Forcing of Compressible Mixing Layers Using Laser Excitation

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I. Introduction

RECENTLY there has been much interest in the enhancement and control of supersonic mixing. This interest is driven by applications of supersonic mixing in scramjet combustion, in noise reduction for the high-speed civil transport, in thrust vectoring, and in reduction of the heat signature of high-speed aircraft. For many years, it has been known that supersonic (compressible) mixing layers have a much slower growth rate than their subsonic (incompressible) counterpart. Papamoschou and Roshko[1] correlated this decrease in growth rate by defining the convective Mach number for mixing layers with the same specific heat ratio as $M_c = (U_1 - U_c)/a_1$, where the theoretical convective velocity is given by $U_{c\,\mathrm{theoretical}} = (a_1 U_2 + a_2 U_1)/(a_1 + a_2)$. U_1 and U_2 are the high- and low-speed freestream velocities, respectively, and a is the corresponding speed of sound. This trend in growth rate has been verified by several investigators.[2–4] Note that the convective Mach number is sometimes modified to take into account recompression shocks that may be present within the shear layer at high compressibility levels.[5,6] In addition to the growth rate, the convective Mach number has been used to correlate the characteristics of large-scale, roller-type structures in the mixing layer that play an important role in entraining and mixing the two streams.[7] Clemens and Mungal[4] and Elliott et al.[8] found that, as the convective Mach number increases, the two-dimensional structures become less organized and more three dimensional, which may help to explain the decrease in growth rate.

Several investigators have shifted their attention to methods of controlling and enhancing the growth rate of supersonic mixing layers and, subsequently, supersonic jets. Gutmark et al.[7] presents a complete review of these control and enhancement techniques. These techniques have various levels of effectiveness and drawbacks. Thus, there is a continued interest in developing more flexible and controllable forcing techniques. In this regard, laser excitation is proposed as a method to enhance and possibly control the large-scale structures in compressible mixing layers.

Previously, laser excitation has been used to excite the fluid medium directly to induce flow instabilities.[9] In the present study, the laser energy is focused on the nozzle surface at the exit of the jet. This focused laser energy on the surface causes a localized thermal bump at the wall, which enhances the formation of the large-scale structures in the mixing layer.

II. Experimental Facility

Figure 1 gives a schematic of a preliminary laser excitation arrangement investigated at the Gas Dynamics and Laser Diagnostics Laboratory at Rutgers University. The laser used was a Spectra Physics GCR-230 Nd:YAG pulsed laser. By multiple Q-switching, the Nd:YAG laser can be double pulsed with time delays adjustable from 15 to 200 μs, having a pulse width of 10 ns. This pulse width effectively freezes the motion of the large-scale structures during imaging. The scattered signal marking the flow is a result of condensation particles formed from the mixing of the cold supersonic stream with the moist ambient air, a process called product formation by Clemens and Mungal.[4] Images are recorded on a Princeton Instruments 14-bit intensified charge-coupled device camera and stored on a Pentium 100 MHz personal computer, which also provides camera control and laser synchronization. The laser beam used in the excitation is formed from the back reflection off the first prism, resulting in 16.6 ± 0.2 mJ of energy for the excitation pulse. The excitation beam is focused onto the exit of the nozzle using a 250-mm-focal-length lens, resulting in a focused beam diameter on the surface of 0.62 ± 0.03 mm. The excitation beam from the initial pulse is focused on the jet exit so that the aluminum nozzle surface experiences either only slight or no ablation, suggesting surface temperatures on the order of 930 K.

The temporal surface temperature has been measured by Tsao et al.[10] when a pulsed laser is applied to heat an aluminum surface. Although they employed a slightly longer wavelength (694 nm) and pulse duration (35 ns), Tsao et al.[10] found that the thermal region on the wall heated between solid and partial melt conditions has a duration of approximately 230 ns. It would be expected that this is an upper limit for the duration of the wall heating in the present laser excitation experiment inasmuch as the pulse duration was 30% lower and the nozzle wall experiences additional cooling through forced convection with the supersonic flow.

The two converging diverging axisymmetric supersonic nozzles available for this preliminary study have an exit diameter D of 12.5 mm and exit Mach numbers of 1.36 and 2.0, resulting in convective Mach numbers of 0.63 and 0.85, respectively. A laser sheet was formed transversely through the jet so that the mixing layer could be visualized. Note that only the side of the mixing layer experiencing excitation is imaged. The first pulse from the laser provided the excitation to the jet. The corresponding image was recorded from the second laser pulse, which was delayed in time. This captures the effect that the laser excitation had on the mixing layer as it developed in time. The average images shown are based on 375 instantaneous images. Images were normalized to reduce the Gaussian intensity profile across the laser sheet. The velocity, distance, core centroid, and thickness given subsequently were calculated from the images with an uncertainty of less than one pixel in most cases.

III. Results and Discussion

Figures 2 and 3 show instantaneous and averaged images of the mixing layer formed from a Mach 1.36, perfectly expanded jet without and with laser excitation, respectively. With no laser excitation,

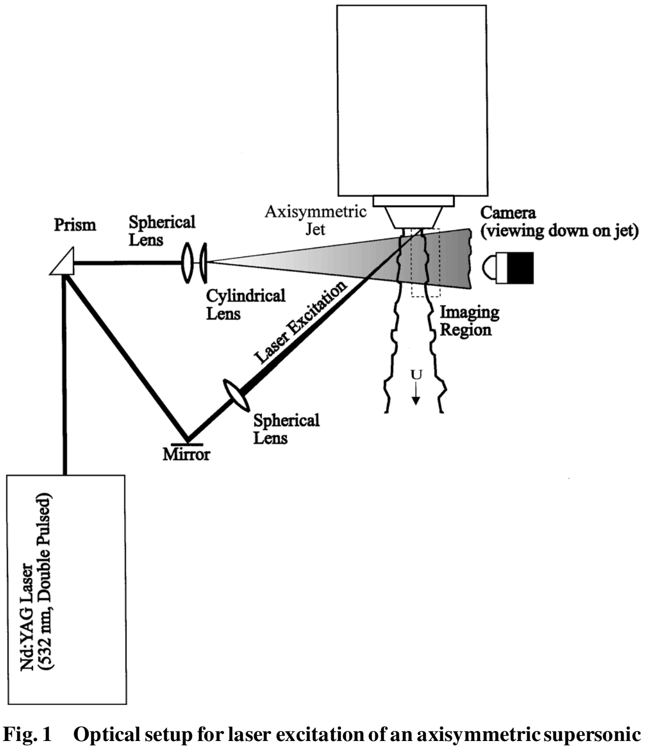

Fig. 1 Optical setup for laser excitation of an axisymmetric supersonic jet; note that the effect of the excitation from the first laser pulse is recorded in the image taken from the second delayed laser pulse.

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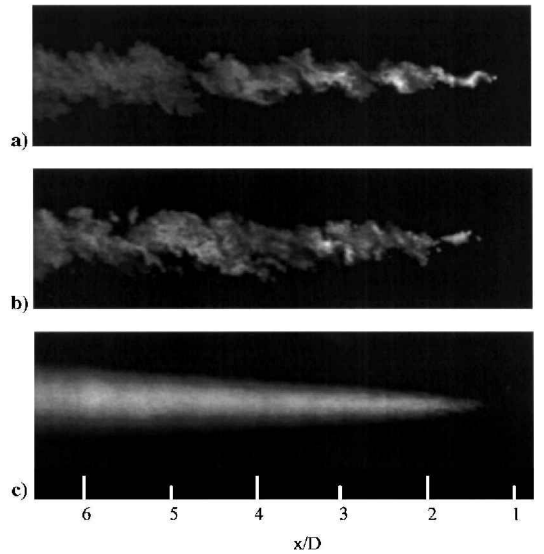

Fig. 2 Streamwise view of the mixing layer from an $M = 1.36$ axisymmetric jet without laser excitation; image c is averaged from 375 instantaneous images.

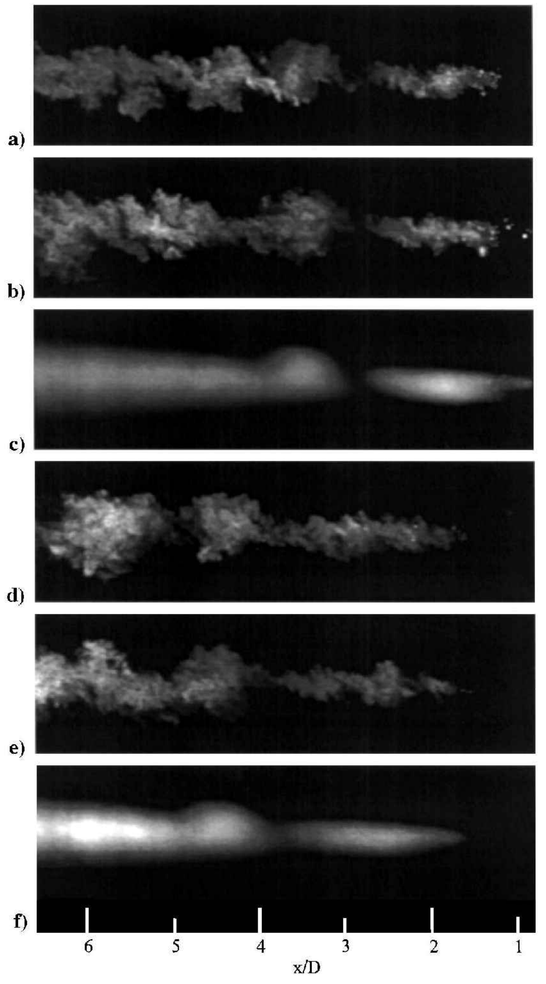

Fig. 3 Streamwise view of the mixing layer from an $M = 1.36$ axisymmetric jet with laser excitation.

the instantaneous images (Figs. 2a and 2b) show only slight indications of well-defined, roller-type structures in the mixing layer. This is an expected result, as already mentioned, because other investigators have reported that these roller-type structures are rarely seen for convective Mach numbers above 0.6 (Refs. 4 and 8). The average image illustrates a mixing layer that grows downstream with no indication of spatially stable vortices because they occur infrequently and at random locations.

Figure 3 shows instantaneous and average images of the same mixing layer ($M = 1.36$) with laser excitation. The delay time between the laser excitation pulse and the imaging pulse was 150 μs for Figs. 3a–3c and 190 μs for Figs. 3d–3f. All of the instantaneous images show a roller-type structure in a stable position in the mixing layer with a well-defined core and braid region characteristic of lower convective Mach numbers. This structure convects downstream as the delay time is increased between the excitation and imaging pulses. The differences between the appearance of the large-scale structures in the average images with (Figs. 3c and 3f) and without (Fig. 2c) laser excitation give strong evidence that the forcing scheme is effective. The thickness of the mixing layer (defined by the distance between 10% and 90% of the intensity at the shear layer center) at the structure core position is 32% larger ($\pm$4%) than the unforced case, on average, for the time delays studied. This may indicate that multiple pulses could greatly enhance the mixing layer growth rate. Spanwise images (not shown here) indicate that the effect of the excitation extends around 32% of the circumference of the jet at $x/D = 3.0$. Not only has laser excitation forced a primary roller-type structure, but a second elongated structure has been induced behind it in both cases.

With a knowledge of the time delay between the excitation pulse and the imaging pulse τ and the distance of the primary structure from the excitation point x_c, the experimental convection velocity is calculated as $U_{c(\text{measured})} = x_c/\tau$. The measured convective velocities for the core and braid region of the roller-type structure were found to be 297 m/s and 244, respectively, with an uncertainty of $\pm$4 m/s. The theoretical convective velocity is 217 ± 5 m/s. The theoretical convective velocity is lower than the measured convective velocity, which has been reported by other investigators when the convective Mach number is high and the mixing layer is between subsonic and supersonic freestreams.[11] The theoretical convective Mach number is closest to the convective velocity of the braid region,

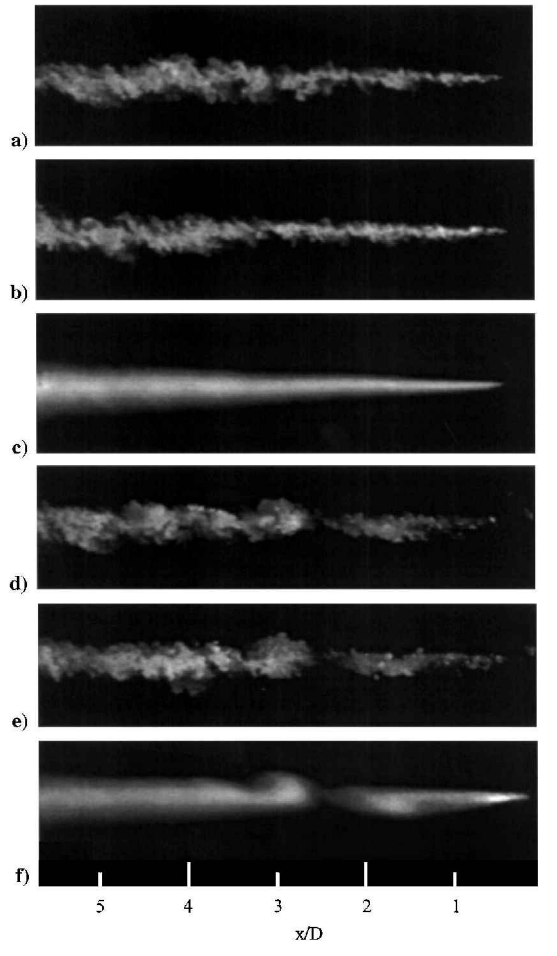

Fig. 4 Streamwise view of the mixing layer from an $M = 2.0$ axisymmetric jet without and with laser excitation.

where there is a pressure peak as seen in the theoretical model of the roller-type structure and recent experimental measurements.[12] This supports the idea that the excitation causes a pressure peak in the mixing layer that induces the roller-type structure.

Instantaneous and average images were also taken for a Mach 2 jet ($M_c = 0.85$) with no excitation (Figs. 4a–4c) and with laser excitation (Figs. 4d and 4e) having a delay time of 100 μs between the excitation and imaging pulses. For the unforced case, the decrease in mixing layer growth rate is clearly observed compared to the lower-convective-Mach-numbercase shown earlier. Also there is no indication of organized large-scale, roller-type structures. With laser excitation, however, a spatially stable, roller-type structure is observed in the instantaneous and average images with distinct core ($39 \pm 4\%$ thicker than the unforced case) and braid regions, as observed for the lower-Mach-number case. The convective velocity measured for this case is 365 m/s for the core and 309 m/s for the braid region, with an uncertainty of ± 4 m/s. Again the measured convective velocity from the braid region is closer to the theoretical convective velocity of 297 ± 5 m/s, with the measured value slightly higher as already discussed.

The forcing mechanism for the large-scale structures in the present study may be similar to wall heating used to force Tollmien–Schlichting waves in subsonic boundary layers[13] and subsequent Kelvin–Helmholtz waves in free shear layers.[14] Liepmann et al.[13] reported that the forcing of the instability can be explained by the boundary-layer momentum equation and by observing that heating the surface (for a gas) has the same effect as an adverse pressure gradient. If the temperature is large enough, this could lead to a local region of separation, which may force the large-scale structures observed in the present experiments. Note, however, that the forcing was not large enough to cause the nozzle to unstart or create strong shocks, which would have appeared in instantaneous schlieren images that were taken. Further experiments are needed, however, to confirm this explanation.

IV. Conclusion

An innovative method of controlling and forcing the creation of large roller-type structures in compressible mixing layers is presented. A laser beam from a pulsed Nd:YAG laser is focused on the nozzle exit of axisymmetric supersonic jets with Mach numbers of 1.36 and 2, resulting in convective Mach numbers of 0.63 and 0.85, respectively. Laser excitation causes a thermal bump at the wall, which induces the formation of a roller-type structure in the mixing layer. Instantaneous and phase-averaged images were taken of the mixing layer to investigate the ability to induce the large-scale structure and measure its characteristics. The convective velocities of the core and braid regions of the structure were found to be higher than the theoretical values. The thickness of the core region was found to be from 32 to 38% greater than the shear layer thickness without excitation. Future experiments will be conducted to verify the mechanism inducing the formation of the roller-type structure and to investigate other excitation beam geometries and multiple pulse forcing.

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Artificial Dissipation Schemes for Viscous Airfoil Computations

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Introduction

IT is generally accepted that, in solving the Navier–Stokes equations for practical high-Reynolds-number turbulent flows, the spatial discretization must contain some sort of numerical dissipation, either implicitly, as in upwind schemes, or explicitly, through an artificial dissipation scheme. The dissipation is required to prevent high-frequency oscillations, especially when the flowfield contains shock waves, and to provide stability. Dissipation is needed even in viscous flows because they are essentially underresolved, that is, the shortest wavelengths present in the real flow, which are limited by viscosity, are generally not resolved using practical meshes.

Several researchers have shown that the popular scalar artificial dissipation scheme[1] can be a major source of numerical error, especially in laminar boundary layers and in drag prediction.[2–4] This problem is reduced with upwind schemes and matrix dissipation.[5] However, the scalar dissipation scheme is inexpensive and easy to implement. Consequently, some researchers have proposed scalings for the scalar dissipation scheme in an attempt to reduce numerical errors. These include scalings based on local Mach number and vorticity.[6]

The purpose of this Note is to examine the effect of the artificial dissipation scheme on the prediction of lift and drag in thin-layer Navier–Stokes computations of subsonic and transonic airfoil flows. In addition to the matrix dissipation scheme of Swanson and Turkel,[5] we present and evaluate a new scaling of the scalar

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