Design of an Acoustically Excited Jet for Laser Diagnostics Development

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An acoustically excited jet facility has been designed, constructed and tested. The facility can be used for both instruction and research. The main use of this particular facility is to serve as a flow testbed for the development of laser diagnostics. The design is a simple round air jet with a speaker, amplifier and signal generator used to excite the flow into periodic vortex structures. Structures were visualized using a laser sheet for flow visualization with water droplets seeded into the flow. Preliminary results are presented showing that the flow can be excited into a variety of different flow regimes, with Strouhal numbers ranging between St = 0.423 to 1.477, and with each regime defined by the characteristics of the acoustic signal (frequency, velocity, and amplitude for example). The frequency was found to have the most noticeable effect on flow characteristics. In addition, some preliminary results obtained in the facility using a new 3-D laser imaging system are presented.

Nomenclature

D	=	Nozzle Diameter
H	=	Nozzle Height
V	=	Jet Exit Velocity
St	=	Strouhal Number
f	=	Excitation Frequency
dP	=	Change in Pressure
ρ	=	Density of air

I. Introduction

Acoustically excited jets have intrigued researchers for decades due to their easy-to-manipulate vortex structure and aesthetic qualities. Each jet has its own unique characteristics depending on the intended use of the facility. The facility presented here is used to educate students on the formation of vortex structures, along with use in a laser diagnostics laboratory as a test bed for the development of a system for 3-D laser imaging. Clifford Brown states: "jet excitation occurs when a perturbation alters the instabilities already present in the shear layer between a jet and its ambient medium."[1] The perturbation in this design is a speaker axially aligned with the exit of the jet. Focused here is the ability to excite the flow into a periodic structure, and then using a laser diagnostic system, the structure is analyzed in 2-D and 3-D states.

Excited jets have been studied over the past 35 years. One of the first groups to study acoustic jets was Crow and Champagne.[2] They used advancing Reynolds numbers to produce different types of vortex structures and studied the evolution of the structure as they moved downstream. This work was followed by Wicker and Eaton[3] who experimented with near-field vortex structure and dynamics of excited jets. Ahuja, Lepicovsky, and Burrin[4] also experimented with flow structure including inner and outer shear layers, and introduced a visualization technique similar to the technique used in this paper. Schram and Riethmuller[5] focused on vortex pairing and spacing based on nozzle diameters. Other information about acoustically excited jets includes Ho and Huerre[6], and Olsen, Rajagopalan and Antonia[7].

A common term used to describe the formation of vortical structures exiting a jet is a dimensionless number called the Strouhal number. The Strouhal number is calculated by multiplying frequency by the

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characteristic length of the system and dividing by the velocity. In this case the characteristic length is the diameter of the jet.

$$St = (f^* D)/ V \tag{1}$$

The facility designed in this paper is useful for many reasons, one is the flows produced are complex, rich flow fields that are easily altered using the acoustic signal. The facility is also economical in that it is relatively cheap to construct. This paper focuses on the design of the facility and the types of flows that can be produced. Since research has shown that it is possible to create vortex structures using acoustics, the next step is to develop a way to analyze the flow field in more detail. The design presented here is a simple axial jet using a speaker, amplifier, and signal generator to excite the flow into periodic vortex structures. In order to see the structures clearly, a high-speed digital camera was used with the facility. When the camera is set up to trigger at the same instant the function generator modulates the flow, an instantaneous image of the flow can be taken. Once the facility has satisfying results with 2-D imaging, the next step will be using a mirror to photograph the entire vortex structure and compiling the photos into a 3-D map of the flow field.

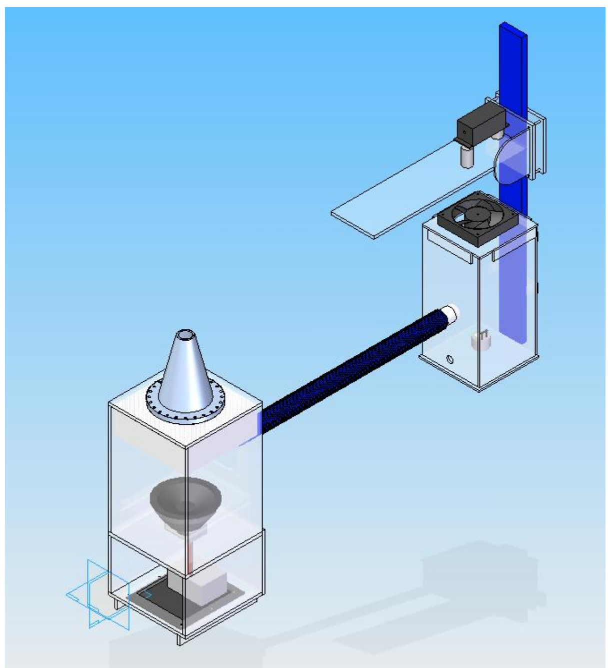


Fig. 1 - Schematic of an Acoustically Excited Facility

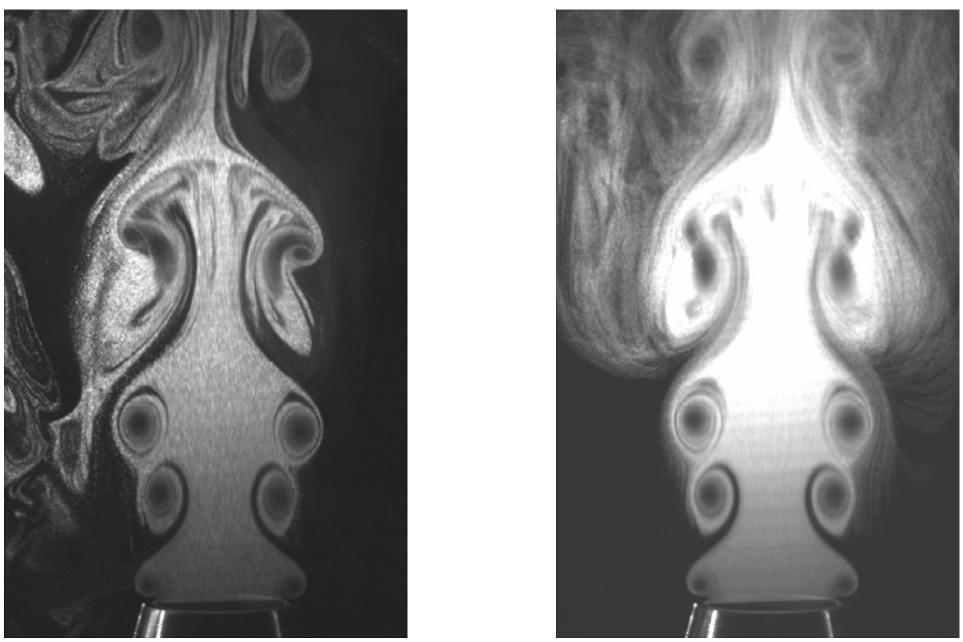
II. Design

The design goal of this facility is to design a simple apparatus (Fig. 1) that can create visible vortex structures using acoustic vibrations. This is accomplished by seeding the air with small water droplets and using the aid of a fan to blow the air though a nozzle with the diameter of D = 1.25 in and a height of H = 6.5 in. The water droplets are created using a mister that uses ultrasonic frequencies (on the order of f = 1.7 MHz) to shake molecules off the surface of a pool of water. Once the air travels through a pipe, it is ejected into a box where a stereo speaker is recessed in a 9 in x 9 in x 13 in Plexiglas case and wired to a 50-watt speaker amplifier. The speaker is axially aligned with the nozzle to ensure the flow is excited straight through the opening. Honeycomb has been placed just underneath the nozzle along with wire mesh and a circular grid plate (placed half way inside the nozzle) to ensure the flow is conditioned to be as smooth and uniform as possible. To form the vortex rings, a function generator that produces a sine wave signal is sent to the speaker to oscillate the airflow as it travels through the nozzle. This particular setup was chosen based on Parekh, Juvet, and Lee's research.[8] The facility is housed in a large (24 in x 36 in) Plexiglas chamber to prevent the jet from being exposed to cross-flow from drafts in the room.

III. Flow Visualization

To make the flow visible, seed particles, in this case water droplets, are introduced into the flow field to mark the location of the flow as it travels in the shear layer. A Sensicam QE high-speed digital camera which produces images with a 512 x 800 resolution and a 200mW, 532nm diode pumped solid-state laser system are used to visualize the flow field exiting the nozzle of the jet. Cylindrical lenses are used to transform the beam into a planar sheet, which is then aimed through the airflow exiting the nozzle. Using the digital camera, a real time image of the flow is taken and the vortex structure can then be seen in detail.

There are two types of images used in the evaluation of vortex structures. The first is a phase locked picture of the flow at an instant in time where the camera and signal to the speaker are synchronized together (Fig. 2a). The second is a phase-averaged picture (Fig. 2b), which takes a series of images and combines them into a single image to create a picture showing the areas of overlap. Using this technique the phase averaged photo can be used to assess the periodicity of the flow due to excitation and identify locations where the flow is aperiodic. These concepts are illustrated in Figure 2, where the instantaneous image looks very similar to the time averaged image. The water droplets that are seeded into the flow are contained in the core of the jet, so as the vortices are formed it is only the core flow that can be seen. The vortices produced are actually vortex rings that circle the periphery of the nozzle exit. As Fig. 2b shows the sets of vortices are stable structures, so the vortices will appear in the same position at any time, based on the synchronization of the camera and the facility. This also means that if the facility is tuned into the same conditions as the initial figures then the same set of vortices will be formed.



a) **b)**

Fig. 2 – a) Instantaneous and b) Average image of the acoustically excited jet with f=40Hz, V=5.5 ft/s and St = .744

IV. Experimental Results

A. Velocity profile

A pressure transducer was used to measure the total pressure across the nozzle lip for a baseline flow condition (i.e. no acoustic excitation). The flow velocity was then calculated using Equation 2. Figure 3 is the velocity profile for the facility. As Fig. 3 shows, the velocity is nearly constant across the main portion of the nozzle. When the pressure probe reaches the sides of the nozzle wall, the velocity begins to drop. This is likely due to the boundary layer forming on the inside of the nozzle wall. The jet centerline velocity for this case was V = 10.78 ft/s, which is the maximum velocity this facility can produce.

$$V = ((2*dP)/\rho_{air})^{1/2} \tag{2}$$

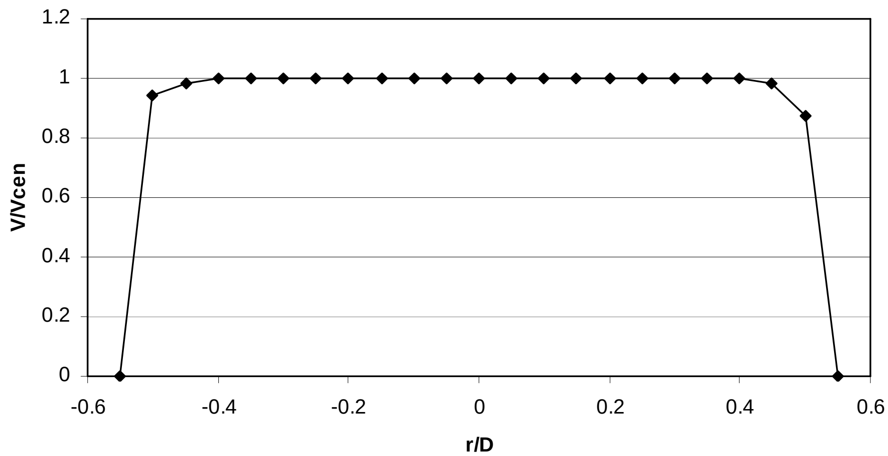
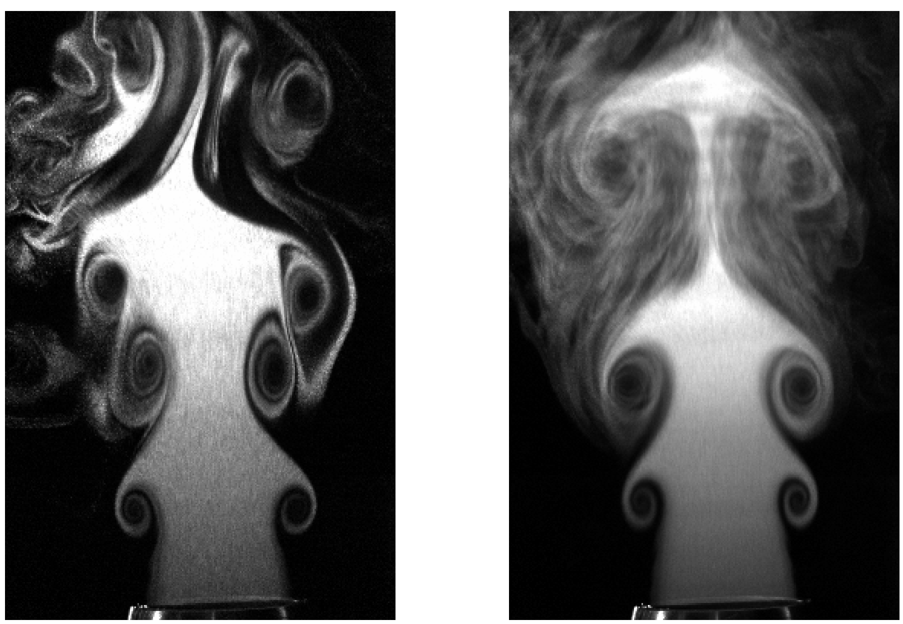


Fig. 3 – Maximum Velocity Profile

B. Flow Regimes

The observed flow fields were found to fall into different flow regimes based on the Strouhal number of the excited jet. The experiment was conducted by taking a set of starting images with the frequency at 30 Hz and the velocity at 5.5 ft/s, this computes to a Strouhal number of St = 0.738 (Figures 4a and b). Subsequent cases were compared to these photos to show the effects of changing the characteristics (frequency, amplitude, and velocity) of the flow. All the images were taken from the same distance away, which is approximately 12 inches.



a) b)

Fig. 4 – a) Instantaneous and b) Average image of the acoustically excited jet with f=30Hz, V = 5.5 ft/s, St = 0.738

Figure 4 shows there are two distinct types of structures. In Figure 4a, the middle two pairs of vortex rings are beginning to absorb each other as they flow downstream, this is called vortex paring.[7] Figure 4 also shows that as the vortical structures move downstream the rings become larger. This is possibly due to the shear layer expanding as the jet moves downstream. Yet, as can be seen in Figure 4b, the averaged image shows that the general structure has only the two bottom vortex rings in stable positions. A possible explanation for the two different structures is instability in the vortex dynamics. Another possible reason is the camera could be capturing the image at a moment when the vortex rings are undergoing a transition, whose timing is not as precise as the excitation.

Fig. 5 – Instantaneous image of the acoustically excited jet with f = 50Hz, V = 5.5 ft/s, St = 0.931

Figure 5 shows the effect of changing the frequency of the vortical structures in the flow field. By increasing the frequency to 50Hz but leaving the velocity at 5.5 ft/s, the Strouhal number is increased to St = 0.931. As can be seen above, Figure 5 shows a structure that has four distinct vortex rings visible. Compared to Figure 4a, the structures are different, although there is a coupled pair of vortex rings that seem to be interfering with each other at the top of the structure. Also, the vortex rings in Figure 5 are notably smaller, and the rings at the bottom form closer together than Figure 4. A reason for the closer distances and greater number of vortices is the higher frequency. A more rapid pulse causes the vortices to form quicker and in faster succession. Also, the reason for the coupled vortex rings rotating about a central point is due to a vortex rings moving downstream. As the ring slows down, other rings catch up to the previous vortex ring and begin to interfere with each other.

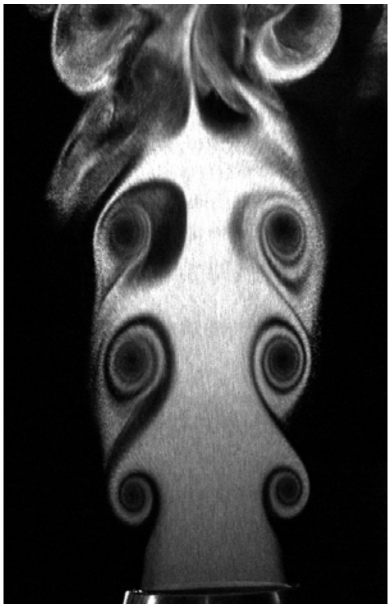
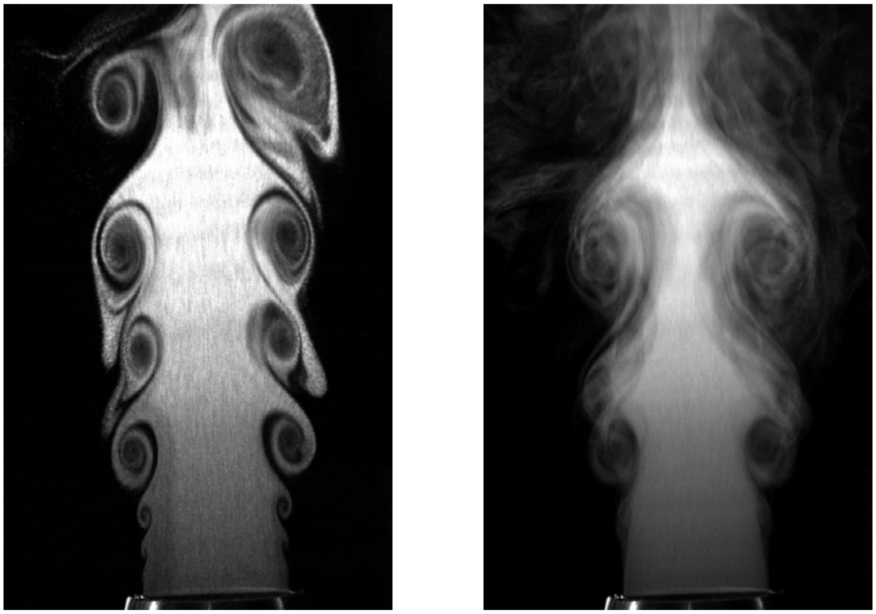


Fig. 6 Instantaneous image of the acoustically excited jet with f=30Hz, V = 5.5 ft/s, St = 0.738

Figure 6 shows the effects of changing the amplitude of the vortical structures in the flow field. Changing the amplitude changes the voltage traveling to the amplifier, which in turn changes the power output to the speaker. Since the Strouhal number only accounts for the frequency, diameter, and velocity, the Strouhal number remains the same for this example as the case shown in Fig. 4. In Figure 6 the structure does closely resemble that of the initial case, except, there is an added vortex ring at the top that is not seen in the original case. This indicates that the increased amplitude provides additional stability for the growth of structures at longer distances downstream.



a) **b)**

Fig. 7 – a) Instantaneous and b) Average image of the acoustically excited jet with f=30Hz, V = 7.3 ft/s, St = 0.426

Figures 7a and b show the effect of changing the velocity of the facility and the effect it causes to the vortical structure. While leaving the frequency and amplitude the same as Figure 4, the velocity was changed from 5.5 ft/s to 7.3 ft/s. In changing this, Figures 7a and b show that the structure is different from the original. The instantaneous image shows many vortices of changing size, but the average image shows that the flow is not as periodic with the position of vortices varying from one image to the next. The randomness of Figure 7b could be contributed to the velocity being too high for the structure to be stable.

An experiment has been started using extremely high Strouhal numbers of *St* = 8.70 to determine the effective frequency range of the facility, to compare naturally excited flow with forced excited flow. Initial results indicate that the effective range is approximately *f* = 4 Hz to 250 Hz at minimum nozzle velocity. More experiments will be conducted to incorporate other velocity ranges.

C. Strouhal Number Similarities

As stated before the Strouhal number is a dimensionless number used to relate the frequency, velocity, and diameter of the system to the flow produced by an exhausted jet. As stated in the above section it is possible for the Strouhal number to be duplicated for the same characteristics of a flow structure with different frequencies and different velocities. Figure 8 below shows a correlation between two Strouhal numbers of the same magnitude, but the frequency and velocity are changed.

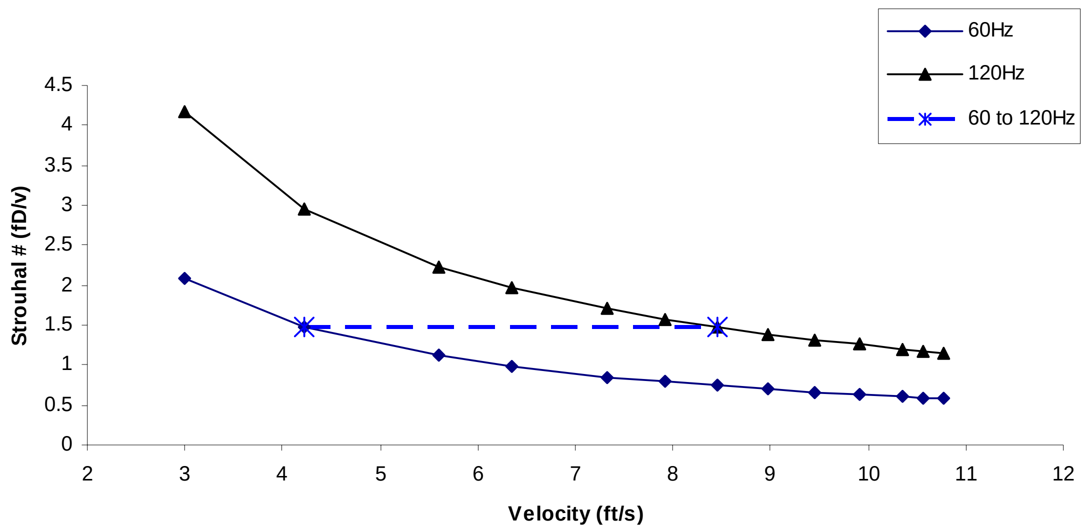


Fig. 8 - Strouhal Number Vs Velocity

The dashed line in Figure 8 shows a Strouhal number of St = 1.477 is duplicated for both the 60 Hz and 120 Hz plot lines at corresponding velocities of *V* = 4.22 and 8.45 ft/s. Since the Strouhal number defines the characteristics of the flow, then the flow fields for these frequencies and velocities should look similar. All the photos were taken at the same distance from the view port, which is approximately 12 inches.

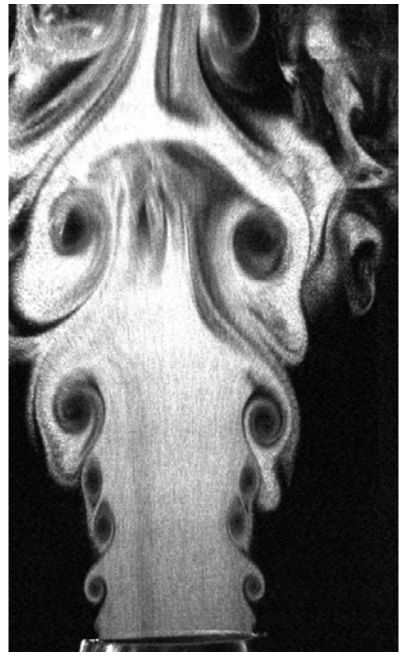


Fig. 9 – f = 60Hz,V = 4.22 ft/s **Fig. 10 – f = 120Hz, V = 8.45 ft/s**

Instantaneous Images for a Strouhal Number of St = 1.477

Figure 9 is an image taken when the frequency was set at 60 Hz and the velocity set at 4.22 ft/s. Using Equation 1 gives a Strouhal number of St = 1.477. As the figures show there are vortices at the nozzle lip that are relatively stable with respect to the averaged image (not shown).

Figure 10 above is a vortex structure that was photographed when the frequency was 120 Hz and the velocity was at 8.45 ft/s. This setup also equates to a Strouhal number of St = 1.477, in which Figure 10 shows that the vortex structure, in general, resembles the structure in Figure 9. A noticeable difference between the two sets of images is that in Figure 10 as the vortex rings move downstream of the nozzle exit, the rings grow larger. Based on these figures, preliminary results show that if the frequency and velocity are increased or decreased by identical magnitudes then the vortex structures will resemble each other. More research is needed to prove this concept for a larger range of frequencies and velocities.

V. Conclusions/Future Work

The main purpose of this facility is to aid in the development of a 3-D laser diagnostic system. This facility is a low-speed, acoustically excited jet with the capability to produce periodic vortex structures for a variety of velocities, and frequencies. The facility designed is of low cost to produce, and is reliable to produce the same vortical structure at any given time. The most efficient way to produce different vortex structures is by changing the frequency, although changing the velocity or amplitude will produce the same effect.

The next step for this facility is to help develop a system for 3-D diagnostics. Being able to see these structures in 3-D would provide a wealth of data that can better describe the structures than any set of 2-D images can. A new diagnostic capability is being developed at ALDL which uses a custom-built pulse burst laser in conjunction with a high-speed scanning mirror and high-speed camera to take 3-D images of the flows. A continuous-wave solid-state diode laser is sliced into 68 pulses, which can be adjusted from 20 to 350 ns, and is then amplified by three solid-state Nd:YAG amplifiers. After converting the fundamental laser output of 1064 nm (infrared) to 532 nm (green), the beam is reflected off of a galvanometric scanning mirror capable of an angular velocity of over 100,000 deg/sec, fast enough to scan the 68 pulses across a flow field in a total time of 136 us. At this speed, low-speed flows are essentially stationary throughout the sweep. Using a high-speed camera capable of taking 68 images at 500,000 frames per second, and synchronizing it with the pulse burst laser, a separate picture is taken for each laser pulse. Using MATLAB and Tecplot to visualize the results, a complete 3D image can be assembled. Below, Figure 11 is initial 3-D images that have been produced.

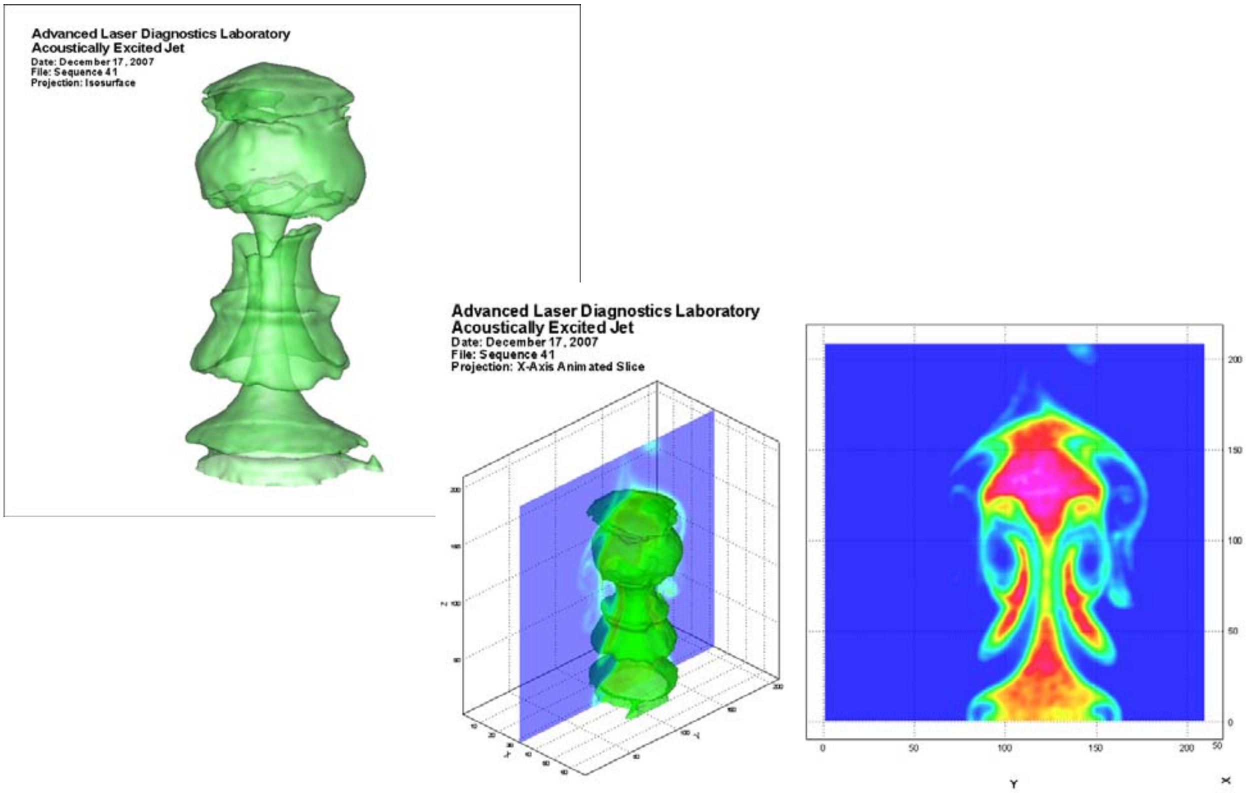


Fig. 11 – Initial 3-D Laser Images

Acknowledgements

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