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OPTICAL PROPAGATION THROUGH A TURBULENT JET

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Abstract

A fast optical tomography system has been used to investigate a heated round jet acoustically excited in axisymmetric and helical modes. This flow diagnostic reveals the development and interaction of large-scale vortices in the near-field region of the jet. In a complementary experimental study of prediction-based adaptive optics, Linear Stochastic Estimation of optical beam deflection produced by the jet has been used in an open-loop control system. A piezoelectric steering mirror was controlled to minimize beam deflection based on temperature inputs. The results indicate that a multi-aperture adaptive-optic control system may be based on multi-point temperature measurements.

Approach

Aero-optics refers to the effect of turbulent fluctuations on optical propagation through shear flows. In collaboration with the Air Force Phillips Laboratory, we have studied the effect of large-scale (or coherent) structure on optical propagation through a low-Reynolds-number round jet. The experiments are carried out at the Phillips Lab in collaboration with the AeroOptics working group led by Dr. Lenore McMackin (see separate report in this volume). We have developed an experimental turbulent jet facility at the Phillips Lab in which flow and optical parameters can be measured simultaneously. The Fast Optical Tomography of Turbulent Organized Structures (FOTTOS) system was employed as well as a newly-developed steering mirror control system for propagation of a thin beam through the jet.

The subsonic heated round jet facility at the Phillips Lab was previously described by Truman et al. (1996). The jet nozzle protrudes upward through an optical bench which supports the optical tomography and beam deflection equipment. The air jet is heated 5 to 15C above ambient to produce index of refraction fluctuations while buoyancy effects are negligible. The centerline jet velocity U_{CL}=8 m/s and nozzle exit diameter D=12.7 mm (0.5 in) yield $Re_D=U_{CL}D/\nu=5100$. The nozzle is moved vertically to place the optical measurement plane (fixed on the optical bench) at different streamwise locations in the jet flow. Acoustic excitation is provided by eight small speakers mounted flush with the nozzle exit plane (Sapayo & Truman, 1997).

<u>Optical Tomography.</u> The FOTTOS optical tomography system is described by Dr. McMackin in this volume and in McMackin et al. (1997). Eight one-dimensional Hartmann sensors, each consisting of a laser source, lenslet array and CCD camera, are arranged around the circumference of the jet flow. There are 64 lenslets in each linear array which is oriented perpendicular to the jet axis. Tomographic reconstruction produces

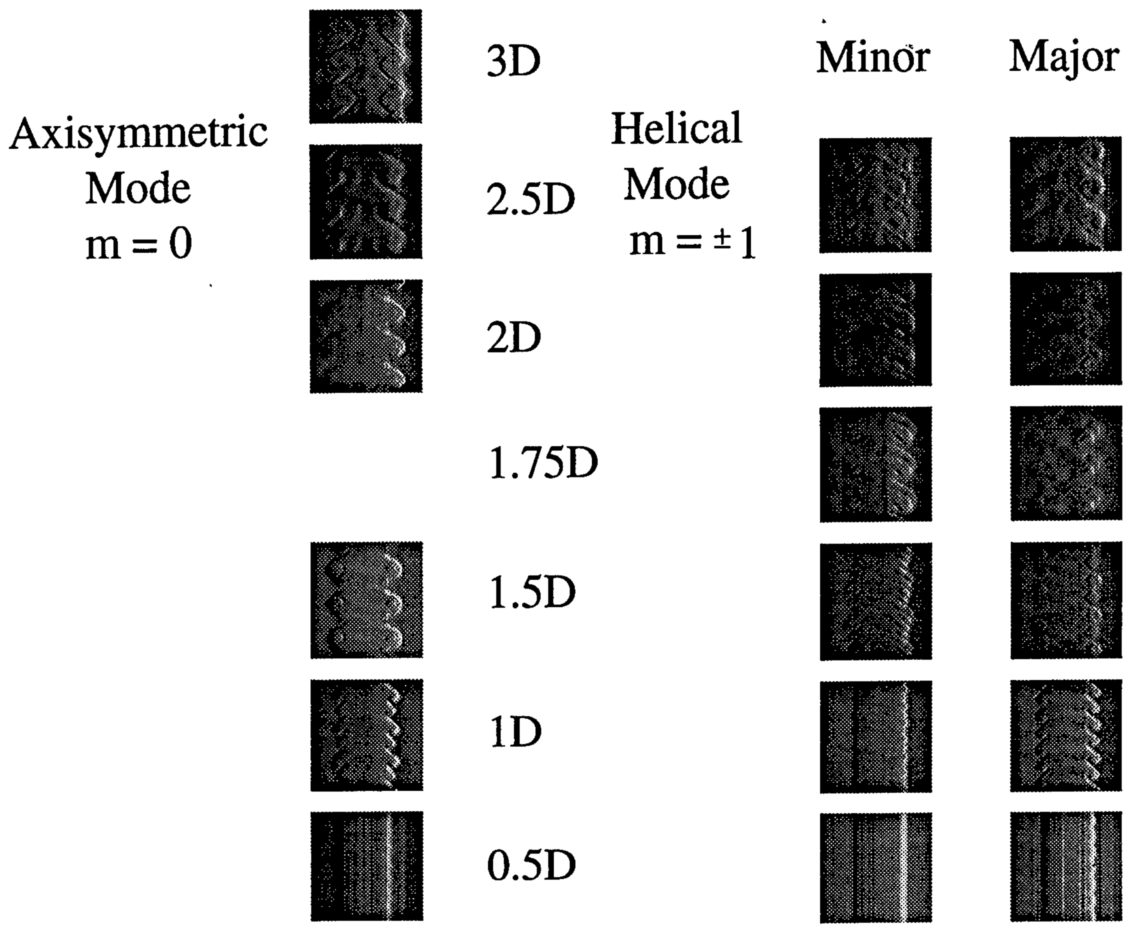

Figure 1. Hartmann sensor views of heated jet.

two-dimensional temperature distributions at the streamwise position of the optical measurement plane. The Hartmann sensor data and tomographic slices are collected at 5 kHz. The spatial resolution of the Hartmann views is the width of each lenslet, about 0.5 mm, while that of the tomographic reconstructions is 1.4 mm.

Optical Beam Deflection. A thin laser beam propagated through the jet has been used to study flow dynamics through beam deflections produced by temperature gradients. After passing through the heated jet, the beam is focused on a lateral effects detector (LED) to measure its deflection, termed jitter or tilt. Anemometer probes as well as the beam lie on the center plane of the flow; only streamwise deflections are considered here. Linear Stochastic Estimation (LSE) has been used to predict beam deflection (a path integral quantity) based on up to 4 point measurements of temperature (Luna et al., 1997).

LSE is a simple yet powerful technique for approximating conditional averages of correlations between turbulent quantities (Adrian et al. 1989). The LSE is formed from two-point spatial or temporal correlations between the quantities of interest, here temperature and beam deflection. The LSE of a turbulent shear flow gives a remarkably good reproduction of the large-scale structure (e.g., Bonnet et al., 1994). According to

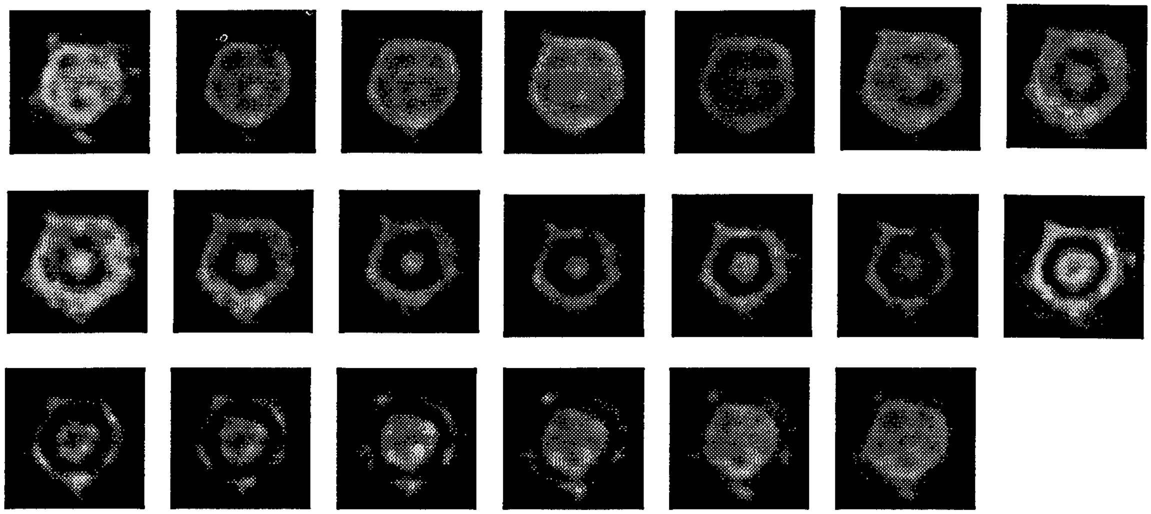

Figure 2. Temperature distribution at 2.5D during one full cycle in axisymmetric mode.

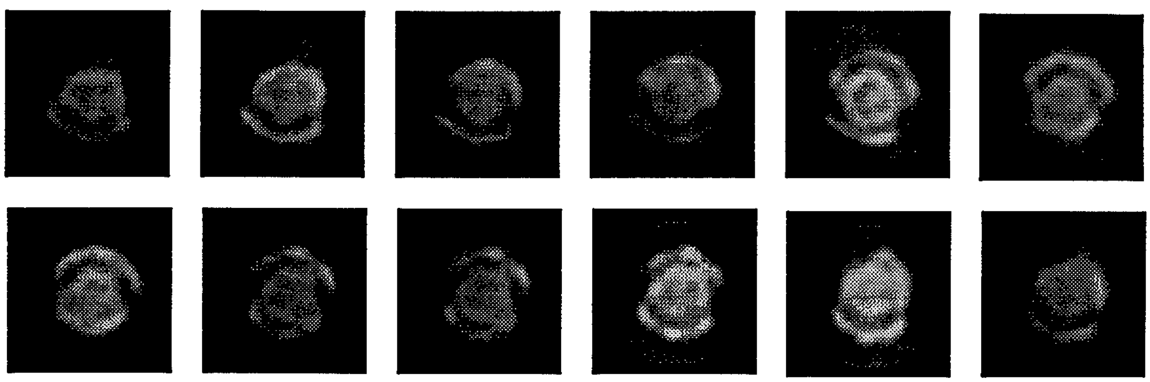

Figure 3. Temperature distribution at 1.5D during one full cycle in $m = \pm 1$ helical mode.

Adrian et al. (1989), the "unconditional spatial correlations have imbedded within them the structures of the conditional fields."

Progress/Results

Axisymmetric and Helical Jet Modes. Understanding the development of helical modes in the jet is important in that control of the large structures can have a significant impact on mixing and noise production. Thus far, the first helical mode ($m=\pm1$) has been studied; higher-order modes will also be investigated. The jet was excited at 530 Hz, the frequency determined in previous studies to excite the jet column mode for axisymmetric modal forcing. Anemometry results and further tomographic results are presented in Sapayo & Truman (1997). Fig. 1 shows Hartmann sensor views for both the axisymmetric and helical modes. For the latter, two views corresponding to projections normal to the minor and major axes of the elliptical structure are shown. Each view contains 64 time slices at a fixed streamwise location shown sequentially in time from top to bottom. [Note that these views are not two-dimensional spatial projections through the

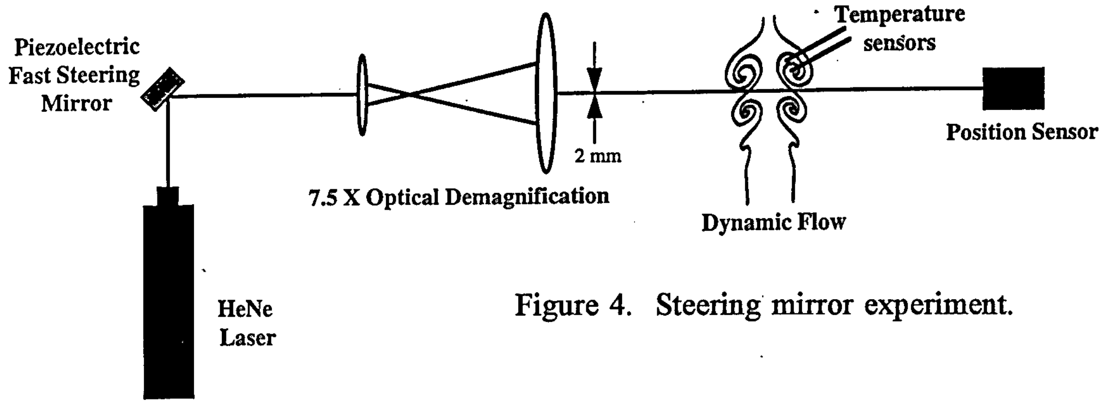

Figure 4. Steering mirror experiment.

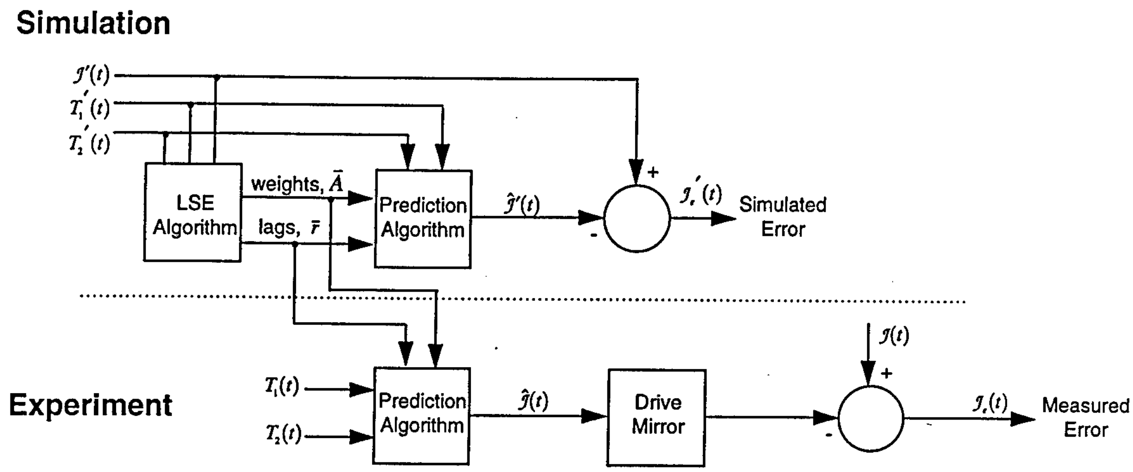

Figure 5. Steering mirror control system.

flow.] With 530 Hz forcing and 5 kHz data acquisition rate, each view shows 7 full cycles of vortex formation before the first pairing. These grey-scale images show deflections on one side of the jet as light and deflections on the other side of the jet with the opposite sign as dark.

For the axisymmetric mode, the alternating inner and outer ring vortices (1D and 1.5D) have paired by 2D. The large ring vortex which results from this pairing is evident in Fig. 2 in temperature distributions at 2.5D from the tomographic reconstruction. These images collected at 5 kHz begin at the upper left, proceed across to the right and then down to the next row. The azimuthal mode m=5 is also clearly evident in these grey-scale images, in which light corresponds to heated air and dark corresponds to cold ambient air.

The elliptical structure in the helical mode can be seen in Fig. 1. Evidence of the helical vortical structure appears in the major-axis view where each large lobe of the vortex trails that on the opposite side of the jet (1D and above). In the minor-axis view, the multiple streaks at 1.5D result from inclined vortex filaments connecting the large lobes. Tomographic images in Fig. 3 clearly show the large lobes alternating in time and streamwise location.

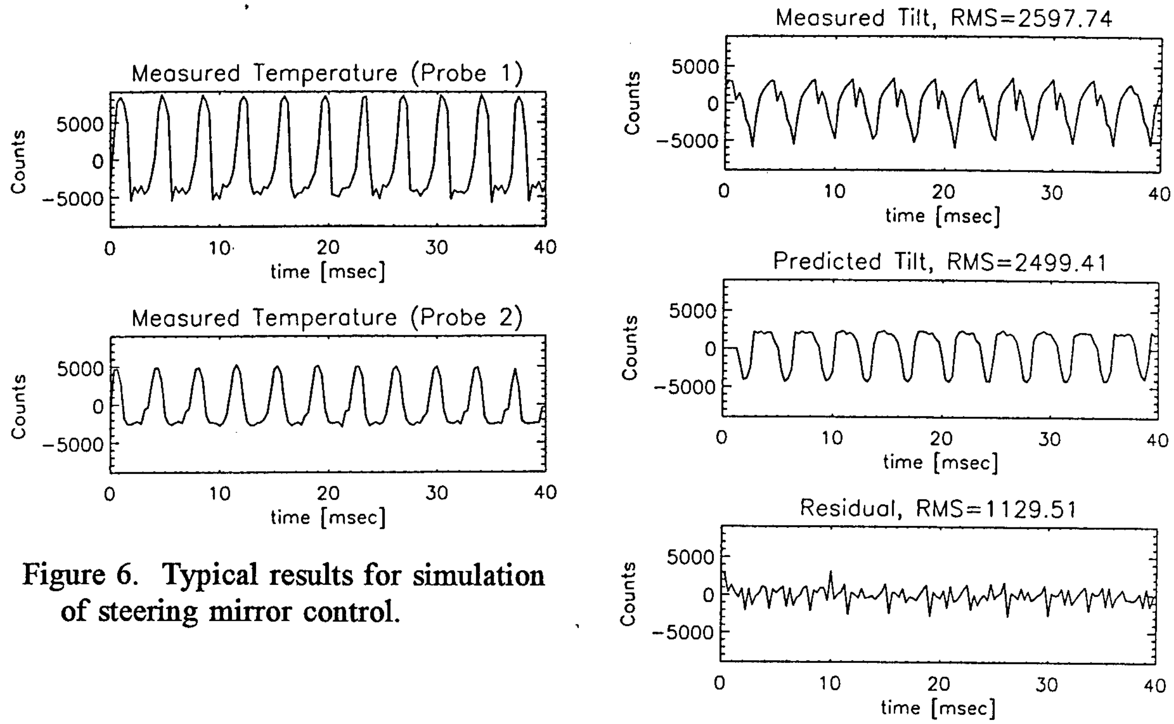

Figure 6. Typical results for simulation of steering mirror control.

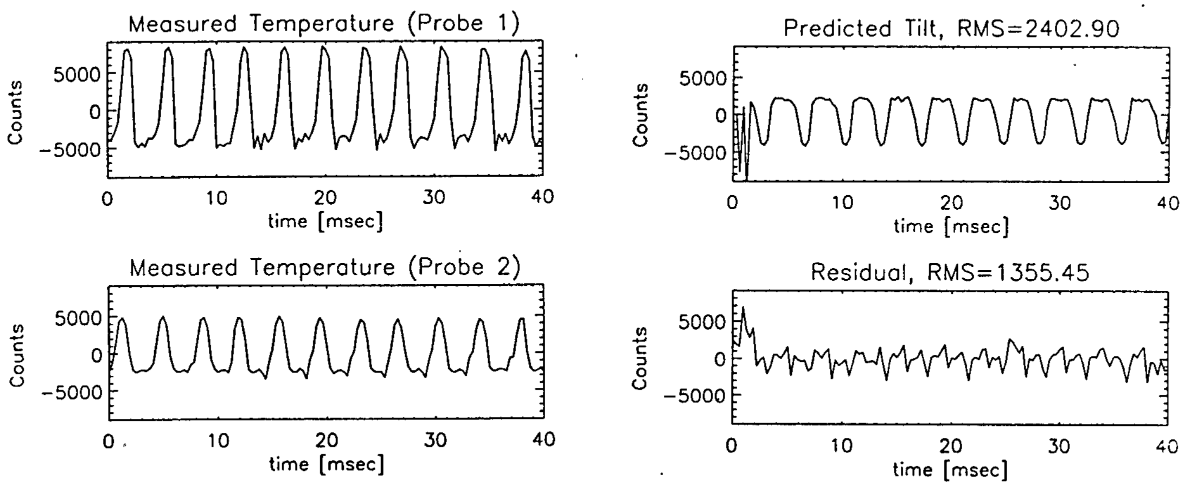

Figure 7. Typical results for experimental steering mirror control.

Open-Loop Control of Beam Deflection. A schematic of the steering mirror experiment is shown in Fig. 4; the mirror counteracts deflections imposed by the heated jet flow to minimize beam deflection (or tilt) detected by the position sensor. A time lag between each temperature measurement and the mirror movement was needed to compute the estimate of deflection produced by the flow. These time lags (which define the LSE reference points) were selected using the novel two-step procedure of Luna et al. (1997). Fig. 5 shows the simulation procedure (or "training") used to compute the weights and time lags for the LSE prediction of jitter for representative data, and the subsequent experimental implementation. Results are presented for the same flow conditions discussed above at the 2D streamwise location. Fig. 6 shows results for the simulation using a 2-point LSE. The residual, the difference between the measured and predicted tilt, is the expected LED measurement when mirror control is initiated. For an ensemble of data sets, 59% reduction in RMS tilt was achieved. Fig. 7 presents one set of experimental results; for an ensemble of data sets, 41% reduction in RMS tilt was obtained. The difference is attributed to imprecise control of mirror position and limited mirror frequency response. When a 4-point LSE using two probes was implemented, simulations produced a 65% reduction in RMS tilt while experiments achieved a 54% decrease. We continue to study the selection of the LSE reference points, both in positioning temperature probes and in selecting time lags. Dr. McMackin's report herein discusses the extension of these ideas to multiple-aperture adaptive optics control systems. Multi-point measurements provided by tomography or PIV provide the means to predict and adaptively control the effects of turbulence on optical imaging or propagation.

Interactions/Transitions

Prof. Truman and students working at the Air Force Phillips Laboratory, Albuquerque, participate in the AeroOptics working group headed by Dr. Lenore McMackin, along with Dr. Ron Hugo, of the Airborne Laser (ABL) program. Currently the group is developing smart sensor capabilities for optical diagnostics.

Acknowledgment/Disclaimer

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