# Development of a Piezoelectric Supersonic Microactuator for Broadband Flow Control

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**Abstract**
An actively deforming converging-diverging nozzle was designed using a compact piezoelectric stack actuator coupled to a micronozzle. The nozzle was designed to achieve a Mach number of 1.5 and 20%-30% change in Mach number during piezoelectric actuation. The design of the actuator is given and preliminary data is presented. A set of key parameters were identified and used to guide the design of the actuator. Supersonic flow was achieved as illustrated using micro- schlieren techniques to quantify the flow field. The new actuator is expected to provide a route towards compact broadband pulsed microjet actuation for a broad class of aerospace flow control surfaces.

**Keywords: flow control, actuator, piezo, supersonic nozzle**

## 1 Introduction

Pulsed and active control of boundary layer flow of aerospace structures has been a very active topic in recent years. The need in this area stems from the increase in applications that require more efficient means of aerodynamic performance. The operation of aircraft could be improved by the control of flow separation over structures like airfoils or compressor blades and by effectively controlling flow oscillations when dealing with high-speed flows of supersonic jets or cavity flows. There is a clear need for robust actuators that can actively mitigate undesirable flow characteristics over a broad regime that include both subsonic and supersonic vehicles.

Two main issues ensue when considering undesirable flow characteristics; the transition from laminar to turbulent flow and unwanted noise from air acoustics. Currently the answer to these flow issues has stemmed from research on active and passive control of the boundary layer flow. Passive actuation techniques such as micro vortex generators or passive resonance tubes have shown some promise, but work in limited operating ranges [1,2]. Advances in active control have proved to provide for more robustness over a broader range of flow conditions. Active control of flow can also be broken up into two categories; open and closed loop control. Closed loop control requires a feedback loop which effects the control signal, and open loop control contains no feedback to modify the control signal [2].

Three types of active control systems prominent in recent research concern steady mass flow, pulsed mass flow, or zero net mass flow. Steady mass flow systems such as steady flow microjets are readily integrated into various aircraft structures due to their size and ability to reduce undesirable vortices [3]. However, varying ambient flow conditions and structure geometries require different mass flow rates to achieve a desirable effect. The ability to vary mass flow motivates the need for active pulsed flow research to enhance flow control and reduce acoustic emissions [3]. Zero net mass flow, or synthetic jets, produce no net mass flow while transferring linear momentum [4]. Issues with pulsed flow actuators have arisen due to limitations with actuation forces and operating bandwidth. Also, the complex flow characteristics resulting from pulsed flow have not been fully understood but are believed to increase overall efficiency by maintaining flow separation control while reducing mass flux.

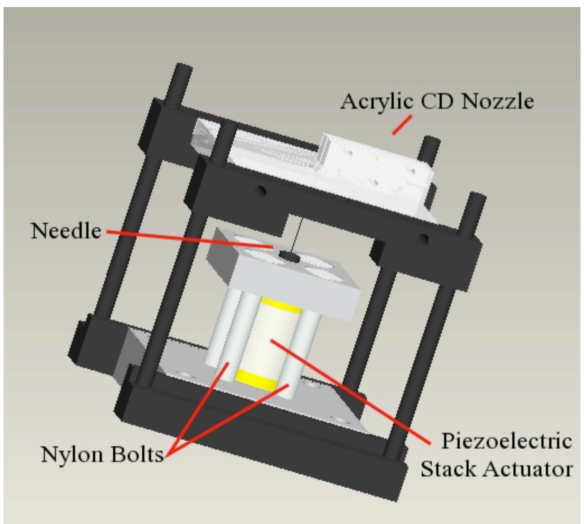
These questions and issues provide the motivation for the development and design of a piezoelectric supersonic microactuator. The initial design of a microactuator which combines the effects of a converging diverging nozzle to produce supersonic flow with the solid state actuation of a piezoelectric stack actuator to obtain pulsed flow by controlling the throat area of the nozzle. Also, the attributes of closed loop control are to be considered to enhance broadband actuation and control flow diversity [2]. It is the combination of these attributes which produce this revolutionary design. The novel design and manufacture of the first generation piezoelectric microactuator is described. The first stages of testing have commenced in order to characterize the displacement of the stack actuator assembly and study the exiting micro-nozzle flow. The initial results provide for the advancement of future generation designs which are also discussed.

## 2 Device Design

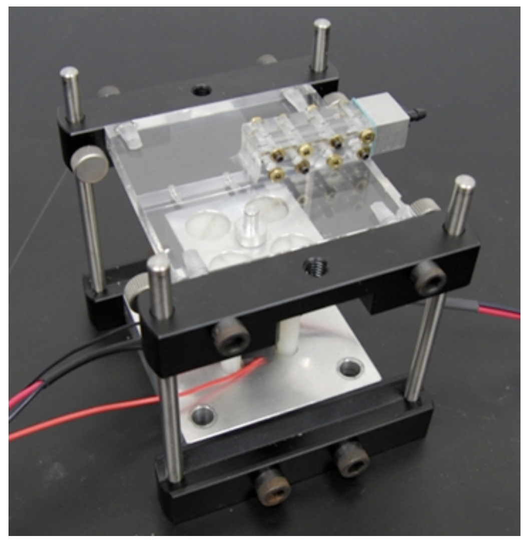
### 2.1 Micro-actuator design

A converging diverging nozzle is commonly used to produce supersonic and steady flow at its exit. In our design, the CD nozzle design is coupled with a broadband piezoceramic stack actuator to create a simple, active supersonic microjet actuator which produces pulsed flow. Piezoelectric ceramics are known for their intrinsic electromechanical coupling and high bandwidth actuation from an applied electric field. By applying the precision and high frequency deformation of a piezoceramic stack actuator to the nozzle throat area (A*), at fixed exit area, a shape change occurs which results in a change in the exiting supersonic flow based on fundamental fluid dynamics.

The A* actuator system is devised of two main parts; the piezoelectric ceramic stack actuator and the converging diverging nozzle. The goal of combining these two components is to provide an adaptive supersonic microjet. The piezoelectric actuator allows for active control and tunable frequency over a broad bandwidth (~1 Hz to 1 kHz). The CD nozzle allows for supersonic jet flow at the microjet orifice. A change in exiting jet flow occurs by actively controlling the throat area of the nozzle near the exit area. The CD nozzle is coupled to the actuator using a needle to precisely control the throat area as shown in Figure 1 and 2.




(a)



(b)

**Fig. 1:** 3D prototype rendering of A* actuator and (b) actual assembly

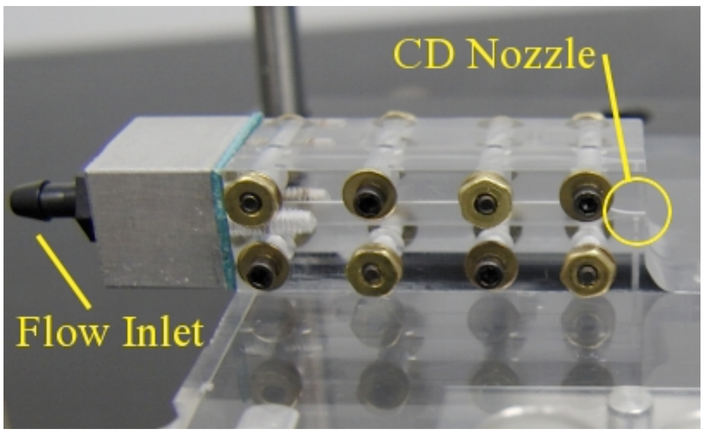
As shown in Figure 1, the first generation actuator is comprised of a piezoelectric ceramic stack actuator that is fixed at the base and an acrylic nozzle is located above the actuator which is also fixed to the base. A needle is attached to the top plate of the stack actuator to transmit force to the nozzle's throat. The initial actuator design has focused on ease of implementation and future designs will incorporate size and weight optimization for integration into aircraft structures. This is discussed in more detail in section 5.

The stack actuator was purchased from Kinetic Ceramics and produces a blocked force of 10 kN and free displacement of 20 microns at 1000 volts based on the supplier data. The design utilizes four nylon screws to fix a plate to the top of the piezoelectric stack to ensure compression during operating to avoid microfracture and increase the piezoelectric response. Based on previous experiments, the nylon polymer deforms with the stack without any significant reduction in stack actuator deformation (18-19 microns). The needle mounted to the top plate is a type 304 stainless steel dispensing needle with an outer diameter of 304 microns.

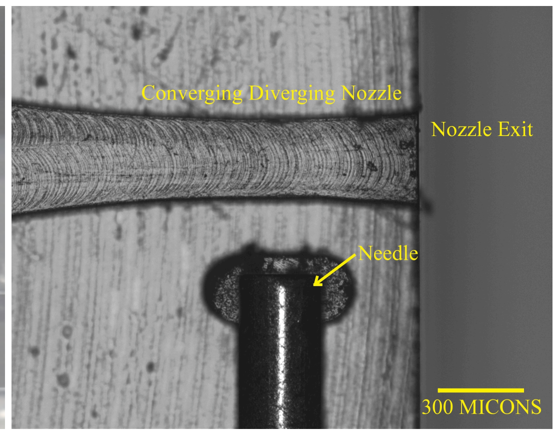
The converging diverging nozzle is CNC machined out of cast acrylic. Acrylic was chosen due to its optical clarity for flow visualization and elastic behavior. COMSOL finite element modeling was used to determine if the acrylic deforms at the throat with a reasonable force without cracking or causing undesirable deformation at the nozzle exit. It is noted that the needle does not come into contact with the airflow. The acrylic nozzle is machined in two mirrored halves. Due to the rectangular cross sectional area of the nozzle at the inlet, an adapter piece is also attached and sealed using a gasket to allow for incoming flow from any source.

The fabrication process for the nozzle begins with a stock piece of acrylic that must be machined into two mirrored halves. The outer dimensions are machined manually as well as the exterior mounting holes. Once the exterior shape has been finished, the nozzle face is placed facing up into a vise that holds it secure while the machine code for the nozzle and needle channels is executed on the HAAS Minimill. Once this process is complete for both sides of the nozzle, it is polished with up to 1200 grit wet sand paper and buffed until transparent.

A schematic of the CD nozzle is shown in Figure 2. The nozzle's dimensions were based on the magnitude of the change in throat area and selected by optimizing the change in momentum of the flow. A set of geometric parameters were selected that were feasible for fabrication. The nozzle was designed for an average exit Mach flow of 1.5. Using this Mach number and machining constraints, a corresponding throat width and height were chosen. The exit area dimensions were calculated by determining the critical throat area ratio based off the selected throat area. The incoming flow is allowed to become stable before entering the converging portion of the nozzle. The throat area of the nozzle is 300 microns high by 500 microns wide. The throat of the nozzle is uniform for a length of 300 microns to allow space for the needle and deformation of the acrylic. The nozzle's exit area is 351 microns high by 500 microns wide. The width of the nozzle is kept constant at 500 microns. A change in momentum of 9.60% is calculated with a change in flow from Mach 1.63 to Mach 1.34 as the throat of the nozzle deforms up and down. A channel is located 150 microns directly below the throat of the CD nozzle for the needle. The end of the channel has rounded corners to allow for adequate machine tooling space and reduce the stress concentrations that would result from sharp, rectangular corners.




(a)




(b)

**Fig. 2:** CD nozzle assembly and (b) microscopic view of the exit. The lower region is the location of the needle used to control the throat geometry via piezoelectric actuation.

The two acrylic halves of the nozzle are aligned via four dowel pins and secured together with eight bolts located above and below the nozzle. The acrylic nozzle assembly attaches to the stack actuator assembly using two optic rails. The rails provide horizontal adjustment of the acrylic nozzle for needle placement and allow the nozzle to be fixed during operation. The overall assembly was designed for the ease of testing and manipulation of the microactuator for future generation designs. The acrylic nozzle can easily be swapped or modified without any disassembly of the stack or testing equipment.

### 2.2 Nozzle Deformation

COMSOL finite element analysis was used to analyze the deformation and stress concentrations associated with the throat and needle channel geometry. The first generation design that was machined and tested incorporated a channel for the needle with a geometry equal to the profile shape of the needle. This design's aim was for ease of initial machining of the acrylic and fit testing for the needle. However, when a load was applied from the piezo stack actuator during initial testing, the throat of the nozzle fatigued too easily. The second generation design used during preliminary tests was redesigned to reduce stress concentrations at the corners of the needle channel. The second generation channel design reduced the peak stress from 15 MPa to 7.7 MPa. Another design was also analyzed and further reduced the peak stress to 2.6 MPa. This third generation design is currently being machined. The COMSOL stress and deformation analysis is shown in Figure 3.

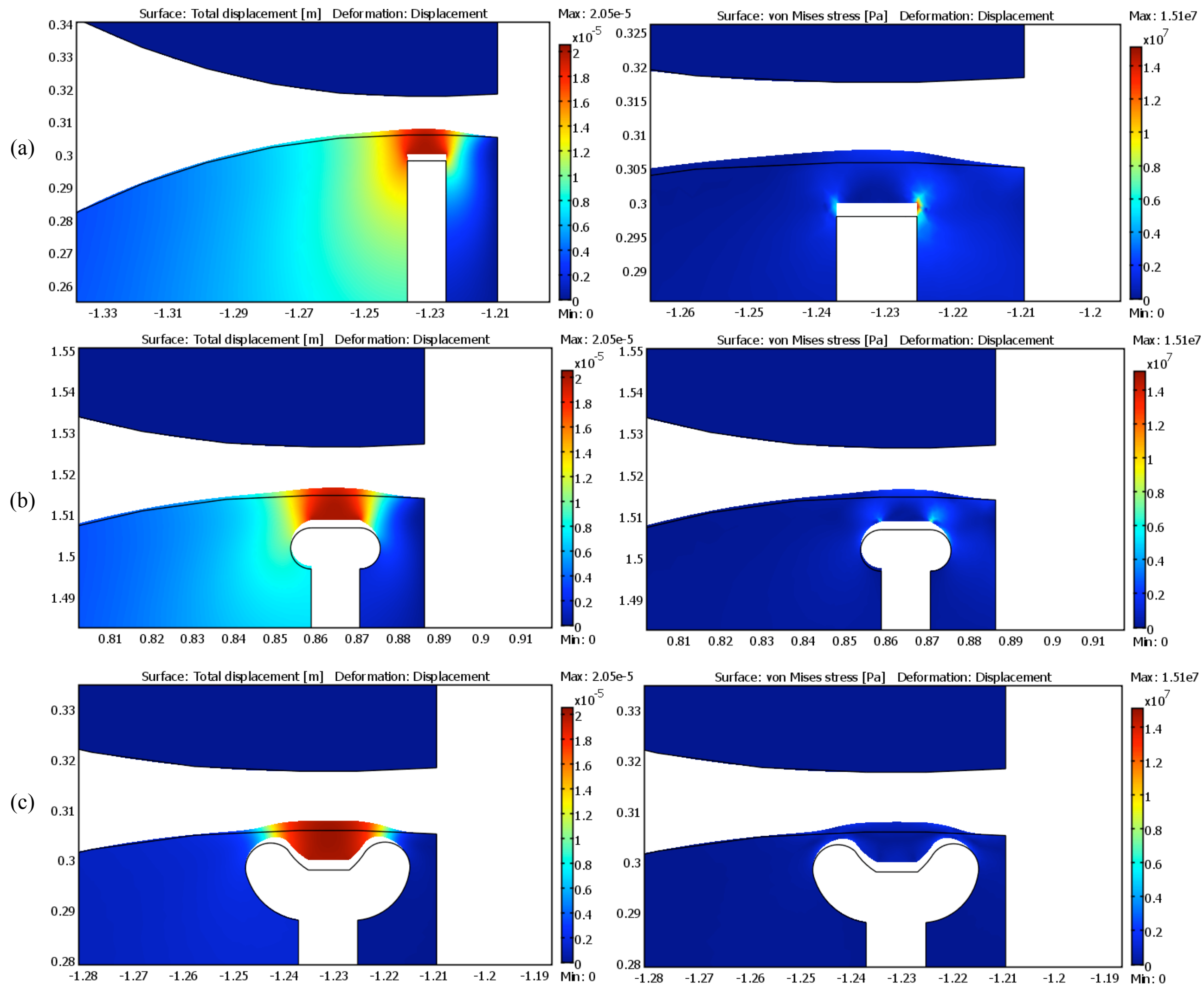



**Fig. 3** COMSOL model of CD nozzle indicating surface deformation on the left and stress concentration on the right. (a) First generation nozzle design (b) Second generation nozzle design used during mentioned testing (c) Third generation nozzle design

As mentioned earlier, the piezoelectric stack actuator can produce up to 10 kN of blocked force. Due to the small size and length of the needle, buckling due to an axial load was considered. This effect was calculated with a needle of length 0.5 inches will buckle at 150.1 N using Euler's buckling equation, $P_{cr} = \pi^2 EI/(KL^2)$, for a tube with two fixed ends. The parameters include E as modulus, I moment of inerirta, L is the needle length, and K is an effective boundary condition parameter. It should be noted that there is uncertainty in L and K since the needle is constrained by the acrylic channel. The needle can be constrained leaving less than 0.08 inches unconstrained which results in an axial load greater than 5 kN prior to buckling. The constraint therefore provides sufficient robustness to deforming the throat of the nozzle.

## 3 Experimental Implementation

### 3.1 Hardware and Setup

The experiments were performed at the Advanced Aero Propulsion Laboratory (AAPL) of Florida State University. An optical table is used to conduct flow visualization using a micro-schlieren system, and a miniature Kulite pressure transducer is to be used to measure unsteady pressure. dSpace is coupled with Matlab and Simulink to control the piezoelectric stack actuator and collect data. To power the piezoelectric actuator, a Piezomechanik 1000V/7A switching amplifier is used. Tests conducted include measurement of the stack assembly's displacement and Schlieren imaging of steady flow through the CD nozzle.

Due to the size of the A* actuator, a high magnification schlieren system with a resolution in the tens of microns was assembled at the AAPL. The micro-schlieren flow visualization setup, shown in Figure 4, includes a source strobe light, a series of high magnification achromatic lenses in line with a graded filter, and a Kodak Megaplus 1.4 camera. The Kodak camera has a CCD array resolution of 1008 by 1018 pixels. The source light was a stroboscopic white light lamp with adjustable light intensity and frequency. The nozzle's exiting flow field along with the needles movement could be measured and recorded.

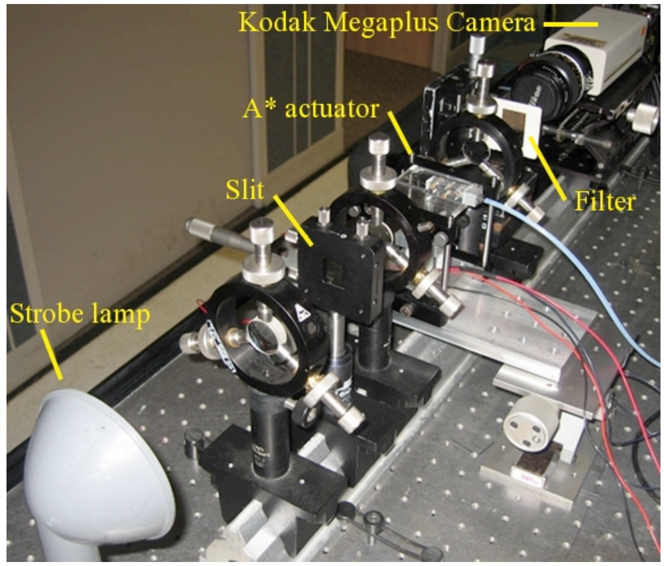


**Fig. 4** Micro-schlieren optics setup

### 3.2 Procedure

To characterize the piezoelectric stack actuator assembly, the magnitude of the deformation was measured using a Lion Precision Elite Series CPL290 capacitor probe. The stack actuator displacement was coupled with the strain measurements of an Omega 1-Axis 350 Ohm strain gauge. Due to the compact nature of the A* actuator's complete assembly, the strain gauge was implemented for future monitoring of the stack actuators motion instead of the capacitor probe.

Flow visualization tests were conducted in order to determine the flow characteristics and needle positioning of the first generation actuator. Air and carbon dioxide were used to visualize the output flow from the converging diverging nozzle. The piezoelectric stack actuator was not used during these preliminary tests. The gauge pressure of the incoming flow was monitored using an Omega inline digital pressure transducer to assess if the supplied pressure was producing the desired supersonic flow. Due to the transparency of the acrylic nozzle, it is possible to position the needle precisely using the optical setup to determine when the needle comes into contact with the end of the needle's channel. The results are discussed in more detail in section 4.2.

## 4 Experimental Results

### 4.1 Fluid flow visualization

The output flow of the converging diverging nozzle was tested for the design Mach number of 1.5. The incoming pressure was set at 53.95psi (39.25psi gauge pressure) to theoretically allow air to reach this supersonic speed. The resulting flow was found to be supersonic and underexpanded. Both carbon dioxide and air were tested at this pressure. Images from the micro-schlieren flow visualization setup are shown in Figure 5.

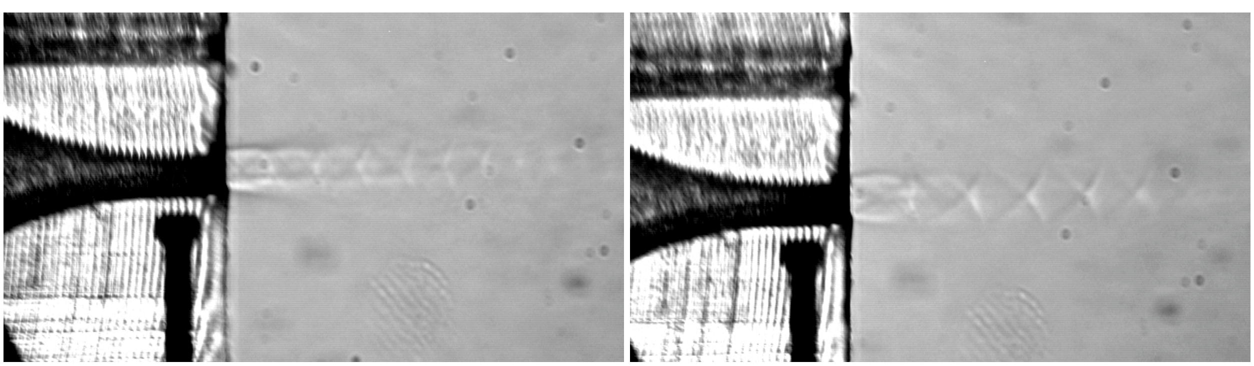

(a) (b)

**Fig. 5** Schlieren flow visualization images using (a) carbon dioxide and (b) air as the fluid

One main benefits of the acrylic is its optical clarity and the ability to view the position of the needle under magnification. The micro-schlieren optic setup allowed for proper positioning of the needle to prevent unnecessary loading prior to actuation which can lead to premature failure or fracture of the nozzle and actuator. Images of the needle under magnification from the Schlieren system are shown in Figure 6.

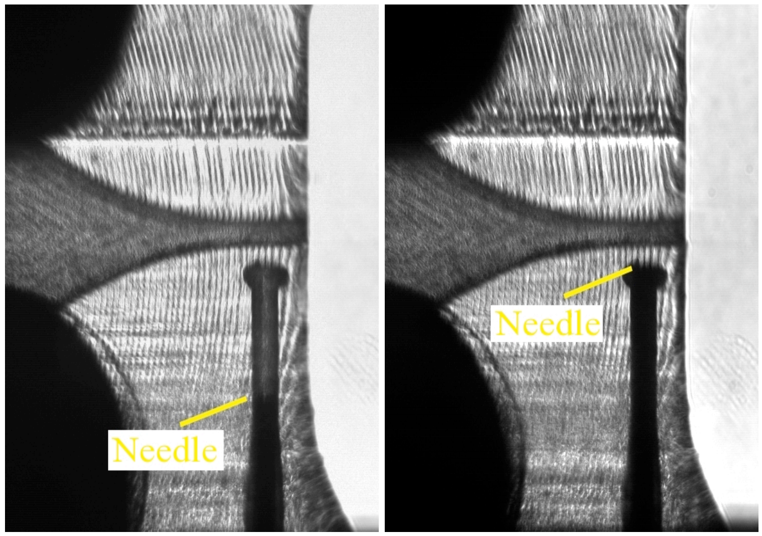



**Fig. 6** Needle location using Schlieren optical setup. The needle is not in contact with the throat in (a) and is in contact in (b)

## 5 Conclusion and Discussion

In the present research, a new pulsed supersonic microactuator was designed and fabricated. The micro nozzle produced supersonic flow at the desired reservoirs pressure. The micro-schlieren flow visualization results also demonstrate sufficient visualization of the needle / throat region which will be actively deformed to modulate the Mach number. Current work is focused on obtaining pulsed microjet actuation, review of nozzle materials to mitigate potential fracture or fatigue at the nozzle throat, and new designs that lead to more compact geometries.

The aim of future work is to miniaturize the actuator in size but maintain the performance and robustness of previous designs. The need for small lightweight pulsed flow actuators is evident in the aero-space field of research to allow for the integration of these devices in aircraft structures such as rotor blades. New piezoelectric actuators coupled with novel design and micromachining methods will be utilized to achieve this goal. The current design using two large plates and external bolts to package the system. Piezoelectric stack actuators are available in stacked ring geometries, well-known in sonar technology, which allow pre-compression by a single internal bolt. This design will provide a small platform for integrating the next generation of micro-machined nozzles for pulsed microjet testing and integration into a broad range of aerospace structures.

## 6 Acknowledgments

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