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6. AUTHOR(S)

PROFESSOR DOUGLAS R. SMITH

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF WYOMING
1862 LAND GRANT INSTITUTION
P.O. BOX 3295

LARAMINE, WY 82071-3295

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
801 NORTH RANDOLPH STREET
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The PIV instrumentation was requested to support two AFOSR-funded research projects. The first project is entitled Hybrid Control of Turbulent jets" (Grant No. F49620-00-1-0255). The hybrid approach combines both passive and active control techniques to enhance the mixing characteristics of a turbulent jet flow. The second project is entitled A Study of the Formation and Scaling of a Synthetic Jet" (Grant No. F49620-01-1-0301). This project is examining the internal and external flow-fields in a synthetic jet actuator and aims at developing scaling laws and design rules for these actuators.

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1 Equipment Purchased

The requested funds were used to purchase and install a particle image velocimetry (PIV) system with stereoscopic capability at the University of Wyoming.

Particle image velocimetry is a technique for obtaining quantitative velocity information over an extended region, typically a plane, in a moving fluid. The principle underlying the PIV technique is relatively simple and straightforward. The fluid motion of interest is seeded with small tracer particles, which follow the fluid motion. Using two short-duration pulses of laser light for illumination, two successive images of the particle positions within the fluid are recorded. Particle image displacements from one image to the next are used to find the displacement vectors of the particles in the fluid. A displacement vector is then converted into a velocity vector by dividing into it the time interval between the images. Typically, the time interval between images is very small (<1 msec), resulting in small displacements, and necessitating a high-resolution camera.

In a stereoscopic PIV system, two cameras view the illuminated particles from two different vantage points, and consequently give two slightly different particle displacement vector fields. The principle of parallax is then employed to extract particle displacements out of the plane of the laser sheet. Here, the laser sheet is oriented perpendicular to the prevailing flow direction. The out-of-plane displacements may then be used to correct for perspective error in the in-plane displacements, and the final output is a two-dimensional map of three-component velocity vectors.

The system purchased with the awarded funds was manufactured by Lavision Incorporated. Prior to the selection of this system, vendor bids were sought from three PIV system manufacturers. Note that worldwide, there are four respected manufacturers of such a system. On-site demonstrations were given by two of the manufacturers, and the principal investigator also worked with one of the systems while undertaking a summer research fellowship at the U.S. Air Force Academy. Based upon these evaluations, the Lavision system was chosen as the best fit to the expected requirements of the system.

During the bidding process, the specifications of the PIV system were revised from including 8-bit, 1 Mpixel cameras to 12-bit, 4 Mpixel cameras. The increased bit resolution expands the capabilities of the system to permit quantitative assessments of flow visualization pictures by mapping gray-scale values to seed concentration levels. The increased pixel resolution of the cameras increases the number of velocity point measurements in the final vector field.

In addition to the Lavision PIV system, funds from the award were used to purchase an optical table from Newport Corporation. This table has been used in the installation and alignment of the PIV system in the experimental facilities.

2 Summary of Supported Research

The PIV instrumentation was requested to support two AFOSR-funded research projects. The first project is entitled "Hybrid Control of Turbulent Jets" (Grant No. F49620-00-1-0255). The hybrid approach combines both passive and active control techniques to enhance the mixing characteristics of a turbulent jet flow. The second project is entitled "A Study of the Formation and Scaling of a Synthetic Jet" (Grant No. F49620-01-1-0301). This project is examining the internal and external flow-fields in a synthetic jet actuator and aims at developing scaling laws

and design rules for these actuators.

2.1 Hybrid Jet Control

In the first project, the hybrid technique combines passive control in the jet nozzle with active excitation of the jet shear layers at the nozzle lip to achieve a performance enhancement. In this hybrid approach, passive control is used to establish a flow that possesses an enhanced receptivity to active excitation; active control then exploits this receptivity to achieve the desired performance enhancement. In this study, swirl is used to increase the receptivity of select jet modes, and small, zero-mass-flow control jets around the perimeter of the jet exit are used to excite these modes for mixing enhancement. The immediate goal of this study is to advance current understanding of incompressible, turbulent jet flows and to build a strategy for the hybrid control of these flows. The requested 3-D PIV system will provide the detailed three-dimensional velocity fields necessary to develop a rational understanding of the turbulent jet structure and how the hybrid technique modifies this structure.

More specifically, to understand how an active flow control actuator modifies a turbulent flow requires a rational understanding of both the actuator flow characteristics and the interaction between the actuator and the turbulent flow. The flow control device employed in the hybrid control study is a synthetic jet actuator, and although a synthetic jet appears steady in the far-field, in the near-field of the actuator the flow field is unsteady, three-dimensional and characterized by large velocity fluctuations with periodic changes in sign of the primary velocity component. To accurately characterize the performance of a synthetic jet actuator requires careful phase-locked measurements near the device orifice. PIV, which can provide instantaneous snapshots of a two-dimensional velocity field, is well-suited to measurements of synthetic jet devices, and will significantly simplify the calibration and evaluation of the synthetic jet actuators.

Greater flow-field complexity is expected from the interaction between the synthetic jet actuator and the shear layer formed at the jet lip. Preliminary observations suggest that the interaction of a synthetic jet with the shear layer contains features similar to those appearing in the interaction of a steady jet with a cross-flow. The primary feature of this latter class of flows is a counter-rotating vortex pair that is formed as the jet is turned downstream and becomes aligned with the cross-flow direction. In this region of the flow, the fluid motion is strongly influenced by counter-rotating fluid motion in a plane perpendicular to the mean flow direction. A focal point of the hybrid control study is to understand how the counter-rotating structure interacts with the "naturally-occurring" large-scale turbulent structure of the jet and to develop a spatial and temporal model of the resulting flow field. To make this evaluation and to develop a model representative of the flow field, it is essential to have a detailed map of the flow-field velocities. The advantage offered by the 3-D PIV system is the ability to measure all three velocity components from which structural changes in the jet can be more readily inferred.

2.2 Synthetic Jet Formation and Scaling

The emphasis of the second study supported by this instrumentation is a series of experiments using water as the working fluid and optically-transparent synthetic jet actuator models. To fully explore the formation and scaling of a synthetic jet, the experiments will probe the interior and exterior flow-fields of a synthetic jet actuator.

This study has two broad objectives. The first objective is to advance our understanding for how to design and optimize a synthetic jet actuator for maximum jet performance. This objective is being met by investigating the basic fluid dynamics of the synthetic jet formation. In a synthetic jet actuator, a periodic train of fluid vortices is created at the exit of a small cavity. These vortices become unstable at short distances away from the cavity and ultimately breakdown to form a steady jet of fluid. The current study is investigating the roles of vortex formation and cavity geometry in determining the strength of the jet. Once complete this understanding will then be used to meet the second objective of the work, which is an understanding for how synthetic jets control a fundamental flow process. In this case, the flow process of interest is boundary layer separation. The second objective will be met through an exploration of the interaction between a synthetic jet and a turbulent boundary layer. Of particular interest here is the formation and structure of a counter-rotating vortex pair in the boundary layer downstream of the synthetic jet actuator. As discussed above with regard to the hybrid jet control study, the PIV instrumentation is particularly well-suited to this problem, as it can effectively and efficiently provide velocity field information from which flow structure can be readily extracted.