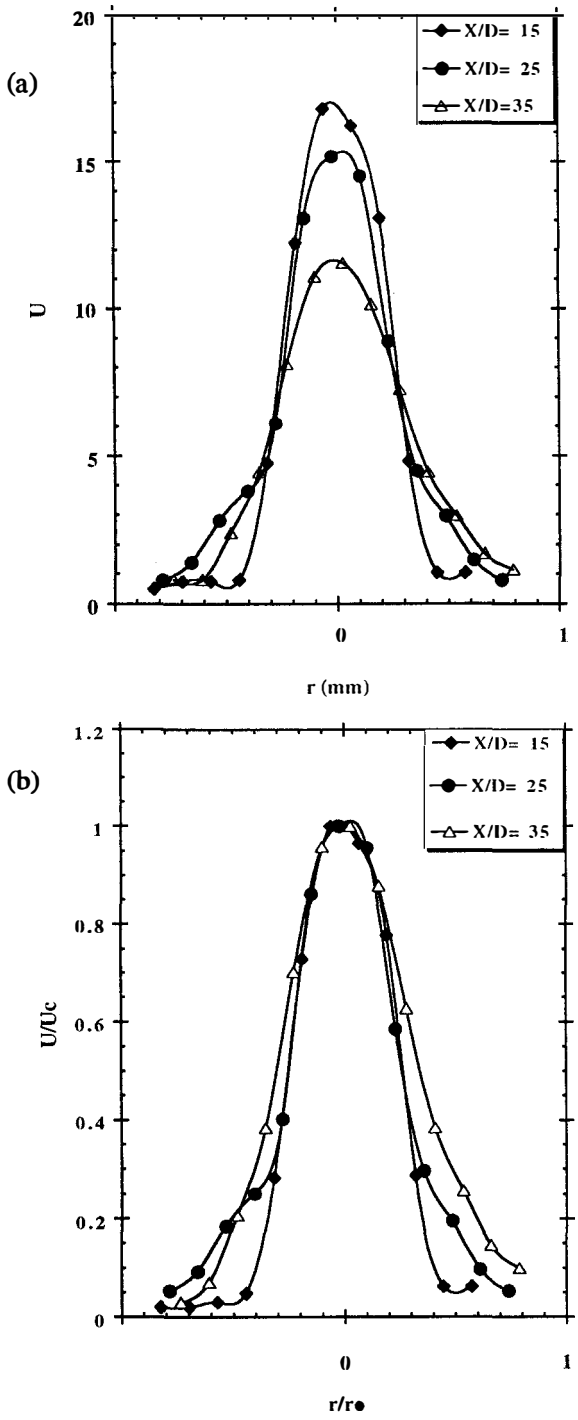


Figure 5 Measured time-averaged streamwise velocity of the microjet.
a) Plotted using radial coordinates (U in m/s).
b) Plotted using similarity variables.

Finally, a spectrum of the centerline (streamwise) velocity was measured at x/D = 40 using a conventional miniature hot wire sensor and is shown in Figure 7. The spectral component at the excitation frequency and its higher harmonics shows that an oscillatory component of the fluid velocity is prominent even in the far field of the jet. It is noteworthy that the spectrum is virtually

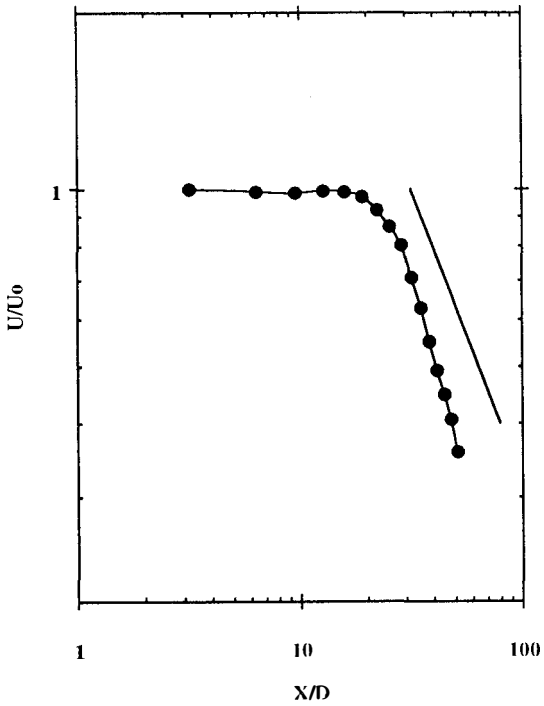


Figure 6 Measured centerline streamwise velocity decay of microjet.

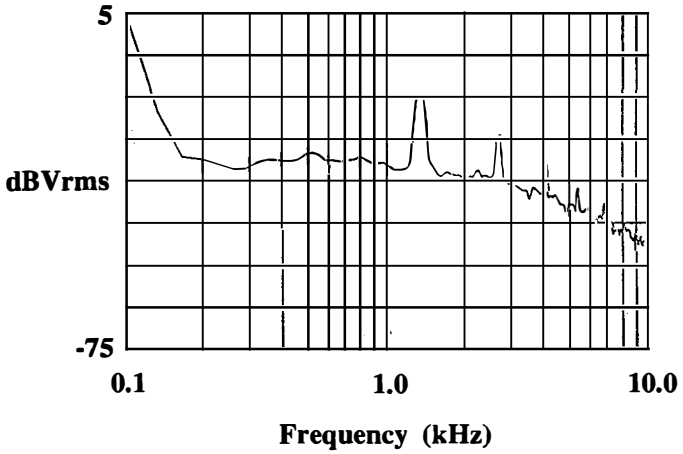


Figure 7 Frequency spectrum of microjet measured at x/D = 40.

featureless below 1000 Hz and that no subharmonics of the excitation frequency are present.

Conclusions

Micromachined jets and jet arrays have been realized using silicon micromachining techniques. These jets can be driven piezoelectrically or electrostatically and can produce velocities on the order of 17 m/s within 15 orifice diameters, and remain established up to 500 diameters or more. Each jet is produced with no mass injection at the edge of an orifice by a vibrating diaphragm and is synthesized by the interaction of a train of vortex

rings. Although these jets are formed by the strong oscillatory motions, they appear to become self similar within fifteen orifice diameter from the actuator surface. These microjets show great promise as vehicles by which macro-scale effects can be influenced by microactuators.

Acknowledgments

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