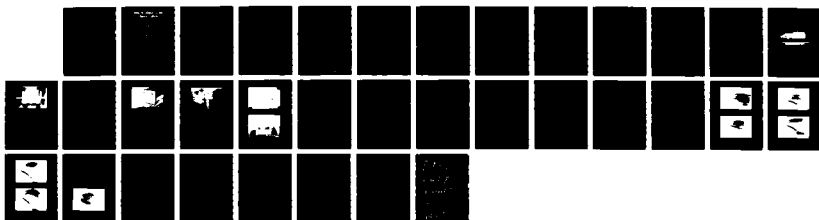


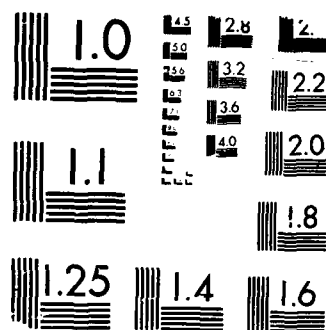
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## THESIS

FLOW VISUALIZATION  
BY LASER SHEET

by

Joseph S. Chlebanowski, Jr.

March 1988

Thesis Advisor:

S. Bodapati

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## REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b RESTRICTIVE MARKINGS	
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.	
2b DECLASSIFICATION/DOWNGRADING SCHEDULE			5 MONITORING ORGANIZATION REPORT NUMBER(S)	
4 PERFORMING ORGANIZATION REPORT NUMBER(S)				
6a NAME OF PERFORMING ORGANIZATION Naval Postgraduate School		6b OFFICE SYMBOL (if applicable) 67	7a NAME OF MONITORING ORGANIZATION Naval Postgraduate School	
6c ADDRESS (City, State, and ZIP Code) Department of Aeronautics, Code 67 Monterey, CA 93943-5000			7b ADDRESS (City, State, and ZIP Code) Department of Aeronautics, Code 67 Monterey, CA 93943-5000	
8a NAME OF FUNDING/SPONSORING ORGANIZATION		8b OFFICE SYMBOL (if applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c ADDRESS (City, State, and ZIP Code)			10 SOURCE OF FUNDING NUMBERS	
			PROGRAM ELEMENT NO	PROJECT NO
			TASK NO	WORK UNIT ACCESSION NO
11 TITLE (Include Security Classification) FLOW VISUALIZATION BY LASER SHEET				
12 PERSONAL AUTHOR(S) CHLEBANOWSKI, JR., JOSEPH S.				
13a TYPE OF REPORT Master's Thesis		13b TIME COVERED FROM TO	14 DATE OF REPORT (Year Month Day) 1988, March	15 PAGE COUNT 33
16 SUPPLEMENTARY NOTATION The views in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense nor the U.S. Government.				
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	Flow Visualization; Smoke; Laser Sheet; Fiber Optics	
19 ABSTRACT (Continue on reverse if necessary and identify by block number) A flow visualization system using smoke and a laser sheet for illumination has been designed and developed for use in the Naval Postgraduate School 32- X 45-inch low speed wind tunnel. Major design features include a portable smoke rake designed for ease of installation and removal, the use of fiber optics to transport the laser light in a safe and convenient manner, and a portable traversing mechanism to traverse and orient the laser light sheet. The capabilities of the flow visualization system have been demonstrated by producing qualitative photographic recordings of complex flow patterns past an airfoil model and a missile model.				
20 DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> OTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a NAME OF RESPONSIBLE INDIVIDUAL Satya Bodapati			22b TELEPHONE (Include Area Code) 408/646-2854	22c OFFICE SYMBOL 67Bu

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Flow Visualization By Laser Sheet

by

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Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL  
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# ABSTRACT

A flow visualization system using smoke and a laser sheet for illumination has been designed and developed for use in the Naval Postgraduate School 32-X 45-inch low speed wind tunnel. Major design features include a portable smoke rake designed for ease of installation and removal, the use of fiber optics to transport the laser energy in a safe and convenient manner, and a portable traversing mechanism to traverse and orient the laser light sheet. The capabilities of the flow visualization system have been demonstrated by producing qualitative photographic recordings of complex flow patterns past an airfoil model and a missile model.



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## ACKNOWLEDGMENT

This thesis was funded in part by the Naval Air Systems Command conducted under the Navy-NASA Joint Institute of Aeronautics.

My gratitude goes to my thesis advisor, Professor Satyanarayana Bodapati, for his guidance and encouragement. My sincere appreciation also goes to Marie Hashimoto and Don Harvey, a couple of true professionals who were always there when I needed help and advice.

I want to thank my family for their loving support during times of extreme difficulties. To my wife, Pat, my son, Joey, and my daughter, Rebecca, thank you for keeping me going. A special thank you goes out to my parents for planting the seed of wisdom many years ago.

## I. INTRODUCTION

### A. BACKGROUND

The motion of most gases is invisible to an observer during direct observation due to the transparent nature of the media. Flow visualization techniques are methods by which the flows are made visible and are a vehicle by which a deeper insight of the flow can be obtained. These techniques are helpful in the selection of flow parameters and in determining regions of interest to be used in the more detailed quantitative measurements. Flow visualization by laser sheet is a method which combines the use of a smoke-like material as a tracer to make flow visible and illumination by laser light.

The use of smoke-like materials to visualize gaseous flow is a method which has been widely used since the turn of this century. Often referred to as aerosols, the variety of smoke-like materials such as vapors, fumes, and mists, are colloid particles suspended in gas. These aerosols are generated by incomplete combustion of organic materials, by vaporization of hydrocarbon oils, or as products of various chemical reactions. The process of combustion or vaporization is normally accomplished in a smoke generator where the product of the process is mixed with a regulated amount of air to yield the desired smoke. The smoke should

be highly visible with a high degree of light reflectivity, nontoxic, and noncorrosive. Methods for introducing the smoke into the flow vary, but is usually introduced ahead of the test model via a single smoke tube or a multiple array of tubes referred to as a smoke rake. (Ref. 1)

The use of laser light as an illumination source for flow visualization has proven to be of great value (Ref. 2). Illumination of smoke by a thin sheet of collimated laser light enables detailed cross sectional visualization of the flow structure. The sheet of laser light is normally produced by passing an exposed laser beam through a glass rod or a cylindrical lens. Recent development of a portable laser sheet by Koga, et al., has demonstrated the convenience and safety aspects of using laser light by concentrating the laser light inside a shielded fiber optic cable (Ref. 3). This development eliminates the need to re-align and adjust multiple mirrors during reposition of the laser light sheet and reduces exposure to laser energy.

## B. THESIS GOALS

This thesis is supported by the Naval Air Systems Command under the overall program of High Alpha Aerodynamics research. The goals of this thesis are threefold:

1. to design, develop, and incorporate into the Naval Postgraduate School (NPS) lowspeed wind tunnel a smoke

flow visualization system combined with visualization by a laser sheet;

2. utilize fiber optics to transport the laser light safely and conveniently; and
3. to demonstrate the capabilities of the flow visualization system and produce qualitative photographic recordings of the cross sectional structure of complex flow fields of interest to aerodynamicists.

## II. COMPONENT DEVELOPMENT AND DESCRIPTION

### A. SMOKE GENERATION

Smoke is produced in a portable Rosco 1500 Fog/Smoke machine which vaporizes a specially formulated Rosco Fog fluid whose major components are a series of polyfunctional alcohols (Ref. 4). The fog fluid is siphoned from an external reservoir and is forced under pressure into a heat exchanger where it is heated to a temperature near its vaporization point. An aerosol is created when the hot, pressurized liquid is discharged through a nozzle and into the atmosphere where it vaporizes. The operating temperature, pressure, and nozzle orifice have been factory set and are not adjustable. Volume output, which is controlled from the fog volume output control, yields a particle size of 0.5 to 60 microns. Smoke output can be controlled in the continuous or momentary mode from a remote control up to 25 feet from the smoke machine. The smoke fluid is nontoxic, noncorrosive, and demonstrates a high degree of light reflectivity in its vaporized state. (Ref.5)

A small chamber with a variable speed blower attached to one end was designed to collect and then pressurize the vaporized fluid in order to vary the exit velocity of the smoke at the smoke tube orifice. The chamber assembly

attaches to the nozzle of the smoke machine and a flexible hose is attached to the output end of the blower. Figure 1 shows the smoke machine and chamber/blower assembly arrangement.

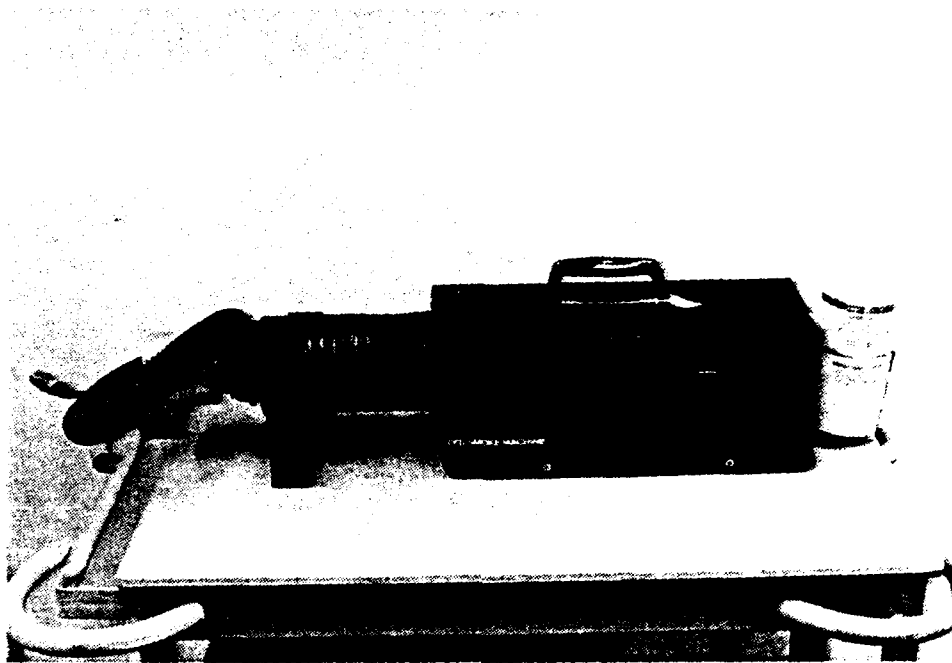


Figure 1. Smoke Machine

#### B. SMOKE INJECTION

Smoke is injected into the air stream through a five tube smoke rake which is suspended inside of the wind tunnel at the end of the contraction section (see Figure 2). Smoke is fed from the chamber/blower assembly via a flexible hose to the main support of the smoke rake which is constructed out of two separate pipes, one sliding within the other. A

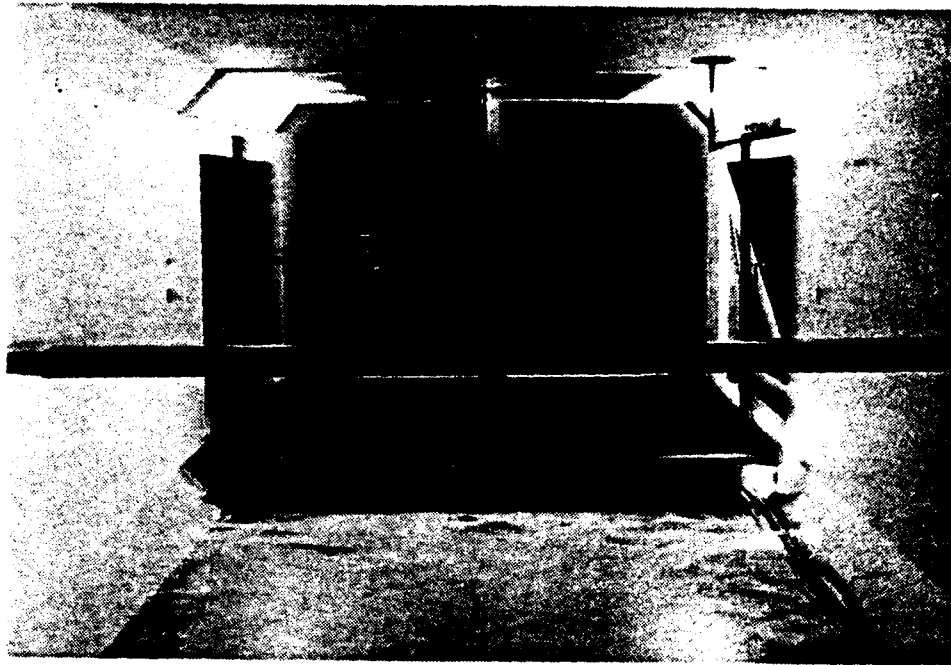


Figure 2. Five Tube Smoke Rake( View from the Settling Chamber to the Test Section)

large spring placed inside of the assembled pipes provides the necessary axial force to hold the smoke rake in place when the pipes are compressed. This design not only eliminated the need for mounting hardware within the wind tunnel but allowed it to be quickly placed at various locations in order to determine the optimum position yielding the best smoke filaments. Smoke is routed from the main support pipe to a rake of five brass smoke tubes that are 0.25 inches in diameter and 18.0 inches in length. To minimize flow disturbances caused by the presence of the smoke rake, the main support pipe and a portion of the smoke tubes are streamlined by encasing the structure in a symmetric airfoil and,

to maintain laminar flow the smoke tube orifices are highly polished and gradually tapered to a razor sharpness (Ref. 6).

### C. OPTICAL ARRANGEMENT

A Spectra Physics, Model 164, 5W Argon Ion Laser is used as a light source and is configured to output multi-line wavelengths from 457.9 to 514.5 nm in a continuous wave operation (Ref. 7). Collection, transportation, and recollimation of the laser beam is accomplished through the use of a Newport Corporation Laser-Fiber Illuminator. The unit consists of a 10 meter long, multi-mode transmitting fiber that is preconnected to a coupled head at one end and a collimator at the other. The transmitting fiber is an armor cabled, 200 micron diameter silica clad fiber with a demonstrated transmitting efficiency of 83%. The coupler attaches directly to the threaded bezel at the output end of the Argon Ion Laser and eliminates any chance of exposure to the laser beam (see Figure 3). The coupler head contains a lens that focuses the laser beam on the fiber end and allows fine position adjustments in the x, y, and z directions. A slide-bar on the coupler can be positioned to block, attenuate, or pass the laser light unattenuated. The laser light at the output end of the fiber is converted to a six millimeter diameter beam with less than a 10 mrad divergence by a single lens contained within the collimator (Ref. 8).



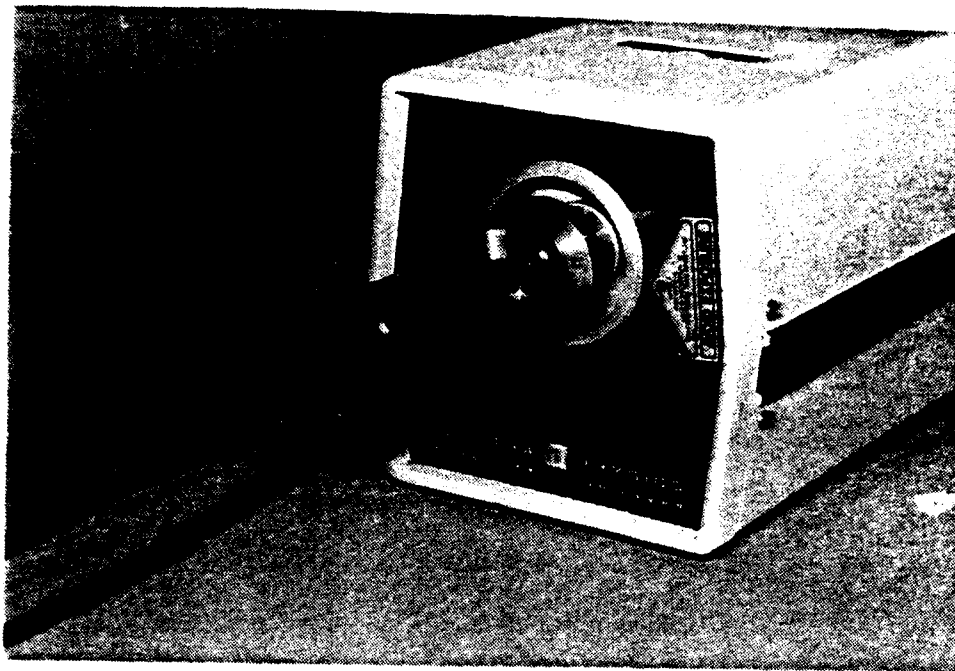


Figure 3. Fiber Optic Coupler Head

Conversion of the collimated output laser beam to a laser light sheet is accomplished by first passing the beam through a 3X beam expander to focus and shape the beam to extend the collimated range, and then through a plano-cylindrical glass lens with a -14.8 mm focal length to create a laser light sheet approximately two millimeters in thickness. The conversion optics, consisting of the collimator, beam expander, and plano-cylindrical lens is mounted on a six-inch micro-optical rail and clamp assembly to facilitate its linear and angular adjustments on the optics mount support rod of the traversing mechanism (Figure 4).

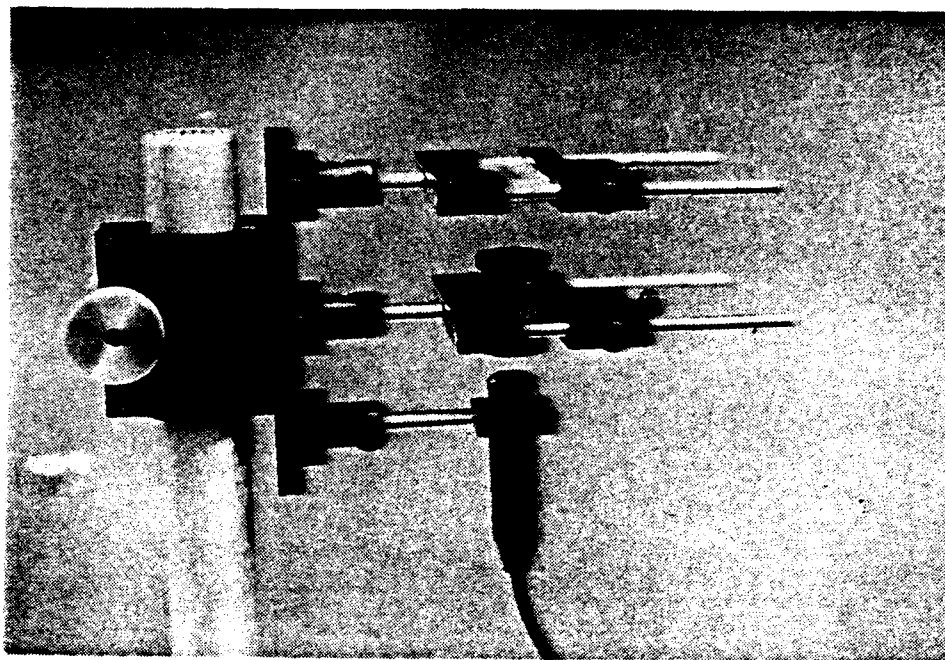


Figure 4. Conversion Optics

#### D. TRAVERSE

A portable traverse was designed to support the conversion optics and provide precise positioning in two dimensions across the full length and width of the test section observation window. Constructed mainly from aluminum, the traverse can be positioned on the side or top of the wind tunnel test section with minimal effort by one person. Once in place, the traverse can be covered with panels to prevent accidental exposure to reflected laser light. Figures 5 and 6 show the traverse mounted on the test section side and top, respectively.

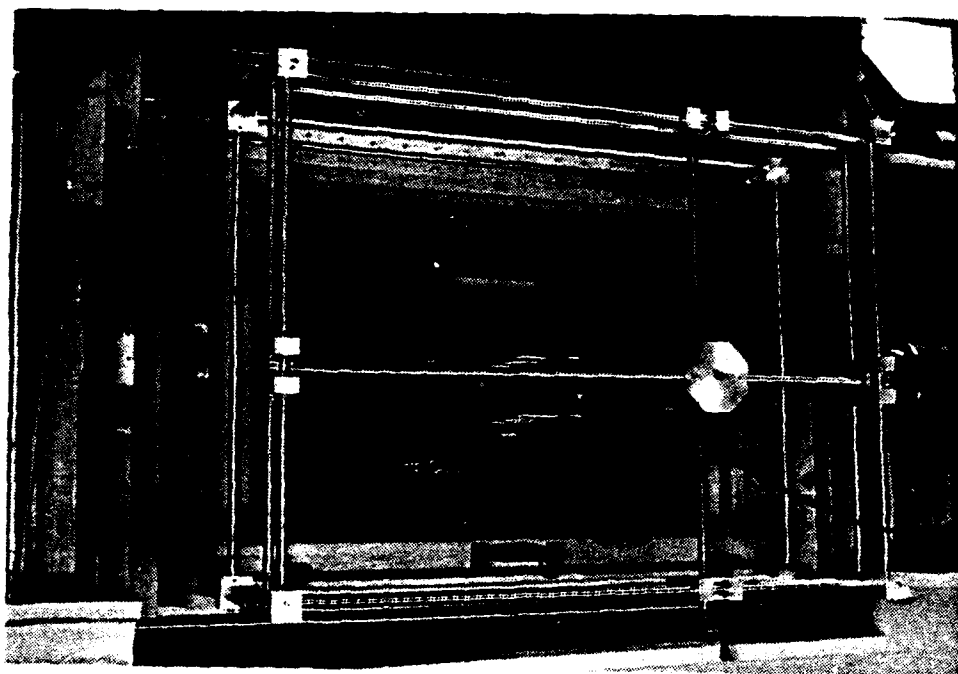


Figure 5. Traversing Mechanism (Side)

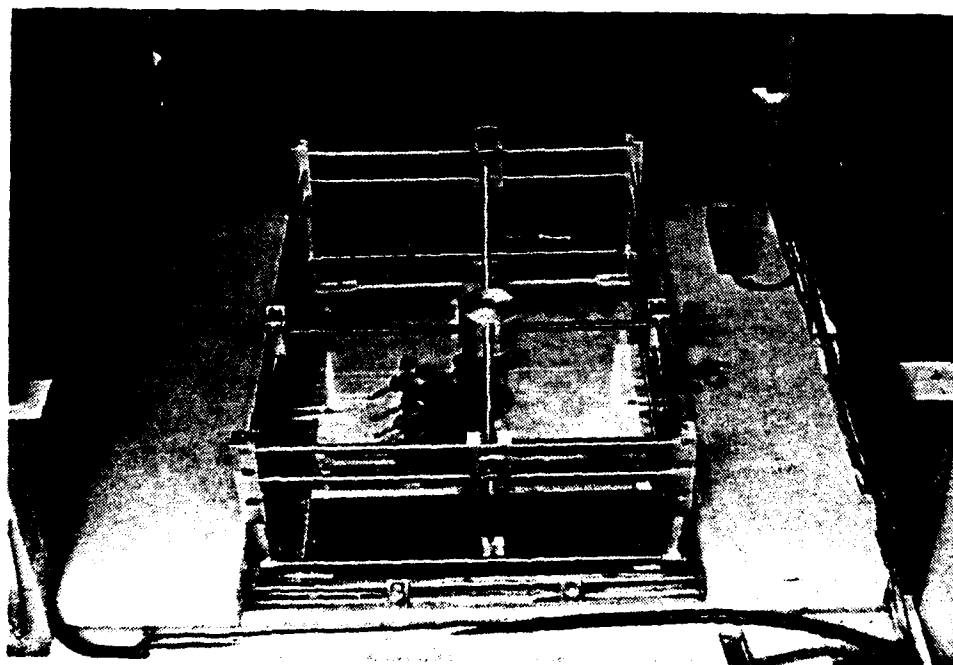


Figure 6. Traversing Mechanism (Top)

### III. FLOW VISUALIZATION SYSTEM INTEGRATION

#### A. WIND TUNNEL DESCRIPTION

The flow visualization system was developed for integration into the Naval Postgraduate School 32-x 45-inch low speed wind tunnel which is a single return, closed circuit design measuring 64 feet in length and between 21.5 and 25.5 feet in width. The wind tunnel is powered by a one hundred horsepower motor coupled to a three-bladed variable pitch fan via a variable speed transmission. Two fine meshed turbulence suppression screens are installed in the settling chamber immediately upstream of the contraction section. The contraction has an area ratio of 10:1. The test section has hinged windows on either side for access and unobstructed viewing. (Ref. 9) During laser operations the outer window is blocked by a plate to prevent injury due to accidental exposure to laser light. A third window is installed at the top of the test section for additional access and viewing.

#### B. FLOW VISUALIZATION SYSTEM LAYOUT

Figure 7 illustrates the basic wind tunnel and flow visualization system layout. The initial step taken in integrating the flow visualization system with the wind tunnel was to determine a location for the smoke rake which

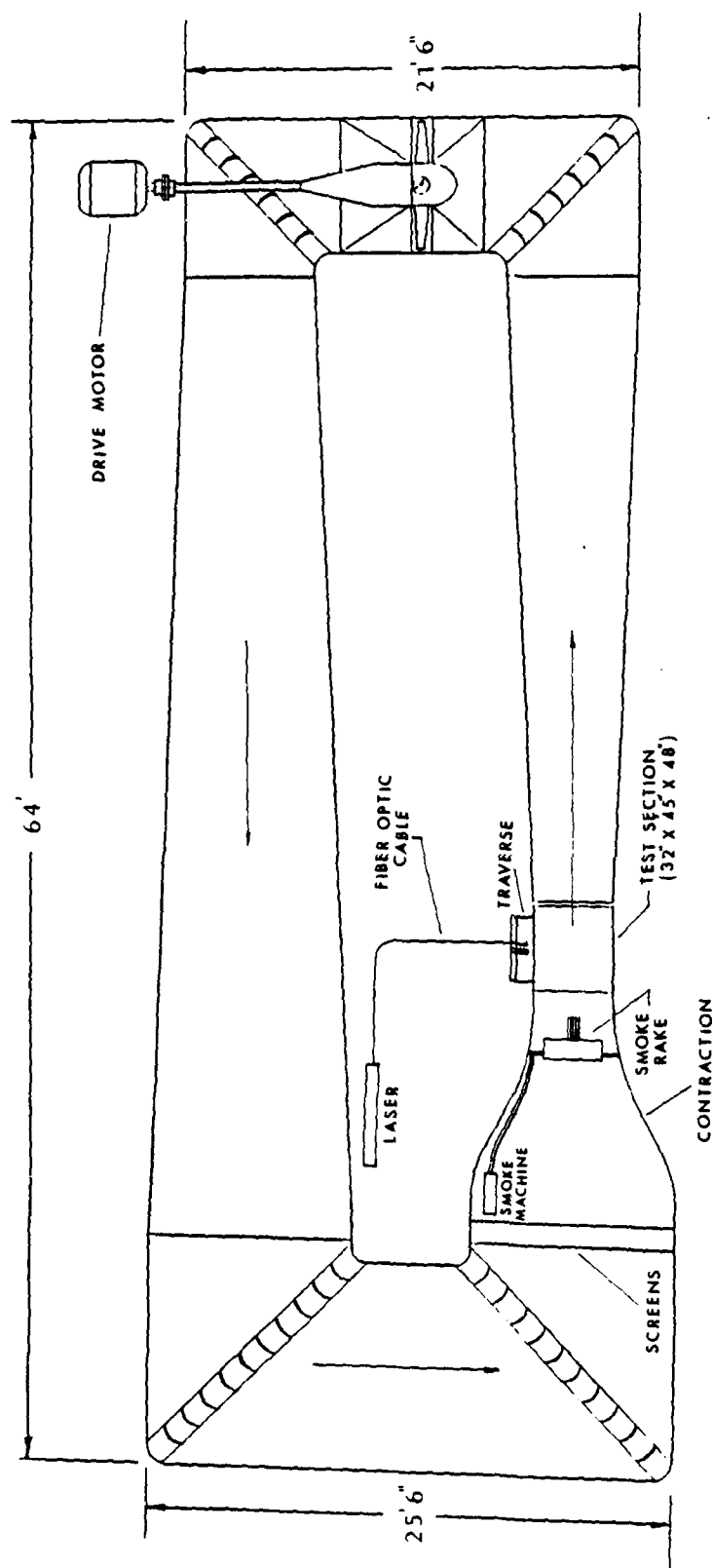


Figure 7. Wind Tunnel and Flow Visualization System Layout

could produce desirable smoke filaments in the test section during operation. Several centerline locations immediately ahead of, and within the contraction section, were investigated using a modified version of the smoke rake described earlier. To test appropriate locations, longer main support pipes that were capable of spanning the 10-foot wide sections were installed on the smoke rake.

The wind tunnel, when operated in low gear, runs the fan at 188 rpm and produces a maximum of 33 ft/s in the test section. Noise levels are extremely low and vibrations are virtually non-existent. The smoke filaments that are produced when the smoke rake is downstream of the two settling chamber screens but upstream of the contraction are sharp and distinct, but become very unstable and wavy by the time they reach the test section. This waviness is suspected to be caused by the high free stream turbulence in the flow and the smoke filament transitioning to the turbulent state. As the smoke rake is moved closer to the test section, the smoke filaments gain stability but become diffused. The diffusion occurs due to the inability to match the exit velocity of the smoke from the smoke tube orifices with the free stream velocity. The broader, diffused smoke filaments are used for flow visualization by laser sheet because of their increased stability and the requirement of the smoke to remain in the laser sheet for illumination. The smoke rake is positioned approximately four feet ahead of the test

section (see Figure 2 and 7). To distribute smoke to any area under investigation, the smoke rake can be moved up or down several inches. Test section velocities of 65 ft/s have been achieved with the smoke rake in place but are normally limited to velocities below 50 ft/s.

The smoke machine is positioned in the settling chamber and controlled via the 25-foot remote control. When operating the smoke machine in the continuous mode, the wind tunnel becomes uniformly filled with smoke within a few minutes, causing unwanted light scattering in all of the part illuminated by the laser light sheet. The accumulated smoke is purged from the wind tunnel by opening large air exchanger doors at low wind tunnel speeds. The momentary mode is the preferred mode of operation because it produces a sufficient quantity of smoke for a limited duration and reduces the amount of smoke that accumulates in the wind tunnel over a period of time.

The purpose of the traverse is to support and orient the conversion optics. The location of the traverse on the wind tunnel is determined by the test model orientation and the area under investigation. The combination of traverse location and conversion optics orientation and position, yields unlimited alignment possibilities for the laser sheet.

#### IV. PHOTOGRAPHY

A 35mm Nikon N2000 camera equipped with a 50mm f/1.4 lens was used for the photographic recording of the flow phenomena around models mounted in the wind tunnel test section. Primary considerations for selecting the 35mm format were the ease and speed of handling, and its mobility. T-max 400 black and white film, with normal film processing, was used for all photographs. Photographs were taken in the manual exposure mode using the built-in light metering data. An aperture setting of f/1.4 and a shutter speed of 1/30 sec produced excellent results and provided the optimum combination for this work.

The laser light sheet itself satisfied the lighting requirement necessary for flow visualization work and eliminates the basic front or back lighting technique used in other smoke flow visualization methods (Ref. 10). One general consideration that must be met with the application of light is the type of background that is used. A black background should be used to improve the sharpness and separation of the subject matter produced by the addition of smoke. Although only the bottom surface of the test section is flat black, the intensity of the laser light sheet assures separation and sharpness even when framing the area



of interest against the white background of the remaining test section walls.

The camera is tripod mounted and the shutter utilizes a cable release. Photographs can be taken from the top or side observation window depending on the model orientation and area to be investigated.

## V. RESULTS

Two models were selected to demonstrate the capabilities of the flow visualization system. A well studied two-dimensional NACA 66(215)-216 airfoil was used to record the changes in the flow patterns as the angle of attack was varied from zero to 50 degrees. A three-dimensional model of a missile provided an opportunity to record the vortical flow phenomenon that is typical of flow over an ogive body.

The flow visualization of the airfoil was conducted using the smoke rake to generate five smoke filaments at a flow velocity of 33 ft/s. The laser light sheet was projected from the side observation window perpendicular to the vertically mounted airfoil and parallel to the flow direction. Figures 8 through 13 are representative photographs of the flow visualization studies with the airfoil model. As seen in Figures 8 and 9, the flow remains attached at low angles of attack but starts to separate near the trailing edge at an angle of attack of 10 degrees. Flow is fully separated at an angle of attack of 20 degrees (as seen in Figure 10). Figures 11, 12, and 13 show the formation and growth of vortices at higher angles of attack of 30, 40, and 50 degrees, respectively.

The missile model was illuminated from the top of the test section which provided the opportunity to photograph



Figure 8. Airfoil at 0° Angle of Attack

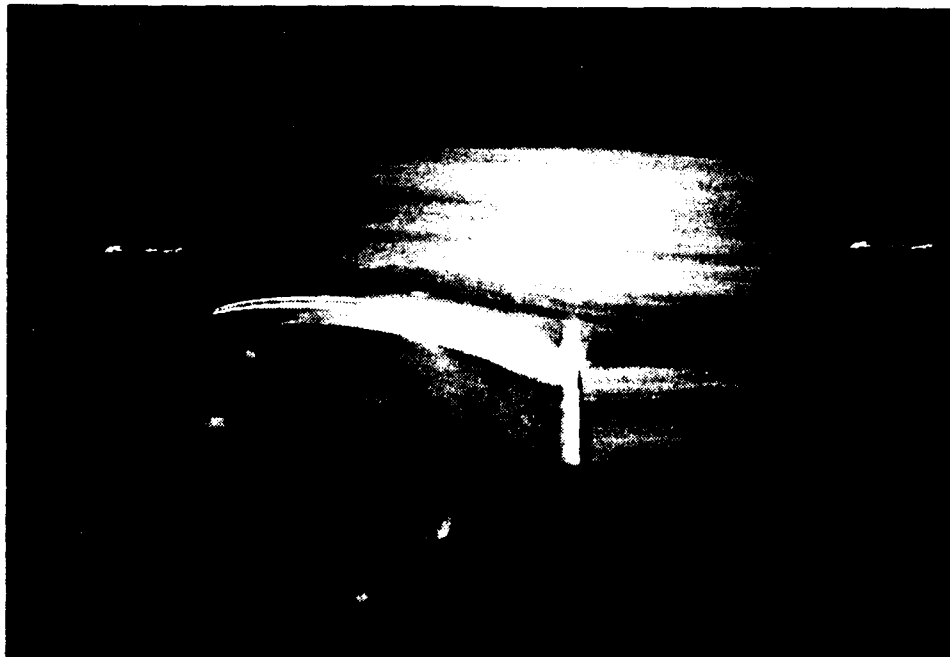


Figure 9. Airfoil at 10° Angle of Attack



Figure 10. Airfoil at 20° Angle of Attack



Figure 11. Airfoil at 30° Angle of Attack



Figure 12. Airfoil at 40° Angle of Attack



Figure 13. Airfoil at 50° Angle of Attack

the missile from the side observation window from a head-on position as it was yawed 60 degrees from the flow direction. The laser light sheet was positioned perpendicular to the longitudinal axis of the missile body at the base of the missile nose cone (Figure 14). A single smoke filament issuing out of a one-inch diameter pipe directly connected to the smoke machine was used at a flow velocity of 50 ft/s. Figure 14 clearly shows two asymmetric vortices on the leeward side of the missile model.



Figure 14. Missile Body at 60° Yaw Angle

## VI. CONCLUSIONS AND RECOMMENDATIONS

### A. CONCLUSIONS

Incorporation of the flow visualization system using smoke and laser light sheet has enhanced the capabilities and utility of the NPS low speed wind tunnel. The system set-up is relatively simple and can be performed by one person in a short period of time. The use of fiber optics has enhanced the safety aspects of laser operations and has proven to be a convenient method for transporting laser light. The ability to visualize the flow will benefit both the researcher and student by providing the added dimension of insight into the physical understanding of complex flow phenomena. It will aid the researcher in identifying the regions of interest for detailed quantitative measurements. The student will be able to better visualize and appreciate the structure of complex flow fields during experimental investigations in the Aeronautics Department of the Naval Postgraduate School.

### B. RECOMMENDATIONS

Although the flow visualization system expands the capabilities of the low speed wind tunnel, more developmental work is essential to improve the flow quality

in the test section as well as to improve the flow visualization system. It is strongly recommended that an improved design and development of smoke injection device be undertaken along with necessary modifications to improve the flow quality in the test section.



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