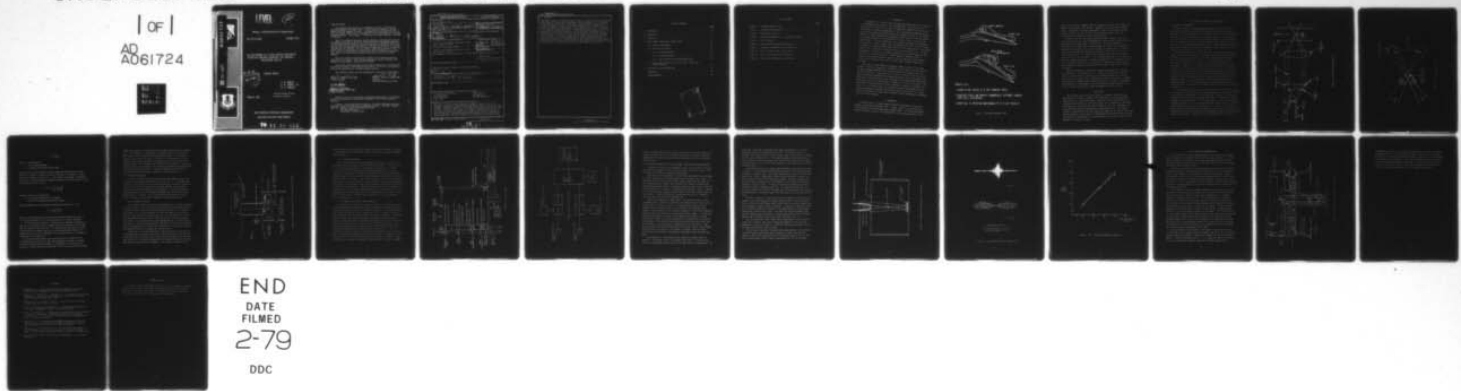


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FRANK J. SEILER RESEARCH LABORATORY

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OCTOBER 1978

THE DEVELOPMENT OF A LASER DOPPLER VELOCIMETRY
SYSTEM FOR UNSTEADY SEPARATED FLOW RESEARCH -
PRELIMINARY RESULTS

INTERIM REPORT

R. A. KADLEC
G. W. SPARKS, JR.
M. S. FRANCIS

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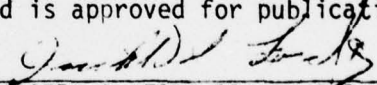
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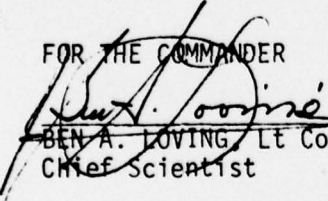
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This technical report has been reviewed and is approved for publication.


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20. Abstract

experimental research program has been to adapt a general purpose Laser Doppler Velocimetry (LDV) two velocity component system to dynamic stall experiments in the Subsonic Wind Tunnel at the USAFA. The preliminary design of the LDV system, its special constraints and the characterization of system signal and noise parameters are described. Results presented for the initial operation of the LDV system demonstrate its performance capabilities. It has been observed that accurate measurements in the wind tunnel environment can be achieved only when optical noise produced by scattered laser light from wind tunnel surfaces is minimized. While the LDV system configuration satisfies all constraints related to the USAFA Subsonic Wind Tunnel geometry and is capable of accurate velocity measurements in the two-dimensional flow field surrounding an airfoil, a reconfiguration of the system is suggested to improve optical alignment procedures and overall system signal-to-noise ratio.

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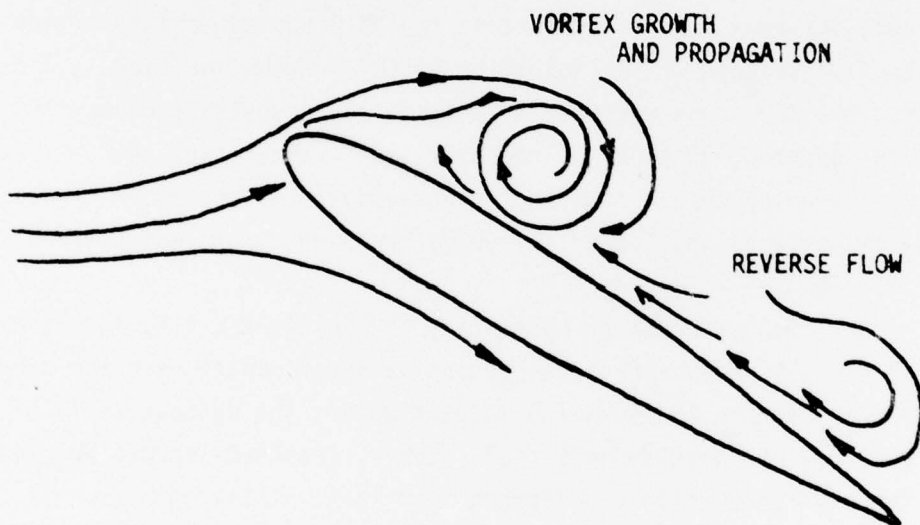
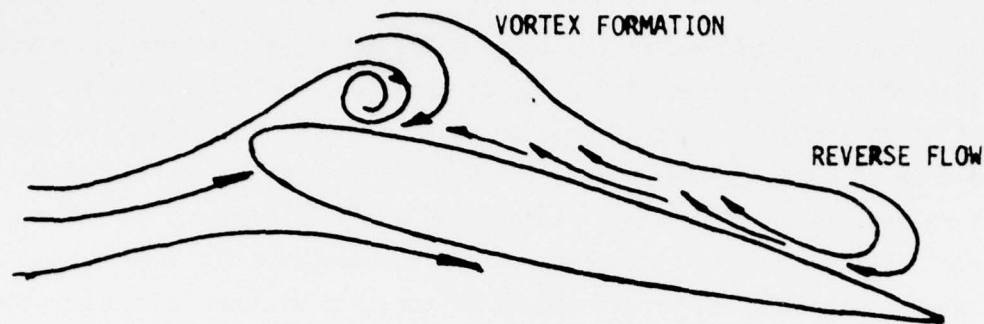
1. INTRODUCTION

The capability to predict the lift, drag, and moment acting on an airfoil is a fundamental requirement to the aerodynamicist. Solutions evolved in pursuit of this objective for a host of engineering problems form the basis of the edifice of classical aerodynamics. While considerable confidence exists when tackling steady flows where viscous and potential regions can be treated separately, little quantitative methodology is available for treating unsteady flows where separation and reattachment of the thin viscous layer near the surface occur. In some applications, this unsteady separated flow phenomenon arises when an otherwise steady flow environment about a solid object is upset by undesirable unsteady effects due either to self-induced motions of the object itself or to fluctuations or instabilities in the surrounding flow. In other applications, the device is designed to operate in an unsteady manner in order to perform its desired function. A recent review by McCroskey (Ref. 1) examines the current research interest in unsteady stall and other unsteady fluid dynamical effects that occur in a wide range of modern engineering problems.

The Frank J. Seiler Research Laboratory (FJSRL) at the U.S. Air Force Academy is presently conducting a comprehensive experimental research program to study unsteady separated flows and in particular, the dynamic stall of oscillating airfoils. When dynamic stall occurs, transient forces and moments develop which are fundamentally different from their static counterparts, the most striking difference being large increases in force and moment coefficients above static values, the occurrence of "moment stall" before "lift stall," and the delay of the stall event to angles of attack in excess of the static stall value. The aim of this study is to achieve a clearer understanding into the physical mechanisms responsible for dynamic stall and to capitalize on these unique stall features by using them to improve the turn performance and maneuverability of flight vehicles.

2. BACKGROUND

The FJSRL study is directed toward a detailed examination of the vortex kinetics associated with dynamic stall. Figure 1 depicts a qualitative view of the flow over an airfoil executing a dynamic stall. It has been speculated that the formation, growth, and propagation of a free vortex residing on the



DYNAMIC STALL

- FORMATION AND CONTROL OF A FREE SPANWISE VORTEX
- TRANSIENT FORCES AND MOMENTS FUNDAMENTALLY DIFFERENT (LARGER) FROM STATIC COUNTERPARTS
- BENEFICIAL TO IMPROVING MANEUVERABILITY OF FLIGHT VEHICLES

Figure 1. Unsteady Separated Flows

airfoil upper surface, together with the accompanying reverse flow region, are central to the dynamic stall problem. However, no sound theoretical models exist. Consequently, detailed measurements of the periodic space/time mean velocity field for an oscillating airfoil exhibiting dynamic stall will provide valuable information about the stall process.

Presently, the two most common techniques used to measure local time-varying velocities are hot-wire anemometry and Laser Doppler Velocimetry (LDV). Both have distinct advantages and limitations. Hot-wire anemometry is a traditionally accepted, highly refined method for unsteady flow studies, and recently it was successfully used by the FJSRL to map the vorticity field in a restricted unsteady separated region behind an oscillating spoiler on an airfoil surface (Ref. 2). However, the technique suffers from two disadvantages which limit its usefulness: (1) a velocity measurement is not absolute, requires careful calibration, and makes long-term drift of experimental conditions a source of error; and (2) a mechanical probe must be inserted into the flow, therefore inevitably disturbing the flow itself, especially in regions of reversal.

The LDV has become an increasingly attractive diagnostic tool for the investigation of fluid flows (Ref. 3). It makes an optical measurement of velocity from the Doppler frequency shift of light scattered by particles moving with the fluid and thus is unobtrusive, absolute, and direct. However, the technique is somewhat complicated and expensive. The FJSRL is developing LDV diagnostics to study dynamic stall and related unsteady separated flows, and this report describes the current development of the LDV system.

3. OBJECTIVES

The objective of this research program is to adapt a general purpose two component LDV system to dynamic stall experiments in the Subsonic Wind Tunnel at the U.S. Air Force Academy. Features of this system include (1) specialized high frequency signal processing, (2) an interactively controlled two-dimensional LDV translation support structure, and (3) an interface with a real-time disc-based minicomputer data acquisition system. This report includes a description of the preliminary LDV system and its special constraints, initial operation of the system, a characterization of system signal and noise, and options for improvement of the system signal-to-noise ratio, which in turn suggest an improved LDV system.

4. LASER DOPPLER VELOCIMETRY (LDV) SYSTEM

4.1 General Considerations

The LDV is based on the fundamental concept of a frequency shift in electromagnetic radiation received from a moving source by a stationary observer. In fluid applications, the source is a small micron-sized particle entrained within the moving fluid which scatters laser light to a detector. The equation relating the frequency difference between this scattered light and an unscattered reference laser beam and one velocity component of the particle can be derived from the Doppler effect. Doppler frequency equations, descriptions of various LDV system considerations, and applications can be found in several references and texts (Ref. 4).

Several different optical schemes that use a laser have been developed around this familiar Doppler shift principle. The most suitable arrangement for many wind tunnel experiments is the dual-beam backscatter technique (Ref. 5) shown schematically in Figure 2. It has been adopted for this experimental study and is used here to elucidate the basic ideas of LDV. Monochromatic laser light is divided into two parallel beams of equal power. The beams are focused with a transmitting lens and cross at a point within the flow, called the probe volume. Particles passing through the probe volume scatter light back through the transmitting/collecting lens and onto a photomultiplier tube which provides an output current proportional to the scattered intensity. This photocurrent is then transferred to the data processing system. The distinct advantages of this scheme for wind tunnel applications and, in particular, the USAFA Subsonic Wind Tunnel, are discussed in Section 4.2.

The mathematical relationship between the intensity oscillations received by the photomultiplier tube and the velocity component of a scattering particle can be obtained from Doppler shift considerations. However, for a dual-beam arrangement, a much simpler and clearer description is obtained from interference fringe considerations. A close-up schematic view of the probe volume is shown in Figure 3. When the two coherent laser beams intersect, their wave fronts interfere constructively and destructively to form a set of parallel plane fringes contained within the ellipsoidal probe volume. The fringes are perpendicular to the plane formed by the two beams and parallel to the bisector between the two beams. From geometry the distance between the fringes is

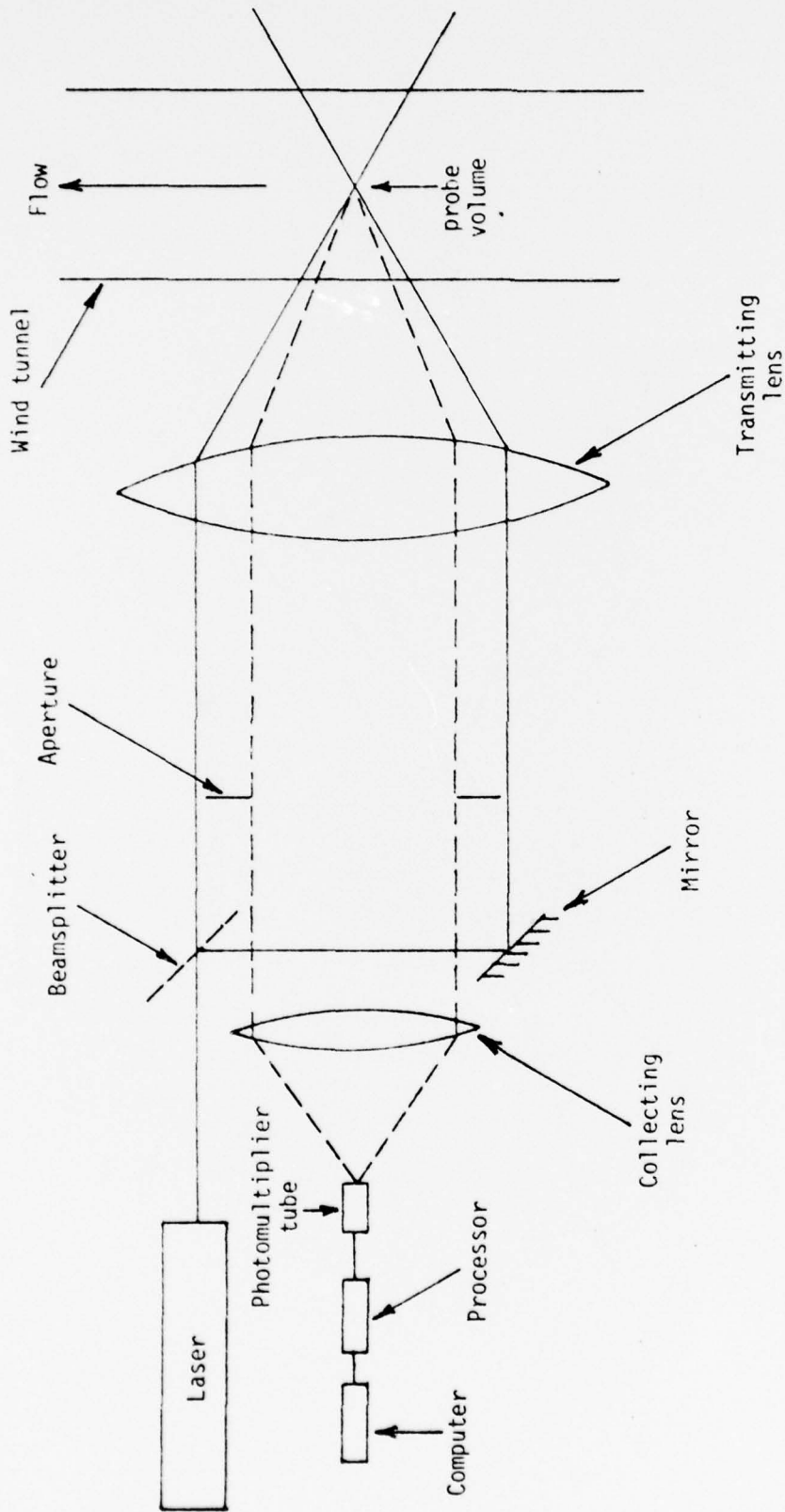


Figure 2. Dual-Beam Backscatter LDV

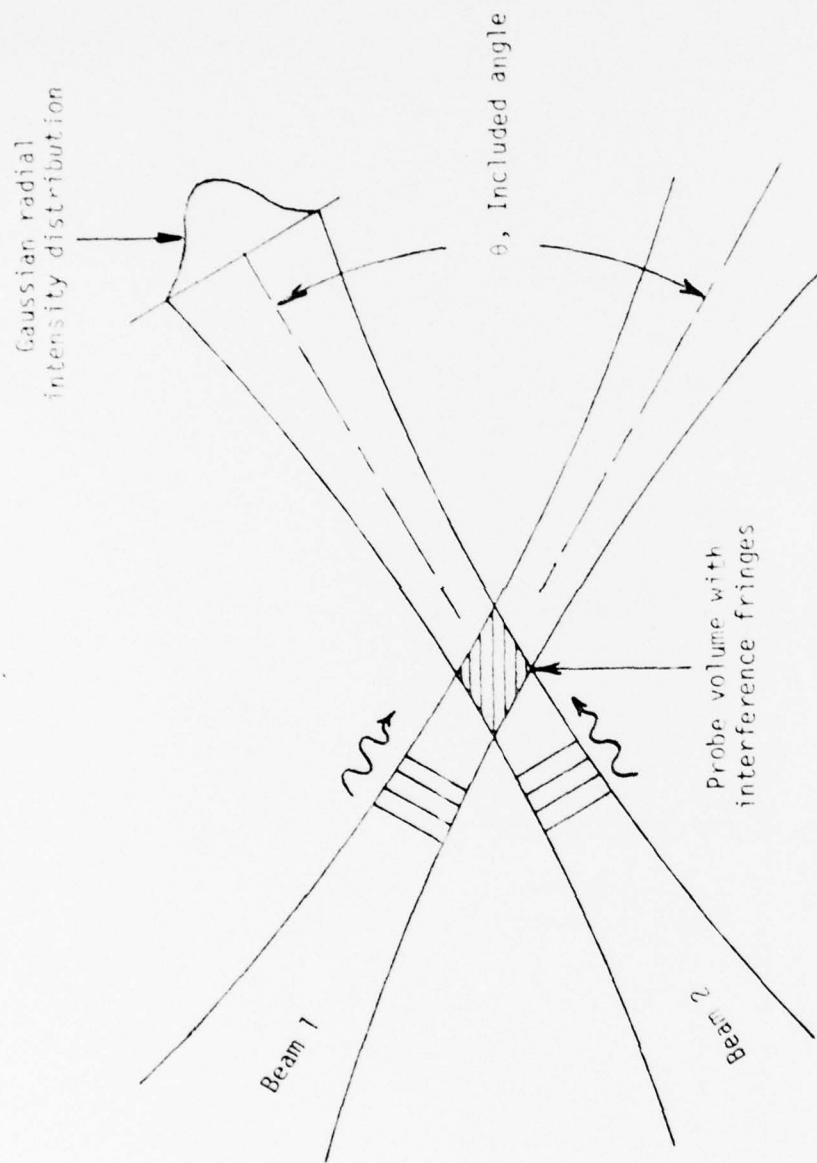


Figure 3. Probe Volume Close Up

$$\delta = \frac{\lambda}{2 \sin \frac{\theta}{2}}$$

where δ = fringe spacing

λ = laser light wavelength

θ = included angle between the two beams.

When a particle moves through the probe volume and intercepts the fringe pattern, it scatters light with intensity variations that depend on fringe spacing and particle transit time. If the transit time between two adjacent fringes is τ , then the velocity component perpendicular to the fringes is just the distance per time, given as

$$\vec{V} \cdot \vec{n} = \frac{\delta}{\tau} = \left[\frac{\lambda}{2 \sin \frac{\theta}{2}} \right] \frac{1}{\tau}$$

where \vec{V} = particle velocity vector

\vec{n} = unit vector perpendicular to fringes

τ = transit time between two adjacent fringes.

Then the frequency of the scattered intensity oscillations, f is $\frac{1}{\tau}$ or

$$f = \frac{2 \sin \frac{\theta}{2} (\vec{V} \cdot \vec{n})}{\lambda}$$

which is the same frequency obtained from the Doppler derivation (Ref. 4). This Doppler frequency is in direct proportion to a velocity component.

For two-dimensional studies, a second velocity component orthogonal to the first can be measured with a second set of dual beams which are rotated 90° with respect to the first set. If different laser wavelengths are used for the two sets of beams, then the two color-coded Doppler signals will represent the two velocity components of a scattering particle, provided all beams cross at the same point.

The dual beam backscatter system described thus far works well for scattering particle velocities that have unambiguous directions. However, since the measured Doppler frequency is proportional to a dot product of velocity, it cannot distinguish direction. That is, two particles with equal

speeds but traveling in opposite directions produce identical output frequencies. This ambiguity can be removed by frequency shifting one of the two dual beams, with an acousto-optic type Bragg cell (Ref. 5). By doing so, fringes in the probe volume move in relation to this frequency shift and a particle within the probe volume at zero velocity will register a Doppler frequency equal to the frequency shift imposed by the Bragg cell. Thus, this imposed incident beam frequency shift provides discrimination between positive and negative velocity components. The basic components of the dual-beam system described here have been incorporated into the FJSRL LDV.

4.2 The FJSRL LDV System

A feasibility study of an LDV system for the USAF Academy Subsonic and Trisonic Wind Tunnels was conducted by the FJSRL (Ref. 7). The purpose was to choose an LDV system that could satisfy the special constraints imposed by subsonic and trisonic applications yet provide accurate, two-dimensional space-time flow velocity capability at minimum cost. The study included a detailed examination of many different trade-offs that led to a preliminary design concept. A summary of the system constraints and the preliminary design, together with some salient trade-offs, are presented here.

4.2.1 System Constraints

The unsteady separated flow research experiments pose a special limitation for the LDV system. All existing or planned experiments associated with the unsteady separation research problem are mounted vertically in the Subsonic Wind Tunnel, and the drive mechanisms for these experiments are positioned below the wind tunnel test section (Figure 4). For two-dimensional studies, this arrangement precludes optical entry into the test section through the side windows, the only other access being through the top of the wind tunnel test section. The dual beam backscatter configuration is the only logical LDV optical arrangement which satisfies this constraint, since both the incident and scattered signals pass through the same entry port.

In addition, a dual beam backscatter system allows the collector optics to be mounted on the same overhead optical support structure as the laser and transmitting optics, thereby requiring only one drive system and eliminating the need for the slave optics detector unit that would be required for a dual beam forward scatter optical arrangement. The structure designed for this

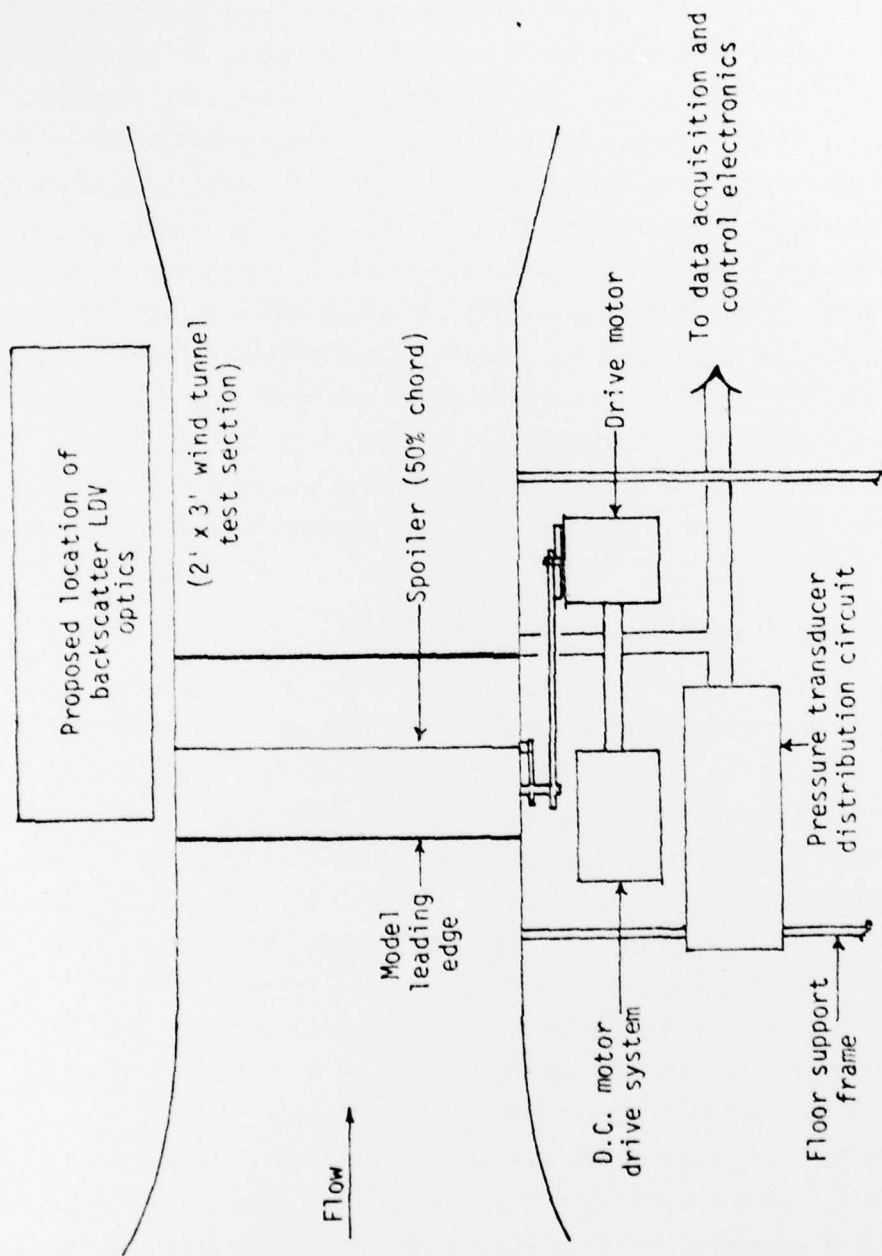


Figure 4. Unsteady Separated Flow - Experimental Schematic

purpose includes a dual-plane optical bench truss with two degrees of freedom in translation, which permits the system to scan the probe volume throughout the flow region.

4.2.2 Preliminary Design

The preliminary optical system designed to meet these constraints at minimum cost with existing state-of-the-art LDV technology is shown in Figure 5. A Lexel Model 95-4 argon ion laser produces two powerful (1.5 watt) visible lines at 5145 \AA (green) and 4880 \AA (blue) which provide the color coded beams required for simultaneous, two-dimensional velocity measurements. Two high power, multi-layer mirrors turn the beam vertically into an integrated optics assembly (TSI, Inc.). This assembly spatially separates the green and blue beams, aligns them, frequency-shifts one green and one blue component, and then focuses the four beams to form a probe volume at approximately the midspan position in the test section. The beams enter the test section through an AR-coated, optical quality glass window that reduces specular backscatter. The backscattered light from particles passing through the probe volume is received by a collection optics, photomultiplier system housed in the transmitting optics assembly (Ref. 7, 8).

4.2.3 Signal Processing and Data Acquisition

Two counter-type signal processing units (TSI, Inc.) are used to analyze the blue and green photomultiplier signals and produce both analog and digital outputs representing two velocity components (Figure 6). These sophisticated units filter the Doppler signals, measure the time for a particle to cross a specified number of fringes, and convert this time to a velocity. The counter uses an operator selected data validation scheme that allows rejection of spurious signals, thus reducing the data input caused by noise and eliminating velocity bias from particles traversing only a few fringes (Ref. 8). Raw velocity data from the signal processors are supplied to a DEC PDP 11/45 data acquisition system with disc storage and real-time capability. The data acquisition system calculates the mean velocity components at each position as data is collected, and results are printed in real time. In addition, filtered Doppler signals from scattered particles are monitored on a 100 Mhz storage oscilloscope. A separate, interactive computer control is planned to command

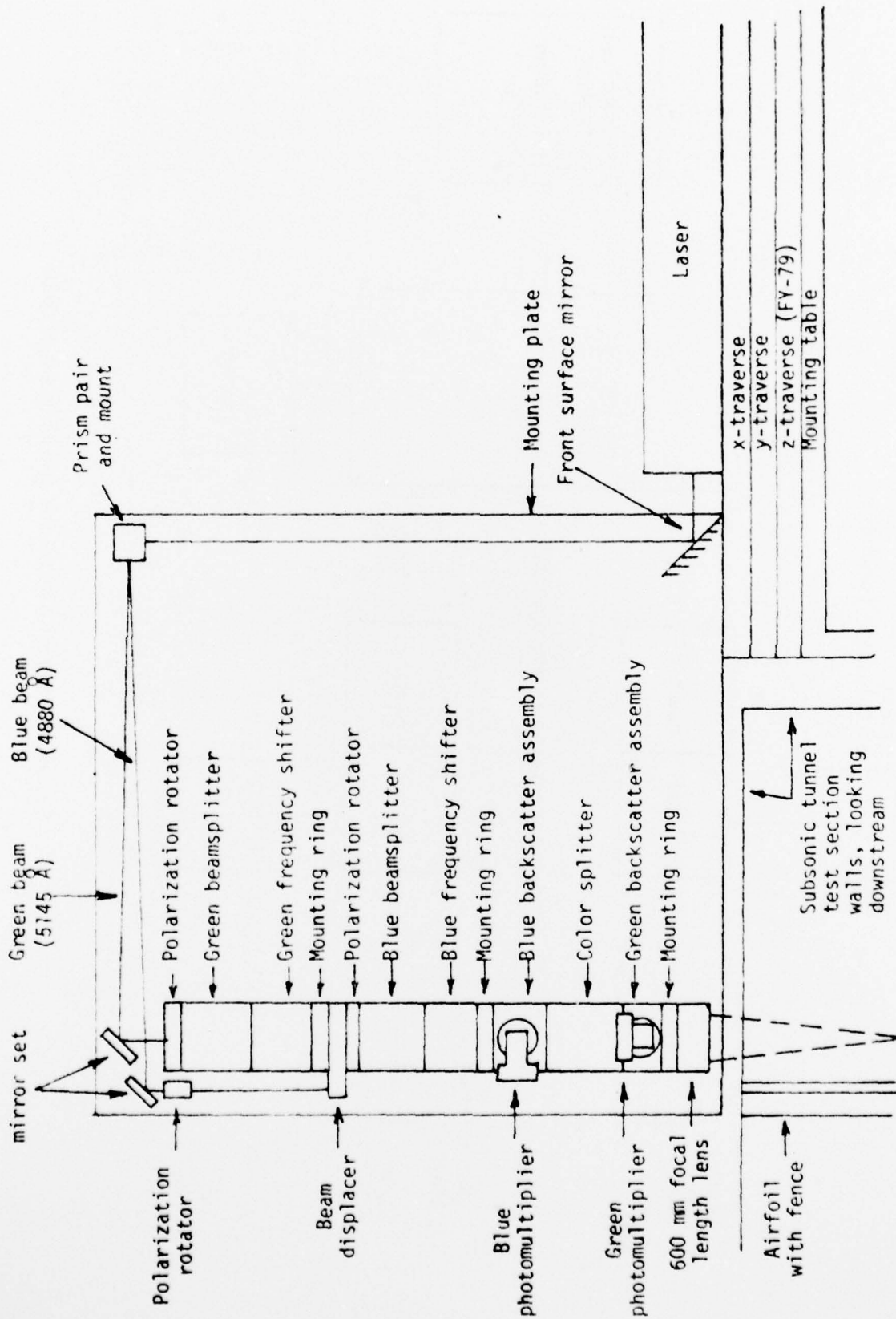


Figure 5. Optical System

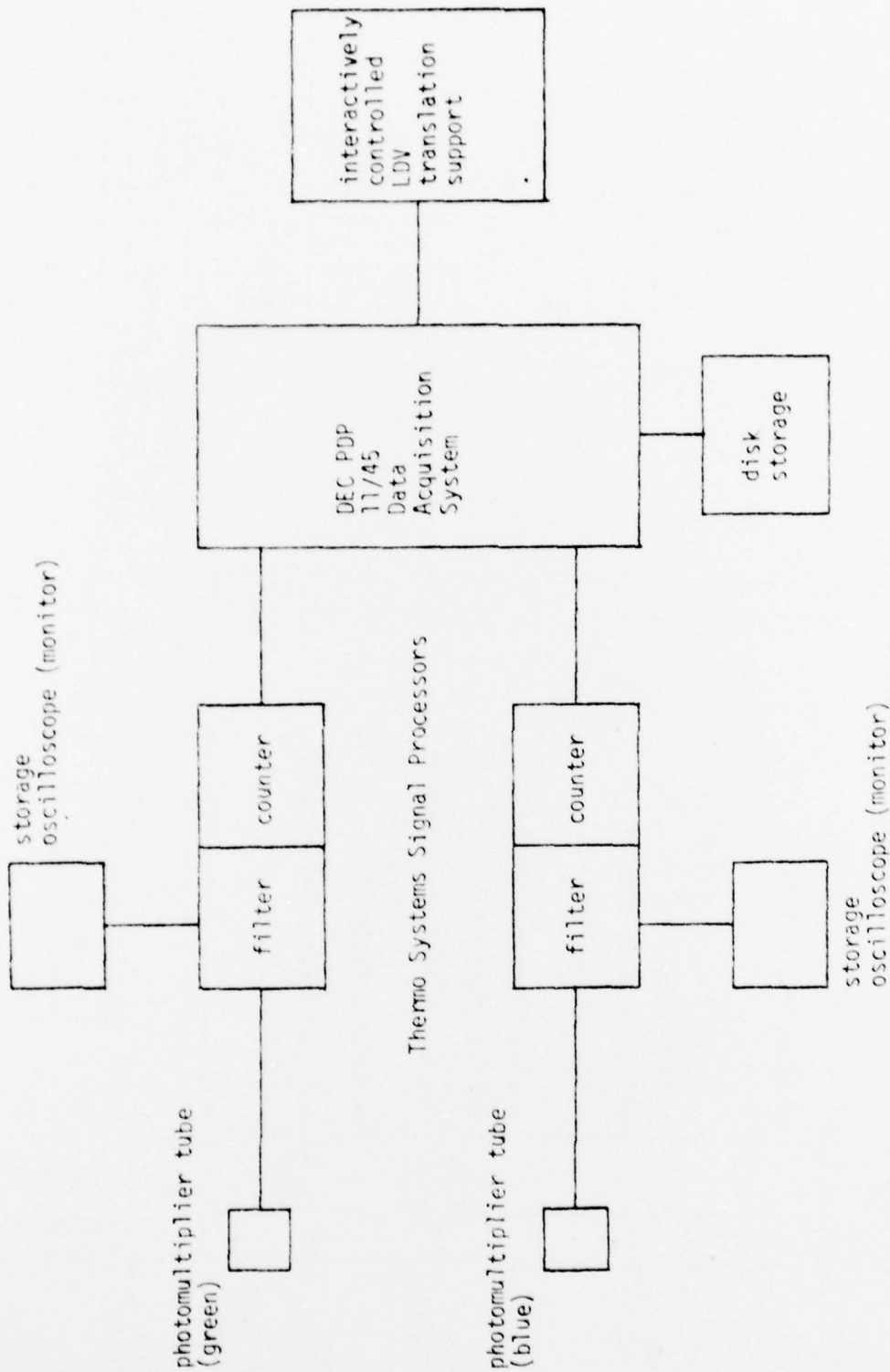


Figure 6. Signal Processing and Data Acquisition

electric stepper motors to drive the LDV optical support structure which will locate the probe volume at a specified X-Y position in the flow. Necessary software for data acquisition and interactive computer control are presently being designed.

4.3 Preliminary Operation of the LDV System - Optics and Signal Processing

Preliminary efforts have concentrated on the initial operation and subsequent design improvements of the optics and signal processing systems. The following brief chronology outlines these efforts.

Laser and Mirror Requirements: Initial high power operation of the argon ion laser produced an output beam characterized by a donut mode (TEM_{01}). In addition, the aluminized turning mirrors used to direct the laser beam into the integrated optics assembly were such that they further accentuated the undesirable donut mode shape. Considerable effort has been spent on modifying and tuning the laser to achieve a fundamental mode operation (TEM_{00}). Further, all mirrors have been replaced with high power, multi-layer coated, argon ion laser mirrors. These modifications provided the high quality, fundamental mode laser beam required for LDV applications.

Optical System Alignment (green beam): The careful alignment of the integrated optics assembly has provided a well defined probe volume at approximately midspan of the test section. The probe volume has been carefully examined with a microscope objective and revealed a well defined fringe pattern. Upon completion of the alignment procedure, a preliminary experiment revealed large noise levels with no observable Doppler signals. It should be noted that the system's sensitivity to alignment drift remains a serious concern with respect to the ease of operational implementation of the entire LDV apparatus. The cantilever configuration and resultant long optical path are believed to be at least partly responsible for this difficulty. Beam pointing drift of the laser during warmup was the major source of misalignment during the power up phase of a cold system. Alignment drift was almost nonexistent after subsequent adjustment and realignment after the laser was warm.

Noise Reduction: The following noise sources are commonly found in practice: (1) ambient light, (2) scattered laser light, (3) spurious laser noise, (4) photodetector shot noise, and (5) electronically induced noise. Of

these, the single most troublesome noise source encountered in the current experiment was that from scattered laser light: diffuse and specularly reflected laser light from the tunnel optical window, from the airfoil surface, and from the wind tunnel floor. It has become apparent that improving the signal-to-noise ratio would present the single biggest challenge to successful system operation. Other LDV dual beam backscatter experiments report a similar difficulty (Ref. 5).

The scattered laser noise sources were systematically eliminated as shown in Figure 7. First, diffuse reflections from the tunnel floor were deflected outside the collection optics solid angle by mounting a mirror flush with the tunnel floor. Next, a beam-picker assembly was positioned to intercept the first surface reflections from the optical window. Although the window was AR-coated, these reflections still represented a noise source larger than the scattering particle signals. Finally, an isolation cone removed additional stray and diffusely scattered laser light. The scheme described here is by no means intended to be a general procedure but only demonstrates the necessity for systematically eliminating laser light reflections in wind tunnel applications.

Preliminary Results: After optical noise was reduced to tolerable levels, Doppler signals were measured for ambient seeding levels in the wind tunnel. Typical results for two different test section velocities portray large-signal, low-noise Doppler particle bursts (Figure 8). In addition to reducing optical noise, selective electronic filtering of the photomultiplier signals greatly enhanced the signal-to-noise ratio. Data rates for these measurements were typically between 2/sec and 200/sec, a figure consistent with typical natural seeding levels reported in other wind tunnel facilities (Ref. 5).

The LDV counter was used to make velocity measurements of these Doppler signals for a range of test section speeds and comparison with pitot tube measurements is given in Figure 9. A parallel procedure was followed for the blue beam operation with similar results.

A major concern resulting from these early measurements is for a reconciliation of previously developed analog (continuous signal) data sampling algorithms specifically designed for use with unsteady flows and the low data rates (discontinuous digital signals) experienced with the LDV technique.

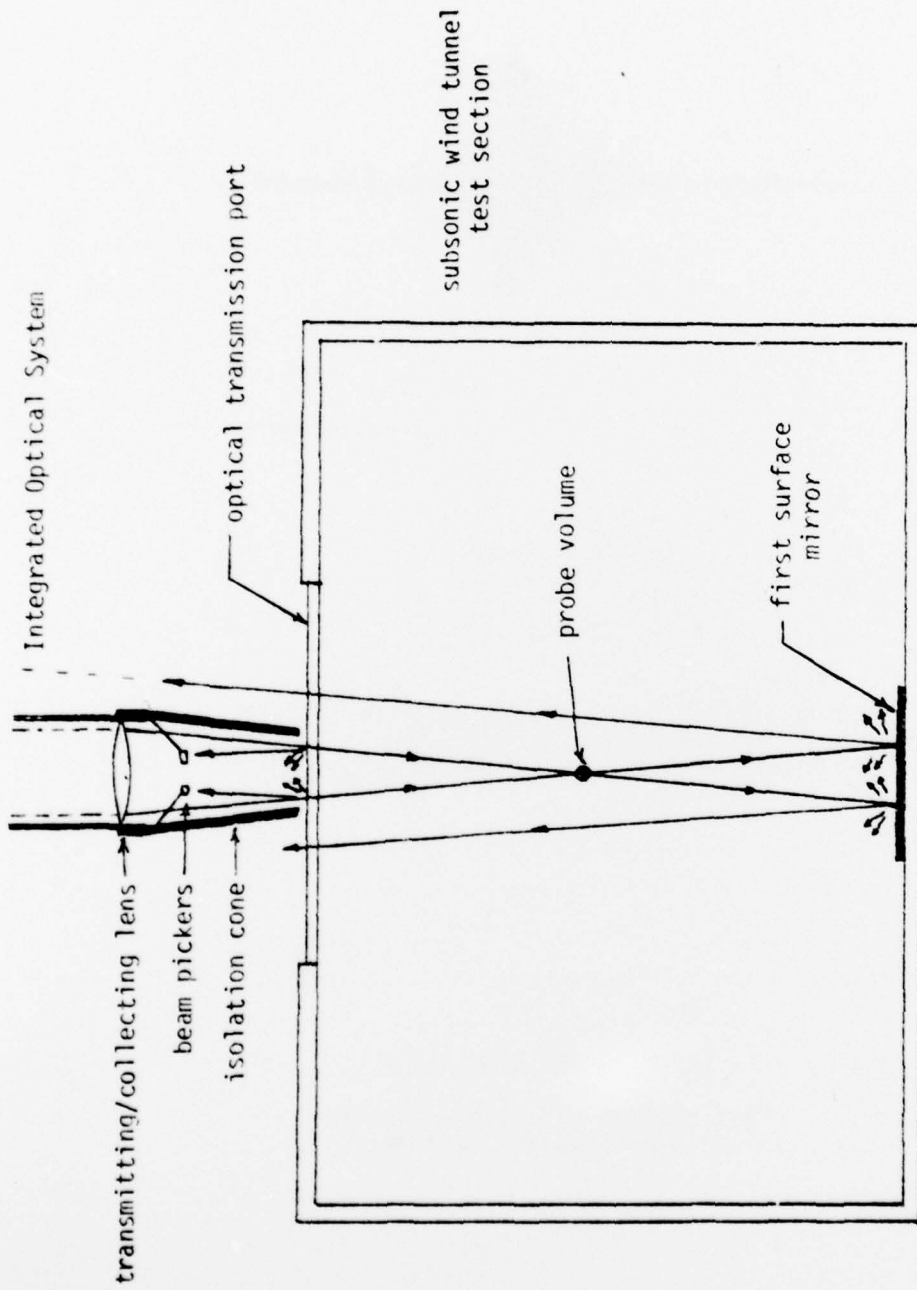
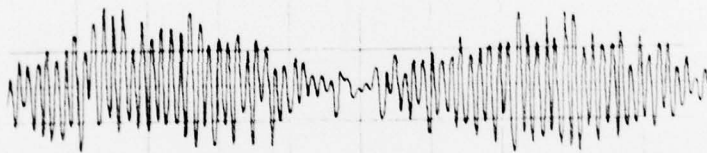


Figure 7. Treatment of Reflected Laser Light Noise



1 μ sec/div



.2 μ sec/div

Experimental Conditions

Test section velocity - 60 ft/s
Doppler frequency - 4 MHz

Figure 8. Typical Doppler Signals (green beam)

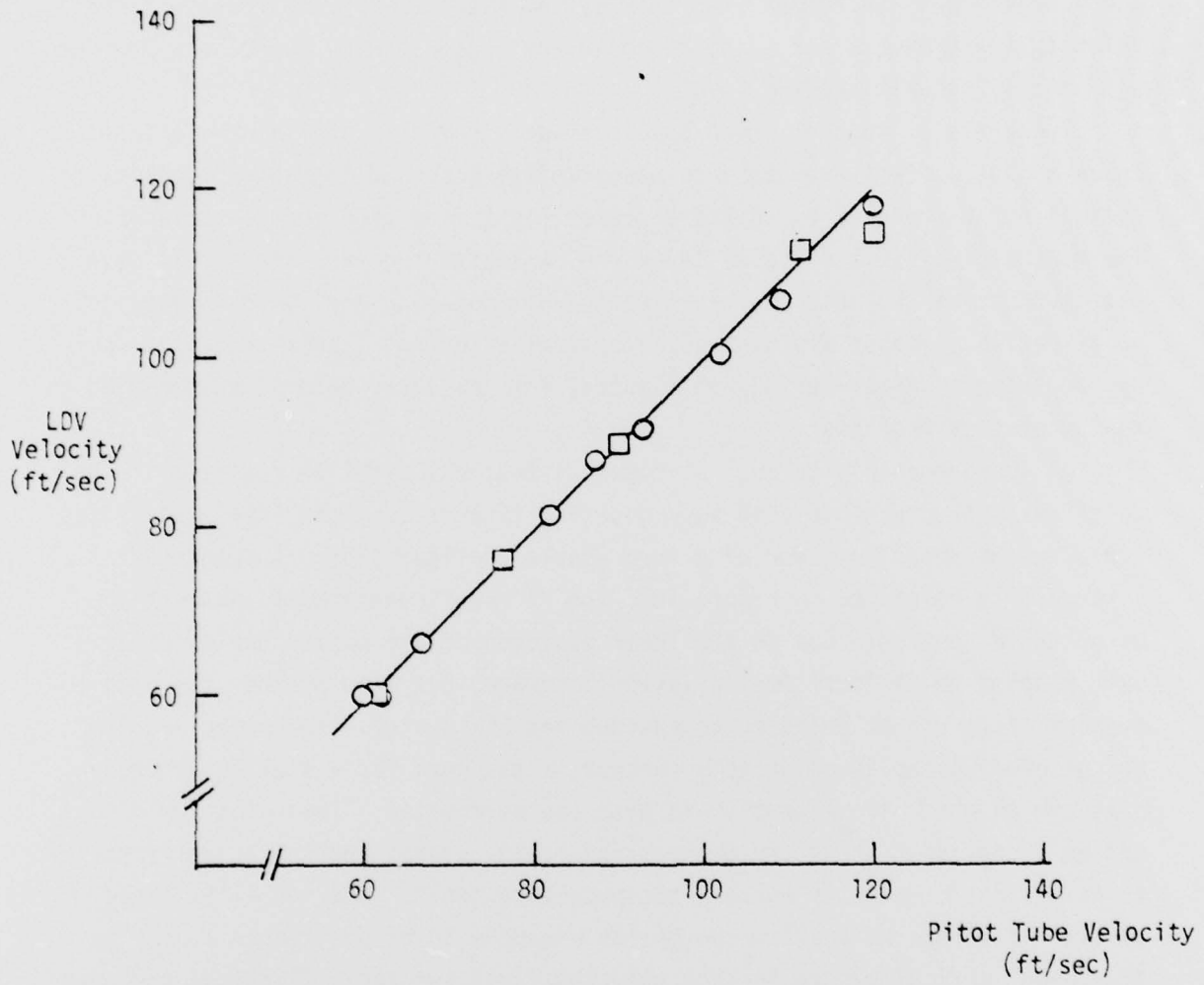


Figure 9. LDV - Pitot Tube Velocity Comparison

5. CONCLUSIONS AND RECOMMENDATIONS

The preliminary LDV system designed and modified as described above was found to satisfy all constraints imposed on the system configuration. Preliminary experiments performed with this system have shown that accurate flow velocity measurements can be obtained in the Subsonic Wind Tunnel environment with purely natural seeding levels.

Two areas of concern which have surfaced from this preliminary effort are those of the system's tendency to become misaligned and its susceptibility to optical noise produced by scattered laser light from wind tunnel surfaces. The reduction of this noise to levels below scattering particle signal levels was found to be the most desirable method of improving the system signal-to-noise ratio. A major improvement in optical alignment stability can be achieved by requiring a warmup period (15 minutes) for the laser before implementing on realignment corrections.

An improvement in optical alignment situations might be realized if the cantilever structure now used as a mounting fixture for both laser and optics could be abandoned in favor of a more stable configuration. A suggested structure is presented in Figure 10. The "T"-configuration is inherently more stable, not only due to the lower position of the optics sub-assembly with respect to the positioning system hardware, but also because the base and support frame can be designed to envelop the LDV system. The major problem encountered in implementing this concept is the need for a stable overhead platform on which the assembly and base can be mounted. This platform need not be a permanent structure but must be rigid, sturdy and sufficiently massive to also support research workers and necessary tools. Additionally, these combined concepts will allow the optics assembly to be positioned closer to the tunnel optical window thereby reducing first surface reflection problems from the port by making the reflections fold directly back into the incoming beams, thus bypassing the photomultiplier tubes.

Recorded ambient particle seeding levels may be high enough to obtain accurate mean velocity measurements for unsteady, separated flows at locations outside reversed flow regions. Seeding may, however, be required if experimental run duration becomes excessive. It is recognized that the interpretation of LDV signals for unsteady, separated flows whose composition is

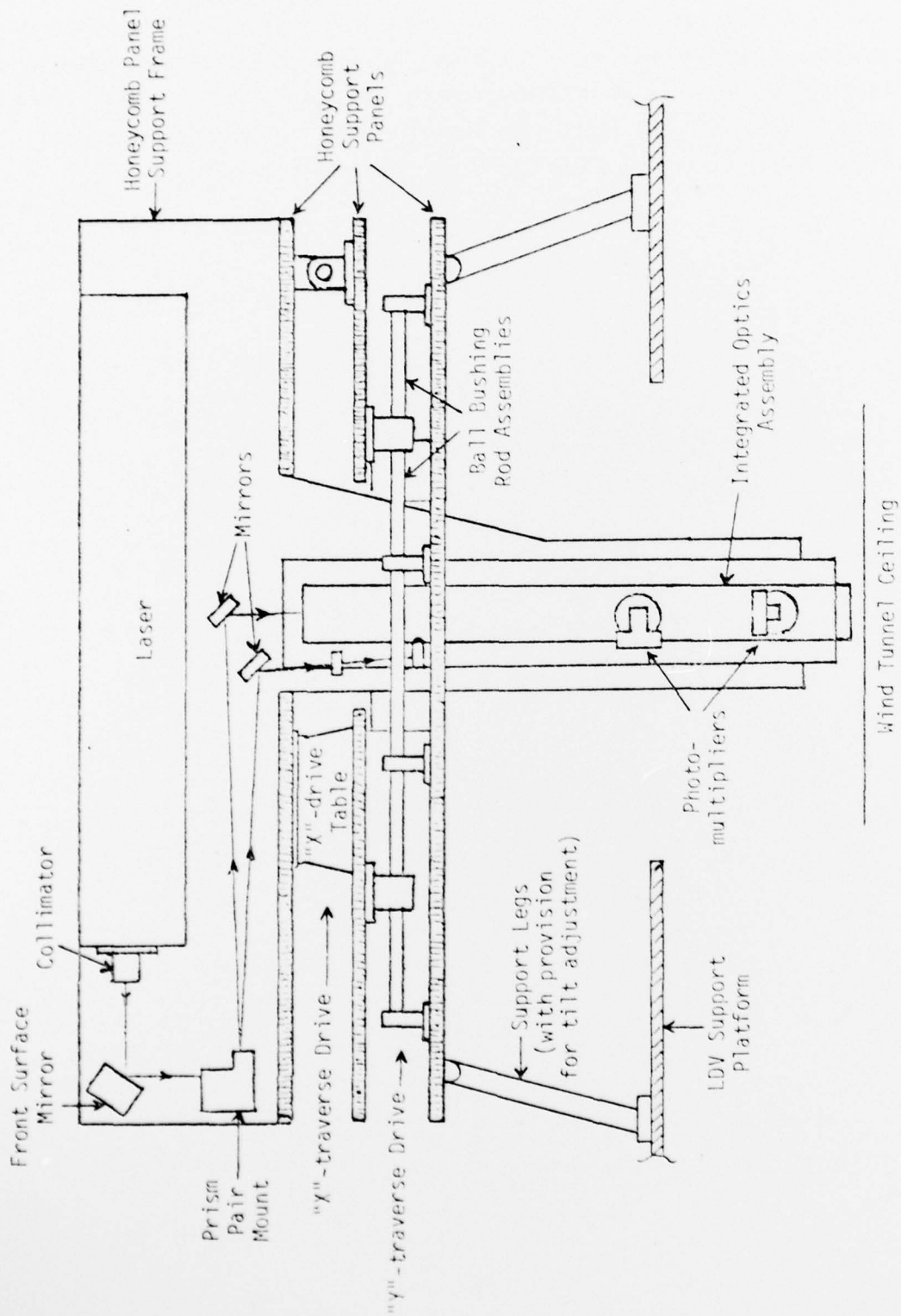


Figure 10. Proposed LDV Configuration (side view)

influenced by particle size and seeding, turbulent flow content, and global unsteady effects with flow reversal pose special problems. Their solution will require a long range comprehensive effort in the areas of data mangement, discontinuous signal averaging, and digital correlation techniques, based on signal-to-noise and sampling considerations. The resolution of these difficulties will then form the first step toward the goal of understanding and modeling unsteady separated flows using LDV diagnostic techniques.

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