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DEVELOPMENT OF A HIGH SPEED LASER SCANNING FLOW VISUALIZATION SYSTEM

by

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TABLE OF CONTENTS

ABSTRACT

The main objective of this thesis is to develop a state of the art high speed laser scanning flow visualization system. Three basic systems were evaluated for their three-dimensional flow visualization potential. These systems are 1) Cylindrical lens laser beam expansion, 2) Rotating polygon laser scanning and 3) Galvanometer laser scanning. The galvanometer laser scanning system was proven to be the most useful in terms of flexibilty and having the greatest laser sheet intensity. With this laser scanning system as the base, a three-dimensional high speed laser scanning system was developed which allows scanning in any arbitrary plane at any streamwise position along a recirculating plexiglas water channel.

This system was used in many different applications in order to gain insight into its true potential as compared to convential flow visualization systems. The primary advantage this system has over three-dimensional dye injection techniques and hydrogen bubble strobe light techniques is that it will provide quantitative information for unsteady three-dimensional flow fields as improved CAD reconstruction and other techniques are currently being developed (Rockwell 1987).

1.0 INTRODUCTION

1.1 Overview

Laser scanning, as applied to flow visualization, is a relatively new concept which employs a laser beam sweeping through a given plane in the flow; it is perceived by the human eye as a continuous sheet of laser light. This sheet of light is obtained by deflecting an Argon-ion laser beam from an oscillating plane mirror attached to a galvanometer, providing illumination of the fluid marking particles. The laser sheet can be oriented in any plane of the flow giving new possibilities in gaining insight into two and three dimensional fluid mechanics.

The laser scanning technique developed at Lehigh is used in a recirculating water channel. Other flow visualization techniques employed in this channel involve the use of a strobe or other sources of incandescent illumination with hydrogen bubble timelines or dye injection as the fluid markers. Replacement of these light sources with high speed laser scanning can enhance the flow visualization capability of these fluid marking media. Hydrogen bubbles are created by forming an electrolysis circuit by inserting a platinum wire and a carbon rod in the water and generating a current through it. When correctly set up (Schraub 1964) hydrogen bubbles are liberated from the wire and provide a very useful fluid marking medium. A very popular use of this method is to pulse a current through a vertical platinum wire at a certain duration and frequency to give timelines of the desired width and spacing. These timelines are then illuminated with a strobe of comparable frequency to give two-dimensional flow patterns which may be captured on film and enhanced using digitization and other computer techniques. This method has been expanded to produce three dimensional computer images of unsteady flows by combining a number of phase-locked two-dimensional images taken at various cross-stream locations (Ongoren 1987).

Dyes injected into a flow are also very popular. They may be anything from simple food coloring to carcinogenic phosphourescent dyes. Illumination for most dye injection techniques is usually provided by an incandescent lightbulb, giving two-dimensional flow patterns: however, laser techniques have also been employed to provide a cross-sectional slice of the flow.

1.2 Previous Use of Laser Flow Visualization Methods

Nosenchuck (1986) has developed a three-dimensional laser illumination technique that does not involve galvanometer scanning. In his system, light from a laser beam is passed through a cylindrical lens and is spread out to form a laser sheet. The laser sheet illuminates a cross-section of the flow in the x-z plane as depicted in figure 1-1.This type of laser sheet is drastically reduced in intensity, compared to the galvanometer scanning method, because the light from a single laser beam must cover a much larger area. The laser sheet intensity at a given distance away from the cylindrical lens is given by (Schmitt and Ruck, 1986):

$$I = \frac{2 P_L f}{s^2 z}$$

where:

P_L is the power of the laser

f is the cylinder lens focal length

s is the laser beam radius

z is the distance from the lens

This is also well approximated by:

$$I = \frac{P_L}{H D}$$

H is the laser sheet width

D is the laser sheet thickness

For a one mm thick laser sheet 100 mm wide, the intensity at that distance from the lens would be 40 mW/mm for a laser power of four watts.

In contrast,the galvanometer scanning method sweeps one constant diameter beam at a high rate of speed, thus maintaining constant intensity at all distances from the galvanometer mirror. Therefore, the laser sheet intensity is exactly the same as the incident laser beam or 5 W/mm for a laser power of four watts and a one mm diameter beam. For this reason, Nosenchuck's method is only useful with flourescent dyes since they enhance the effectiveness of the laser illumination. The vertical position of the horizontal laser sheet is changed by deflecting the incident laser beam from a mirror mounted to the shaft of a stepping motor which can give up to 256 steps per second. Each step changes the vertical position of the laser sheet by a small increment and a video camera mounted above the flow records the image from each step as shown in figure 1-2. A three-dimensional image of the flow structure can be created with his system by combining the images from these horizontal sheets of light, all of which are obtained quickly enough to be considered instantaneous. Figures 1-3 and 1-4 contain examples of a cross-sectional view in a horizontal plane of a turbulent boundary layer and the computer processed reconstruction of many different cross-sections. Since this technique is based on blobs of dye injected into a flow, it is strictly limited to qualitative analyses only.

A team of French scientists from the company A.I.D. use a rotating polygon with plane mirrors attached to each side of the polygon to deflect the light from a laser beam (Fig. 1-5). As the rotating polygon turns at a high rate of speed (up to 5000 rpm) the laser beam is swept back and forth through the flow. The resultant laser sheet is then oriented in a streamwise plane, illuminating light reflecting particles injected into the flow. Their particular type of rotating polygon laser scanning system is fairly expensive compared to the galvanometer scanning system. In contrast to the foregoing technique, only streamwise two-dimensional flow visualization images have been obtained with this rotating polygon system.

2.0 LASER SCANNING TECHNIQUE

2.1 Introduction

Diagrams of the laser scanning system are shown in Fig. 2-1 through 2-4. As indicated, the laser beam originates from the laser head and is deflected from two beam steering mirrors which perfectly align the laser beam in the direction of motion of the flying table. This perfect alignment is neceesary to maintain scanning consistency when the table is at both the near and far ends of the water channel. The laser beam is then deflected from another beam steering mirror mounted directly in the center of the swivelling base and is directed toward the galvanometer mirror, also mounted on the swivelling base. This swivelling base arrangement is convenient because no readjustment of the beam is necessary when changing the orientation of the laser sheet in the flow, one simply rotates the swivelling base. At this point, significant divergence of the beam may have occurred if the laser beam travelled more than several meters. In order to refocus the beam back to approximately one millimeter in diameter, it is passed through a plano-convex lens before it is deflected from the rotating mirror attached to the galvanometer. The rotating mirror then sweeps the beam, creating a sheet of laser light. This sheet is passed through a cylindrical lens, which controls the laser sheet thickness, and then through the floor of the plexiglas recirculating water channel, providing laser illumination for the hydrogen bubbles. The hydrogen bubble image is recorded on video for further analysis and image processing.

2.2 Laser

The laser used is a Lexel Model 95 Argon type purchased from Cooper Lasersonics. Figure 2-5 shows the laser head components. In single line operation it has a two watt capability and emits a green 1.3 mm diameter laser beam with the temperature controlled Etalon assembly fully operational. The Etalon provides extremely stable single frequency operation, necessary for applications such as holography and interferometry. Single line operation means that, within a given bandwidth, only one lasing wavelength is present (547 nm). For laser scanning flow visualization, the Etalon assembly is not necessary. Its removal almost doubles laser power to four watts. Laser power can be doubled again by switching to multi-line operation, which increases the number of wavelengths present to six. This changes the laser beam to an aqua (blue-green) color and is accomplished by purchasing and installing a multi-line mirror holder (Model number 502).

However, it was discovered that the four watt green laser light produces a better image on the video than the more powerful aqua color when used with hydrogen bubbles. Use with dyes may produce a different result, although this has not been determined for this thesis.

A complete description of laser operation (and theory) may be found in the manual; the basic steps follow. Initially, one must ensure that all cooling lines are properly connected to the laser power supply. The cooling water is then turned on with a flow rate of approximately two gallons per minute. At this point, the laser power supply may be turned on as per the detailed instructions in the manual. When lasing is initiated, the laser may be tuned to achieve maximum power output by adjusting the horizontal and vertical tuning knobs individually until the power meter indicates a maximum level. **Caution: Four watts is more than sufficient laser power to cause permanent eye damage if the laser beam strikes the retina; users are advised to wear Argon laser eye goggles for optimum safety.** When turning off the laser, one only presses the off switch and turns the key switch to off. The circuit breaker on the laser power supply must be left on to increase the life of the laser.

2.3 Beam-steering Mirrors

The beam-steering mirrors used in this system were purchased from the Ealing Optics Co. They are 38 mm by 25 mm plane mirrors with an aluminized coating to maximize reflectivity. The mirrors come mounted in a special holder which allows them to be rotated about their horizontal and vertical axes. In addition, these holders are attached to an aluminum post with a set screw for height adjustment. Therefore, the incident laser beam may be reflected from each mirror in any direction in space for convenient alignment.

2.4 Flying Table and Rail System

The recirculating water channel has a test section which is fifteen feet long and can generally accommodate more than one experimental setup at a time. In order to accommodate all experimental arrangements placed at any location in the channel, a linearly translating table arrangement was designed for the basic scanning system and has become known as the "flying table". As depicted in fig. 2-1 through 2-4, the flying table consists of half-inch aluminum plate, 10" long by 33" wide and is mounted to four Thomson pillow block linear bearings (model SPB-16-OPN) which slide on two stainless steel rails one inch in diameter and fourteen feet long. These rails are held in place by four end clamps and are supported by ten 24" aluminum gude rails, all purchased from the Thomson company.

The swivelling base and galvanometer are part of a second linear translation setup which is mounted directly to the flying table. The second linear translation setup moves the galvanometer scanning system perpendicular to the direction of motion of the flying table. This type of design allows positioning of the laser sheet in any streamwise or cross-stream location of the water channel while scanning in any arbitrary plane. The second linear translation setup consists of two .5" diameter stainless steel rails 30" long and 6" apart and a 5" by 10" table made from half-inch aluminum plate. The table is mounted to the rails with Thomson pillow block linear bearings. A Teflon sleeve was inserted into this table with the top of the sleeve three mils higher than the surface of the table. On this sleeve is the swiveeling base, which rotates freely on the Teflon. The swivelling base is 10" in diameter and made from half-inch aluminum plate. Mounted directly in the center of the swivelling base is a beam-steering mirror which deflects the laser beam through a plano-convex lens to the galvanometer mirror.

2.5 Focussing of Laser Beam and Laser Sheet

Focussing of the laser beam is necessary when the laser beam has diverged a substantial amount. This usually happens when it has travelled several meters and after it reflects from each beam-steering mirror. Without refocussing, the laser beam may be too wide for the galvanometer mirror or the laser sheet may be too thick (the laser sheet is as thick as the incident laser beam is wide). If the beam is too wide for the galvanometer mirror, then only part of it will be scanned through the flow, significantly decreasing the apparent intensity of the laser sheet. Therefore, the laser beam must be refocussed to be at least within the boundaries of the galvanometer mirror. This refocussing is done with the 50 mm focal length plano-convex lens which is 25 mm in diameter. As the beam passes through this lens, ts diameter decreases until it reaches the focal length. Since the galvanometer mirror is to be placed approximately two to three inches from this lens, the 50 mm focal length was chosen. The lens diameter of 25 mm is sufficiently large to capture all of the incident laser light. If the galvanometer mirror is placed a distance away from the lens which is very close to the focal length, the beam will be focussed down to almost a point thickness. The intensity of this beam on the galvanometer mirror will be great enough to burn a hole through it, completely defeating the plano-convex lens' purpose. Figure 2-6 shows the optimum placement of the galvanometer mirror relative to the plano-convex lens; the beam diameter should be approximately one mm for best results. After being deflected from the galvanometer mirror, the laser beam divergence will be drastic due to the optical properties of the plano-convex lens. The cylindrical lens placed in the laser beam path beyond the galvanometer serves two purposes. First, it straightens out the laser beam to prevent further divergence. As the laser beam is diverging, it will strike the cylindrical lens with a certain. This width will be maintained after it passes through the cylindrical lens. However, the resultant laser image will no longer be a beam. Cylindrical lenses have the unique property of magnifying an image in only one dimension. The resultant laser image will be slightly expanded along the length of the cylindrical lens having the appearance of a thin narrow sheet, even when the incident laser beam is stationary. This particular 44 mm focal length, 24 mm by 169 mm cylindrical lens was chosen to provide as narrow a sheet as possible, avoiding significant loss in laser intensity. As the galvanometer mirror is swept back and forth, this thin narrow sheet is scanned through the flow creating the much larger laser sheet used for flow visualization.

The second purpose of the cylindrical lens is to control the thickness of the laser sheet. This is accoplished by the positioning of the lens relative to the galvanometer mirror. Placement of the cylindrical lens very close to the focal point of the plano-convex lens will give a very thin laser sheet (less than one millimeter), whereas placement well beyond the focal length gives a thick laser sheet (approximately one centimeter). A thick laser sheet oriented in a cross-stream plane yields thick "fuzzy" hydrogen bubble lines on the video screen. This is due to the resultant image formed by "averaging " the position of each hydrogen bubble as it first appears at the front side of the laser sheet and changes position as it passes through the laser sheet. The very thin laser sheet seems more desirable because its apparent intensity on the video screen is much greater giving very sharp hydrogen bubble lines. This is true, except for the fact that any fine particulate matter present in the flow will also reflect the laser light and scatter around the hydrogen bubble lines, inducing "noise" to the video image. The actual laser sheet thickness used in an experiment is subject to each experimenter's opinion of the hydrogen bubble images and the amount of "noise" tolerable in each video sequence.

2.6 Galvanometer Scanner and Controller

In order to create a laser sheet in the flow, the Argon laser beam must be swept back and forth at such a high rate of speed as to make the sweeping laser beam appear to be one continuous laser sheet. For this purpose, a galvanometer scanner was purchased from the General Scanning Co. The rotating shaft on a galvanometer deflects in proportion to the voltage applied to the galvanometer circuit and rotates according to some periodic (a/c) input applied to the galvanometer. A small mirror is securely fastened to the end of the galvanometer shaft and rotates back and forth, scanning the incident laser beam at a high rate of speed. Figure 2-7 shows the main structural features of the galvanometer and mirror assembly. The type of galvanometer used is the General Scanning Co. G-120D galvanometer scanner. This was chosen for its 12 degree maximum excursion capability from static position (24 degree total deflection from peak to peak) and the feedback control feature which can let the user know the exact beam position relative to the input signal over each cycle. A factory mounted 7 mm by 7 mm plane mirror was also purchased from General Scanning and connected to the galvanometer shaft with a set screw (being careful not to exert too much torque on the galvanometer shaft). The galvanometer scanner is mounted in an aluminum holder with a nylon tip set screw to avoid marring the mounting hub. A scanner control amplifier provides input to the galvanometer circuitry and control of the scanning characteristics. The General Scanning model A6120K Control Amplifier was purchased for this purpose. It comes in easily assembled kit form with exactly the same electronic circuitry as the pre-assembled CX660 scanner control amplifier at approximately half the price. This scanner control amplifier has a built-in ramp input generator which can operate from 1 to 180 Hz. with an amplitude of -5V to +5V. The main operating characteristics of the galvanometer scanner are its frequency (scanning rate) and scanning amplitude (a greater scanning amplitude gives a wider laser sheet). Both are controlled from the scanner control amplifier as is the mirror offset position, which simply sets the static (d/c) position of the galvanometer shaft. The scanner control amplifier is also capable of transmitting an external frequency generating signal to the galvanometer.

Initial use of the galvanometer scanning in the cross-stream plane with the image recorded on the video system produced some interesting results in regard to the scanning frequency and amplitude. Once the frequency is great enough to create a laser sheet, varying the frequency has no effect on the apparent laser sheet intensity. There is, however, a problem when the frequency is too close in synchronization to the 120 frame per second operation of the video camera. In this case, a horizontal line will sweep across the video monitor, making subsequent data analysis very difficult. This effect also exists when the ramp generator input is operating at the maximum 180 Hz. The problem was resolved by connecting an external frequency generator to the scanner control amplifier, allowing operation of the galvanometer up to 500 Hz (1000 scans per second). Any input from the external frequency generator may be selected, however, if one wants to use the feedback control feature, one must use a sinusoidal input since the galvanometer circuitry is not accurate with a ramp input at higher scanning rates. In using the external frequency generator, care in not exceeding the five volt limit must also be exercised when setting the input amplitude. Higher input amplitudes will damage the galvanometer.

The effect of varying the scanning amplitude is that the apparent laser sheet intensity is inversely proportional to the scanning amplitude, i.e., a wider laser sheet will give a less bright image on the video monitor. This result was corroborated by Schmitt and Ruck (1986). Their studies of the effect of laser scanning amplitude on intensity show that the laser sheet intensity is inversely proportional to the square of the scanning amplitude (width) at a given distance (R') from the laser sheet origin as follows:

(3) $$I(R') = I \frac{s^2(R')}{H^2(R')}$$

s = laser beam radius

where $$I = \frac{P_L}{\pi s^2(R')}$$

H = laser sheet width (scanning amplitude)

R'= scanning radius of curvature

To maximimize the laser sheet intensity, one must adjust the scanning amplitude to be as low as possible for a given experiment. For the galvanometer scanning system the laser sheet width is approximately the arclength of the laser beam at a given distance from the galvanometer mirror (R'). Since the maximum total deflection of the galvanometer is 24 deg. with a five volt amplitude input, the arclength (H) is in direct proportion to the voltage amplitude (V) input to the galvanometer and may be expressed as follows:

(4) $$H = \frac{V}{5} \frac{24}{360} (2\pi) R'$$

Using this value of H in equation (3), assuming that beam divergence may be neglected (s(R')= s =constant), yields the following expression which relates the laser sheet intensity I(R') to the galvanometer amplitude input, V, at a given distance from the galvanometer mirror, R':

$$I(V,R') = \frac{P}{\pi} \left[\frac{5}{V} \frac{360}{24} \frac{1}{2\pi R'} \right]^2$$

2.7 Rotating Polygon Scanning System

A rotating polygon scanning system was purchased for comparison to the galvanometer scanning system to ensure that the optimum laser scanning system is installed to give the best results for flow visualization experiments. This system is based on the deflection of the laser beam from a mirrored rotating polygon. As each facet of the mirror rotates past the incident laser beam, the angle of reflection changes. This has the effect of sweeping the laser beam once through the flow as each facet passes by. Therefore, the scanning rate is equal to the number of facets multiplied by the rotational speed of the mirror. For example, if the rotational speed of a hexagonal mirror is 500 revolutions per second (30000 rpm), then the scanning rate is 6 X 500 = 3000 scans per second.

The rotating polygon system was purchased from The Lincoln Laser Co. It consists of a 2" diameter hexagonal mirror, with each facet one inch long, attached to a variable speed, low voltage, hysteresis synchronous motor (model 225). The motor speed is controlled by the model

VFC-2 motor controller. The speed range of the motor is 1200-3000 rpm (20-500 rps), giving a range in scanning rates from 120-3000 scans per second. This range of scanning rates is sufficient to avoid synchronization with the 120 frames per second video camera. However, the particular geometry of this hexagonal mirror gives a wide range of angles of reflection, resulting in a very large scanning amplitude or laser sheet width. This laser sheet has a very low apparent intensity compared to those obtainable with the galvanometer scanning system due to the large scanning width. Schmitt and Ruck applied their finding of the relation between laser sheet intensity and distance from the origin to the rotating polygon principle and obtained the following relation:

$$I(R') = \frac{P}{\pi}\left[\frac{N_f}{2\pi R'}\right]^2$$

where N_f is the number of facets on the rotating polygon

The rotating polygon scanning amplitude is not adjustable since it is only a function of mirror geometry. Decreasing the amplitude would involve either increasing the number of facets on the rotating polygon or decreasing the diameter of the hexagonal mirror. These possibilities were not pursued since the galvanometer scanning system has given satisfactory results.

2.8 Hydrogen Bubble Generating System

Hydrogen bubbles serve as an extremely useful fluid marking medium because of their availibility in water, they do not pollute the water in the recirculating flow channel during long flow visualization experiments and their capability for producing quantitative information from the flow, especially with a high speed laser scanning system (Utsch 1987 and Magness 1987).

As mentioned in the introduction, the bubble generating circuit consists of a platinum wire (usually one mil thick) and a carbon rod (serving as the anode and cathode) and a power supply which pulses a current through the system. With sufficient power, the water molecules dissociate into hydrogen and oxygen molecules. If the platinum wire is connected to the positive lead from the power supply, it will liberate the hydrogen bubbles and the carbon rod will liberate the oxygen bubbles (and vice-versa). The hydrogen bubbles are better for flow visualization because there are twice as many of them and they are smaller. Adding an electolyte, such as sodium sulfate, enhances this process. Utsch developed different platinum wire configurations for quantitative analyses of a three-dimensional flow. One typical configuration is a horizontal multi-wire probe consisting of platinum wire strung horizontally fifteen times across a brass holder (fig. 2-8).

When this probe is placed across a uniform flow the wire produces fifteen equally spaced lines. When a body placed just upstream from the flow forces the fluid, these horizontal lines distort with the fluid motion giving a cross-sectional view of the complicated flow structure.

The power supply used for this type of hydrogen bubble system must be larger than those used for the more conventional single-wire probe setups since it generates hydrogen bubbles at a much greater rate. A power supply specifically designed and built for this purpose produces a maximum of 300 volts at seven amperes. The hydrogen lines may also be pulsed up to a frequency of 100 Hz. depending on the duration of each pulse. One should be careful when working around the water channel when this power supply is in operation.

2.9 Video Recording System

The video system used is an Instar Video system by Video Logic. It basically consists of a video camera, video monitor and black and white video recorder which can record at 120 frames per second or 240 frames per second (not often used). When recording images from the laser sheet the video camera settings (aperature, focal length, etc.) must be optimized for each situation. If the laser sheet is oriented in a cross-stream plane, it is necessary to place a large plane mirror in the flow downstream from the laser sheet to reflect the image to the video camera (Fig. 2-9). All data is stored on video tapes for further analysis and processing.

3.0 APPLICATIONS OF THE LASER SCANNING SYSTEM

3.1 Introduction

The laser scanning system has been applied to several different types of unsteady flow visualization experiments during its development. An AFOSR grant has funded investigations into the unsteady flow structures from swept edges subject to controlled motion (Rockwell 1987.), where the laser scanning system has proved to be very useful and has potential for further development. Another type of flow visualization used with the system is from a blunt trailing edge having a turbulent boundary layer at separation, as well as a cavity flow also having a turbulent boundary layer at separation.

The AFOSR investigations (Magness 1987 and Utsch 1987) used the laser scanning system as part of an "integrated active control and quantitative flow visualization system". In this system, scale wing models were actively controlled with arbitrary forcing functions by microprocessor based forcing mechanisms. Utsch visualized the three-dimensional vortex generation from oscillating wing segments by illuminating hydrogen bubble lines with cross-stream laser sheet slices. Using the laser scanning system with a newly developed three-dimensional tracking technique (involving the use of a hydrogen bubble grid), he will attempt to determine the circulation of the vortical structures as a function of streamwise distance along the wing.

Magness is investigating the flow structure on a delta wing oscillating in pure pitching motion. He uses the laser scanning system to characterize the nature of the three-dimensional flow formation as a function of angle of attack, reduced frequency of oscillation and sweep angle by taking cross-stream laser sheet slices similar to those of Utsch. A CAD technique allows reconstruction of the three-dimensional flow surfaces by combining several laser sheet slices taken at various chordwise locations. Further CAD reconstruction techniques will be developed for three-dimensional surfaces representing flow evolution at an instantaneous angle of attack and evolution with time at a given chordwise location for the results of both Utsch and Magness.

Laser scanning illumination was also applied to the case of a blunt trailing edge with the laser sheet oriented in a stream-wise plane. This type of two-dimensional flow-visualization, using a vertical hydrogen bubble probe, has successfully been accomplished with strobe lights and was attempted with the laser scanning system on both the video monitor system and a Nikon 35 mm. camera for comparison. Orientation of the laser sheet downstream from the blunt trailing edge in a cross-steam plane would have potential for insight into the three-dimensional flow structure of a separated turbulent boundary layer when used with a multiple wire horizontal hydrogen bubble probe. This was attempted in order to discover the possibilities of hydrogen bubble line resolution for this type of flow on the video image.

Strobe light illumination for hydrogen bubble visualization of two-dimensional cavity flows has previously been accomplished with success. Accentuation of flow structure detail within the cavity was attempted with a small amplitude laser sheet confined to the width of the cavity.

Multiple wire hydrogen bubble probes were created and used extensively in these investigations. The first generation of probes were similar to the fifteen wire horizontal probe discussed previously. This probe was convenient for initial investigations of the laser scanning concept. The next type of probe developed was the "omni" probe. This probe consists of a grid of both horizontal and vertical platinum wires as shown in Fig. 3-1. The omni probe concept provides improved detail of the unsteady flow cross-section because it allows one to use the hydrogen bubble line intersections from the vertical and horizontal platinum wires as reference points for the flow development during each oscillation cycle.

3.2 Flow Visualization of Oscillating Wing Segments

This AFOSR project (Utsch 1987) investigated the three-dimensional vortex generation from two interacting wing segments subject to controlled motion. A schematic of this setup can be found in fig. 3-2. Each wing segment is attached to a rotating shaft. The shafts are concentrically mounted allowing each one to rotate freely and independently from the other. At the end of each shaft is a chain and sprocket assembly attached to a stepping motor. The two motors are controlled independently by a Zenith microcomputer allowing arbitrary forcing of the wing segments.

For visualization, a multiple-wire hydrogen bubble probe is placed several inches upstream from the wings. When the power supply is turned on hydrogen bubble sheets surround the wings and are distorted with the three-dimensional flow structure that develops around them. The flying table is placed at some chordwise position (x/c) along the wings with the swivelling base set at the desired scanning plane, usually perpendicular to the free-stream flow. With the laser in operation, the rotating mirror is set into operation at the desired scanning frequency and amplitude. As mentioned in a previous section, the scanning frequency is set at approximately 500 Hz. to avoid synchronization with the

120 frame per second video camera. The scanning amplitude is set as low as possible, covering a sufficient cross-sectional area of the unsteady flow field. Adjustment of the cylindrical lens gives the desired laser sheet thickness. Figures 3-3 shows a typical omni-probe video image obtained with this system. The bright lines in the photos are from the intersection of the hydrogen bubble sheets with the laser sheet. In this image one of the wing segments is fixed and the other is forced at a reduced frequency of k=1.27, where k=fc/U (f=oscillation frequency, c=chord length and U=free-stream flow speed), and a maximum amplitude of 60 degrees. The laser sheet was oriented near the trailing edge of the wing segments at x/c= .9. This flow visualization system clearly shows a cross-section of the three-dimensional vortex which forms on the underside of the oscillating wing as the wing segments get closer together. Figure 3-4 shows a similar omni probe sequence at the different streamwise planes as indicated. Three-dimensional vortex formation is also clearly identifiable with a horizontal multiple-wire probe, as shown in figures 3-5 and 3-6.

3.3 Flow Visualization of a Pitching Delta Wing

This AFOSR project (Magness 1987) investigates the nature of the vortical flow structure over an oscillating delta wing as a function of mean angle of attack, reduced frequency and sweep angle. Plexiglas delta wings are constructed with various sweep angles and are attached to a shaft at the trailing edge as depicted in fig. 2-9. The shaft is held in place by a plexiglas support frame. A chain and sprocket assembly connects the delta wing shaft to a stepping motor. The stepping motor is controlled by the Zenith microcomputer system allowing arbitrary forcing of the wing.

The hydrogen bubble probe setup is similar to the oscillating wing segment investigation. A horizontal probe is placed upstream from the pitching delta wing. The flying table is positioned in a cross-stream plane at some chordwise distance (x/c) from the apex. Laser scanning in this plane illuminates the hydrogen bubble sheets showing a cross-section of the unsteady three-dimensional vortex formation. In order to avoid reflection of the laser sheet back to the video camera , the delta wing is turned upside down, giving a reorientation of the coordinate axes relative to the freestream flow. Fig. 3-7 shows an example of the type of image obtained from the video monitor for this application of laser scanning. This image was taken at x/c=.5 and k=2.0. It gives insight into the hysteresis effect on the vortex formation of a stationary wing to that of an oscillating wing on both the upstroke and the downstroke, all at the same angle of attack. Figure 3-8 gives another example of the type of images obtainable for this application which also compares the vortex formation over the delta wing at various reduced frequencies and angles of attack for both an oscillating wing and a stationary wing.

Another interesting new development in this application of laser scanning is visualization of the vortex core cross-section. The lift of a delta wing is due to the formation of a vortex core over the upper surface of the wing. Magness oriented the flying table and swivelling base such that the laser sheet cut through this vortex core giving further insight into its formation.

3.4 Flow Visualization of a Separating Flow from a Blunt Trailing Edge

This unsteady flow experiment was performed with a turbulent boundary layer separating from a one inch thick plexiglas plate with a square trailing edge, resulting in three-dimensional vortex shedding. The turbulent boundary layer was created by using an overall plate length of sixty inches. This is accomplished by attaching a 48" by 25" plexiglas plate to the 12" by 22.5" trailing edge. The leading edge of the longer plate has a very rough surface over several inches to increase the turbulence intensity as the boundary layer develops. Figure 3-9 contains a schematic of the overall setup. The natural vortex shedding frequency of this trailing edge is approximately 1.9 Hz.

Laser scanning flow visualization of the vortex shedding was first attempted in a streamwise plane for comparison with the conventional strobe light technique. This was done with a vertical hydrogen bubble wire located at the trailing edge with the laser sheet oriented in the same plane. In order to obtain as much of the vortex shedding process as possible, the galvanometer scanning amplitude was set at its maximum position. Figure 3-10 contains typical images from both systems. It is evident from these photographs that with a turbulent separated flow, the strobe light flow visualization method produces a better image than the laser scanning method with the laser sheet oriented in the streamwise direction. This is due to the three-dimensionality of the turbulent boundary layer, i.e., the timelines from the bubble wire are significantly distorted in the spanwise direction. In order to capture them within the laser sheet, the laser sheet thickness must be increased to approximately one cm. The apparent intensity produced by this very wide laser sheet is drastically reduced, creating a poor image on film. Strobe lights produce a sufficiently great intensity in all directions to make the timelines appear to be in one continuous plane.

A cross-sectional view of this type of unsteady separated flow was obtained next with the laser scanning system. This type of image is impossible to obtain with the strobe light technique since only one plane must be illuminated. A horizontal multiple-wire hydrogen bubble probe was placed one cm. downstream from the trailing edge with the laser sheet oriented in the cross-stream plane at various distances downstream from the hydrogen bubble probe. This is very much the same technique performed with the oscillating wing investigations. The resulting images are shown in Fig. 3-11. Image processing the hydrogen bubble lines of each cross-sectional view would assist in reconstruction of the three-dimensional turbulent flow separating from the blunt trailing edge.

3.5 Visualization of a Cavity Flow

Using the same apparatus as in the blunt trailing edge investigation with another one inch thick plexiglas plate located downstream from the blunt trailing edge, a cavity flow was created. The apparatus consists of a 12" by 22.5" plate and its 10" high supports. The plate can be located anywhere along the supports allowing for variation of the cavity width. A vertical bubble wire was placed midspan of the blunt trailing edge. Visualization of the cavity flow was accomplished by orienting the laser sheet in the streamwise direction with the scanning amplitude set just high enough to cover the width of the cavity. This low amplitude scanning produces high apparent intensity on the video image.

Oscillation of the separated shear layer in the cavity flow occurs when the cavity width is increased to a certain minimum. For a flow speed of one foot per second, this minimum cavity width is approximately four cm. Figure 3-12 shows photographs of the oscillating shear layer. Also evident in these photographs are secondary ortices that were not apparent when a conventional strobe technique was used.

4.0 Summary and Conclusions

1) The high speed laser scanning technique developed at Lehigh produces a laser sheet which has a much greater intensity than that of the cylindrical lens technique of Nosenchuck (1986), which must use flourescent dyes to enhance the laser images. For this reason, one may use hydrogen bubble sheets with the galvanometer scanning method to provide quantitative information from an unsteady three-dimensional flow field. Dye injection only provides qualitative information.

2) The laser sheet intensity of the rotating polygon laser scanning method is comparable to that of the galvanometer laser scanning method if the laser sheet width (scanning amplitude) is approximately the same. However, the galvanometer laser scanning method is much more flexible in its ability to control scanning frequency and amplitude and is also less expensive.

3) Construction of a multi-directional linear translating table with a swivelling base is well worth the time and expense. This system greatly increases the flexibility of the galvanometer and associated optical arrangement in preparation for a variety of different experiments.

4) The laser sheet is characterized by the scanning frequency of the laser beam, scanning amplitude and thickness. Scanning frequency has virtually no effect on laser sheet intensity. If a video camera is being used to capture the flow visualization images, one must avoid synchronization of the laser beam scanning frequency with the frame speed of the video. Laser sheet intensity is inversely proportional to the laser sheet width or scanning amplitude. One should use the minimum amplitude necessary for a given experiment.

5) Since the laser scanning system can provide

illumination in any arbitrary plane of an unsteady three-dimensional flow, it has the greatest potential for use in a cross-stream plane. As CAD flow visualization reconstruction techniques are further improved (Rockwell 1987), quantitative information will become available on entire three-dimensional flow fields.

6) Two-dimensional laser scanning in the streamwise plane has no advantage over current strobe techniques when used with hydrogen bubble timelines.

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(1) Schraub, F.A., et. al., "Use of Hydrogen Bubbles for Quantitative Determination of Time-Dependent Velocity Fields in Low-Speed Water Flows", Journal of Basic Engineering, 64-WA/FE-20.

(2) Ongoren, A., Chen, J., Rockwell, D., "Multiple Time-Surface Characterization of Time-Dependent, Three-Dimensional Flows" to be published in Experiments in Fluids, 1987.

(3) Scmitt, F. and Ruck, B., "Qualitative Flow Analysis Using Laser Light Sheets", Laser und Optoelektronik, June 1986.

(4) Nosenchuck, D., private communication, Princeton University, 1986.

(5) Rockwell, D., et. al., "Unsteady Flow Structure from Swept Edges Subjected to Controlled Motion", Progress Report on AFOSR Grant 86-0177, March 1987.

APPENDIX A

Notes on the Improvement of the Video Monitor Image

When capturing a laser sheet image on the video system, one notices that if one views the laser sheet directly with the naked eye (exercising caution), the resolution of the hydrogen bubble lines can be much greater than the same image on the video monitor after it has been optimized. Some of the laser sheet intensity may be lost in the process of recording a laser sheet image on film.

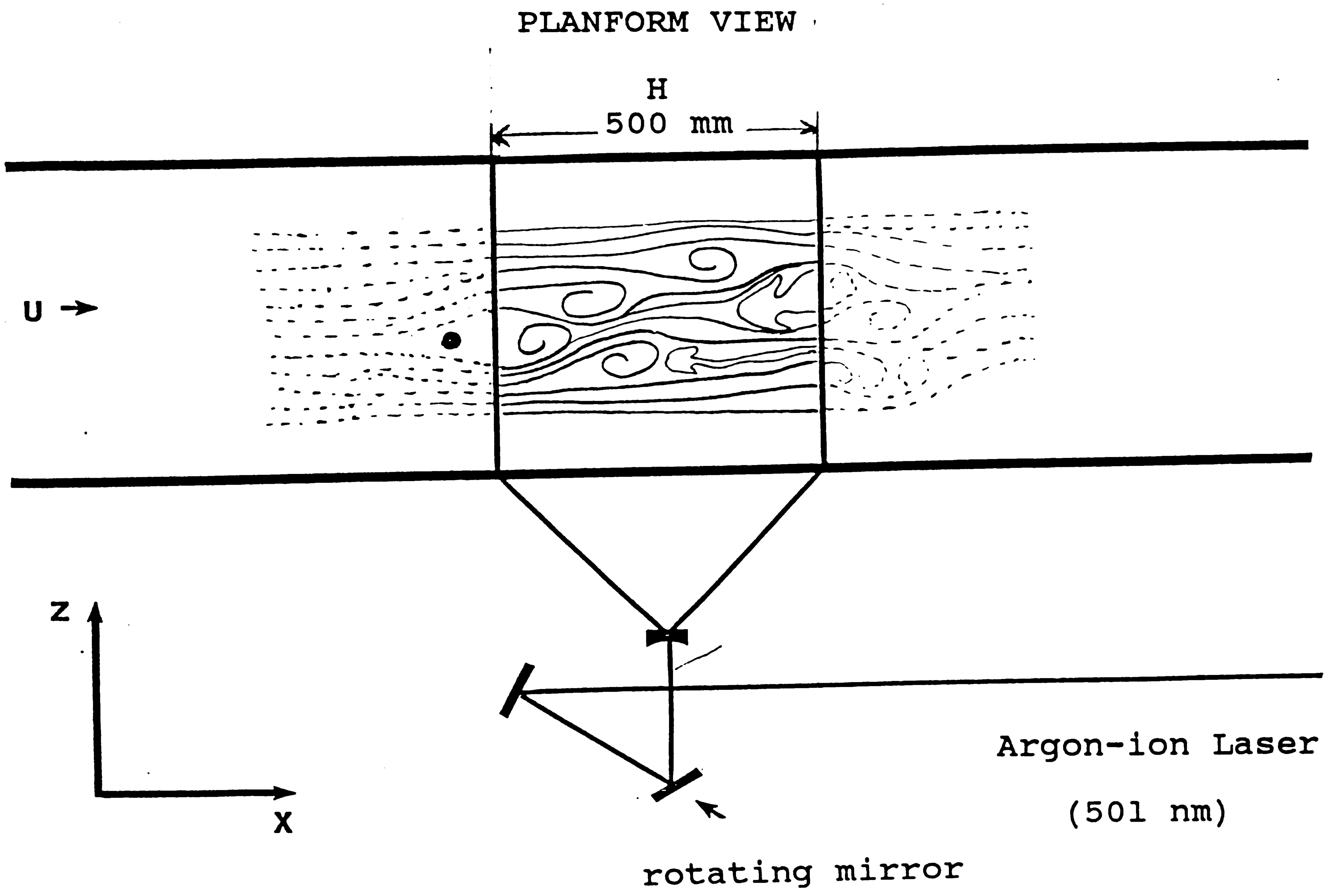
The hydrogen bubble line images vary with the laser sheet thickness. As mentioned previously, a very thin laser sheet will produce greater resolution of the hydrogen bubble lines with the drawback of increasing the reflection of extraneous particles and bubbles. Thickening the laser sheet produces lines which appear to have increased intensity with cross-stream laser scanning. This is due to the fact that many hydrogen bubbles are illuminated over the finite thickness of the laser sheet giving the appearance of brighter lines when viewing the laser sheet in the mirror positioned downstream. However, these lines are not as well resolved due to the change in position of the bubbles as they pass through the finite thickness laser sheet.

It is possible to reduce any extraneous particle reflection while maintaining the hydrogen bubble line resolution with the use of a polarized lens. This lens reduces the amount of light reflected from an image by rotating it to a certain degree relative to the orientation which allows all of the reflected light from the image to pass through. A major disadvantage to this is that the intensity of the overall image is diminished. Therefore, while the extraneous particles may essentially disappear from the video monitor, the desired hydrogen bubble lines lose intensity as well.

A green filter was placed in front of the video camera lens in order to enhance the intensity of the green laser sheet. This made a marginal improvement on the contrast of the hydrogen bubble lines as they appeared on the video monitor.

APPENDIX B

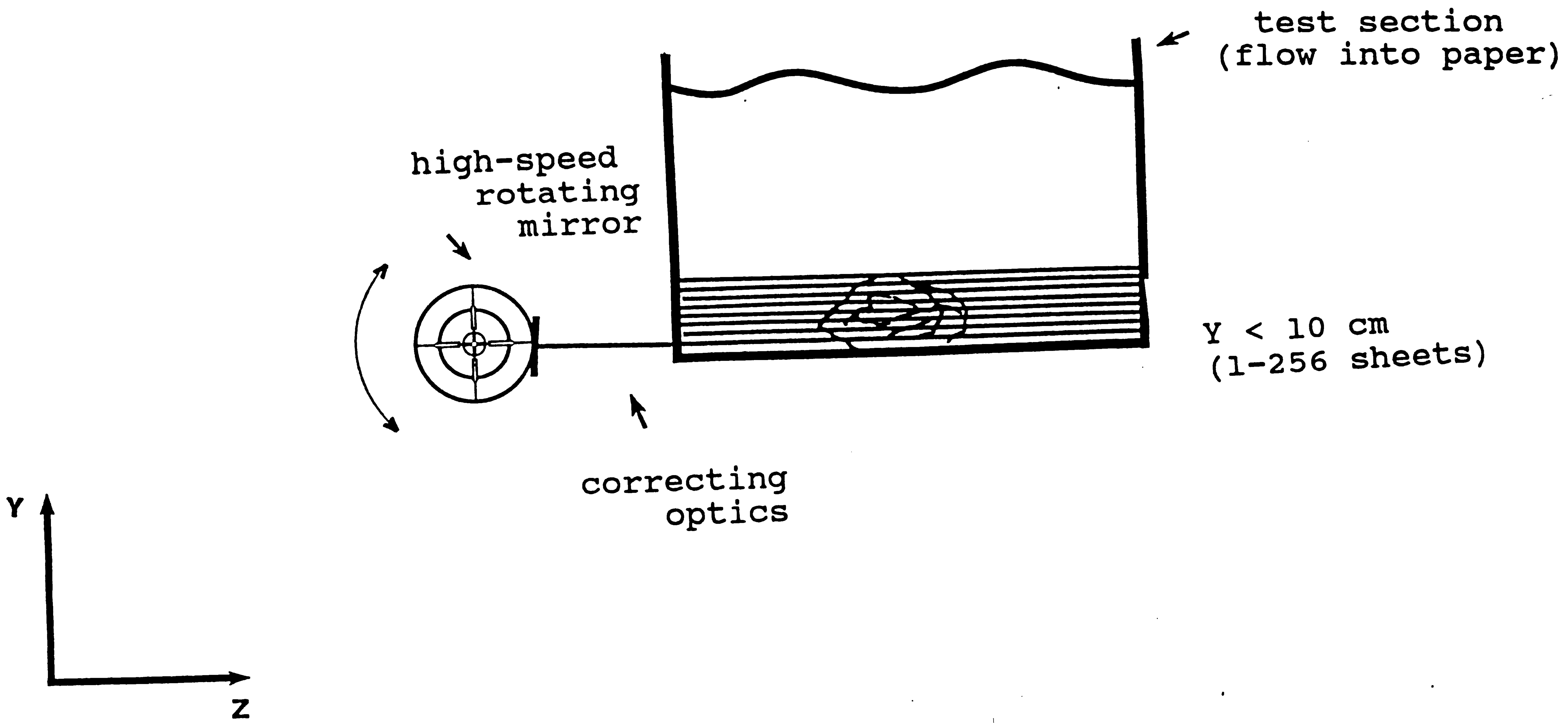
FIGURES



SIMPLIFIED SCANNING LASER SHEET LAYOUT
(Nosenchuck 1986)

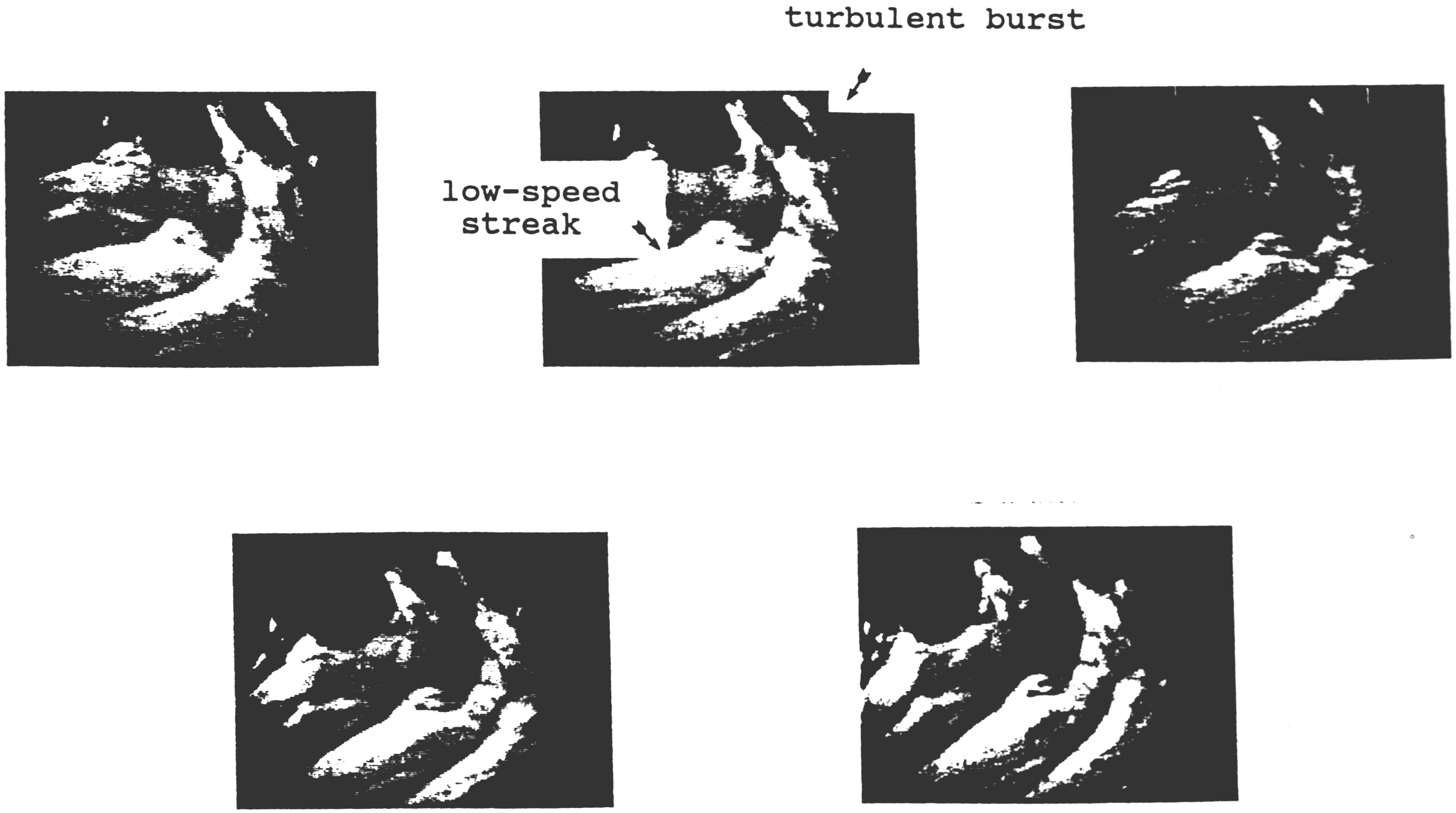
Fig. 1-1

SIDE VIEW



SIMPLIFIED SCANNING LASER SHEET LAYOUT
(Nosenchuck 1986)

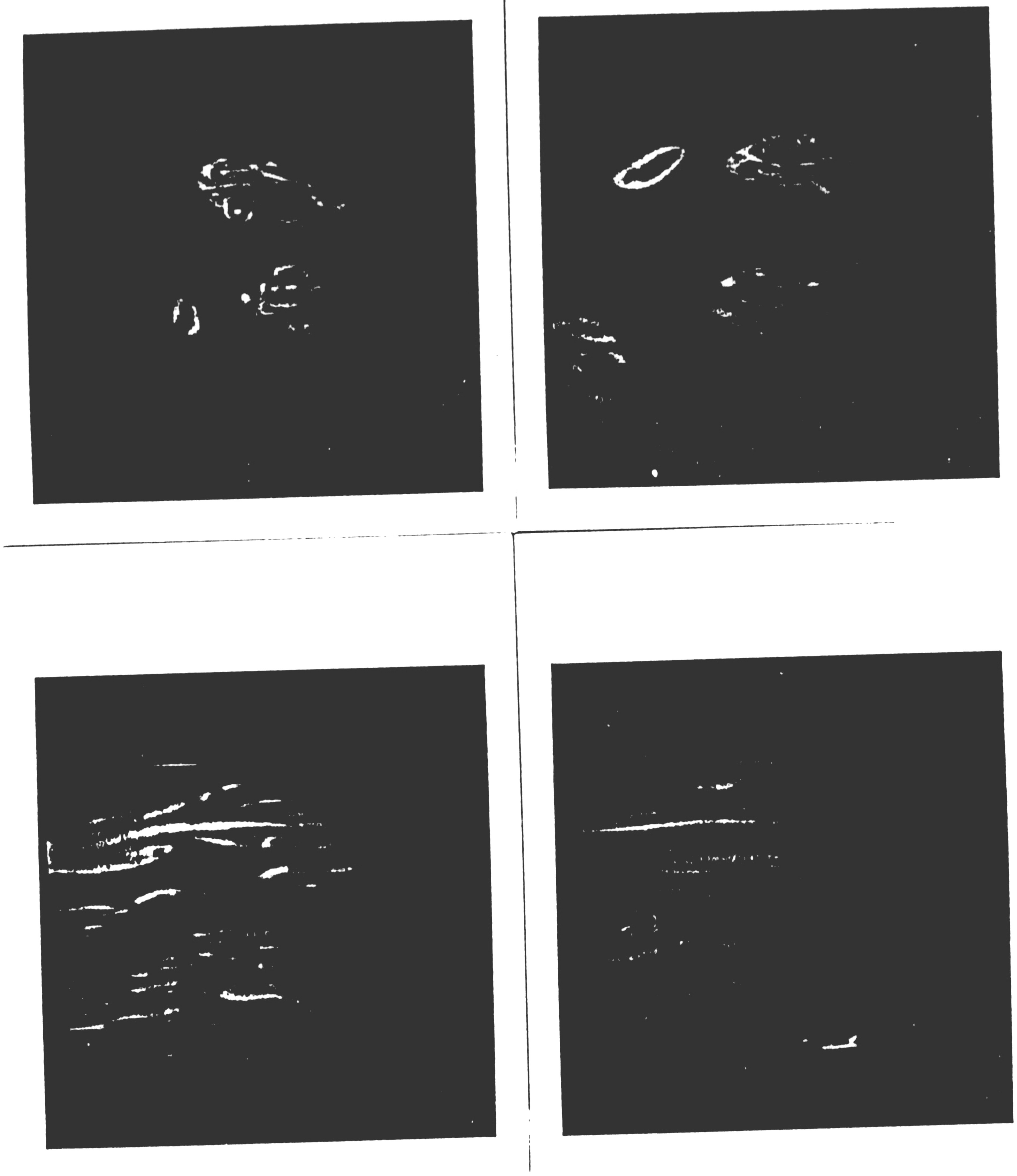
Fig. 1-2



3-D LASER SHEET IMAGING
(Nosenchuck 1986)

Multiple views of 3-D Instantaneous Flow Field
Under a Turbulent Spot

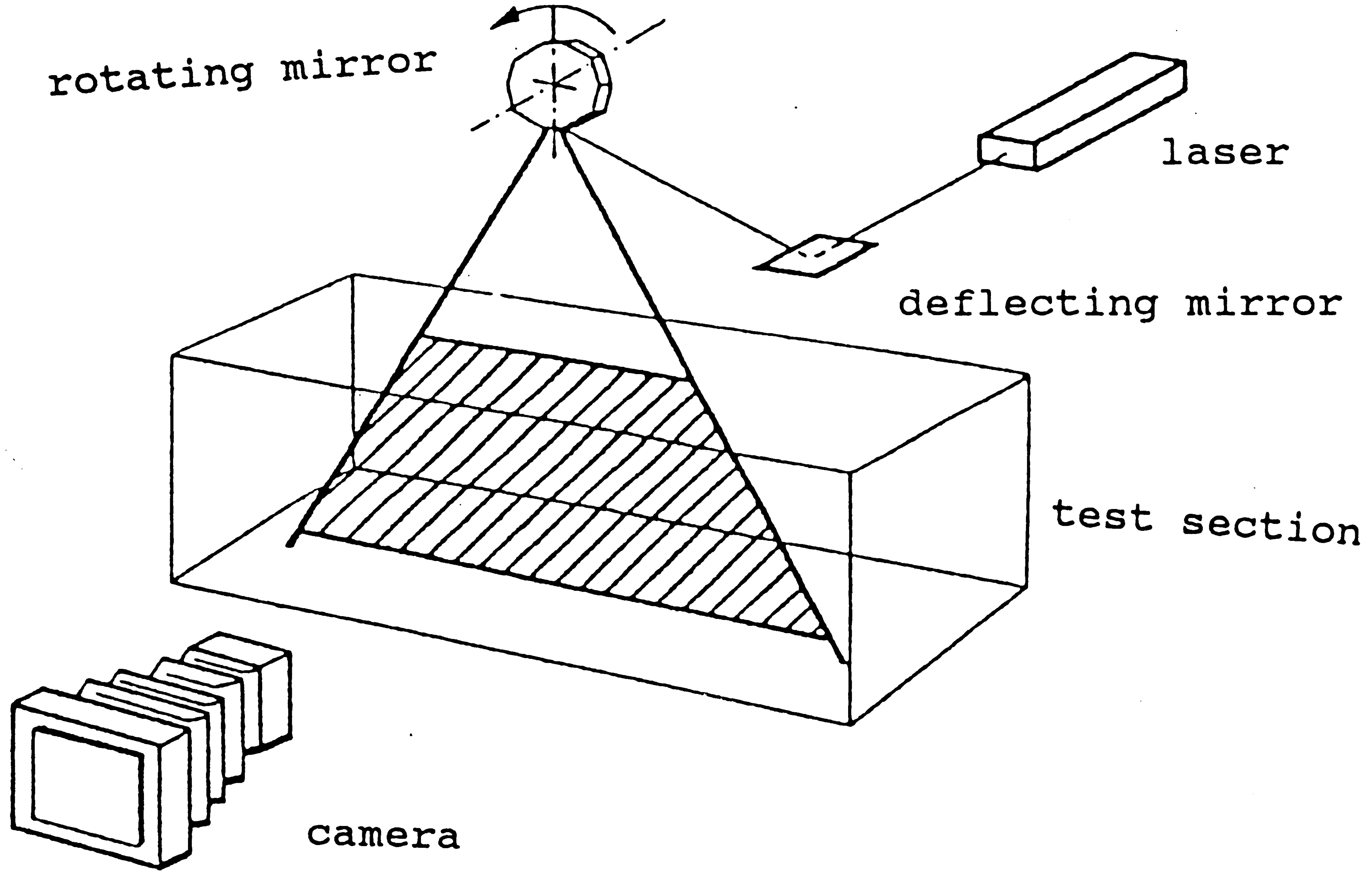
Fig. 1-3



SELECTED SHEETS FROM SINGLE LASER

SCAN OF A TURBULENT SPOT - Nosenchuck (1986)

Fig. 1-4



ROTATING POLYGON SYSTEM

Fig. 1-5

TOP VIEW OF GALVANOMETER LASER SCANNING SYSTEM

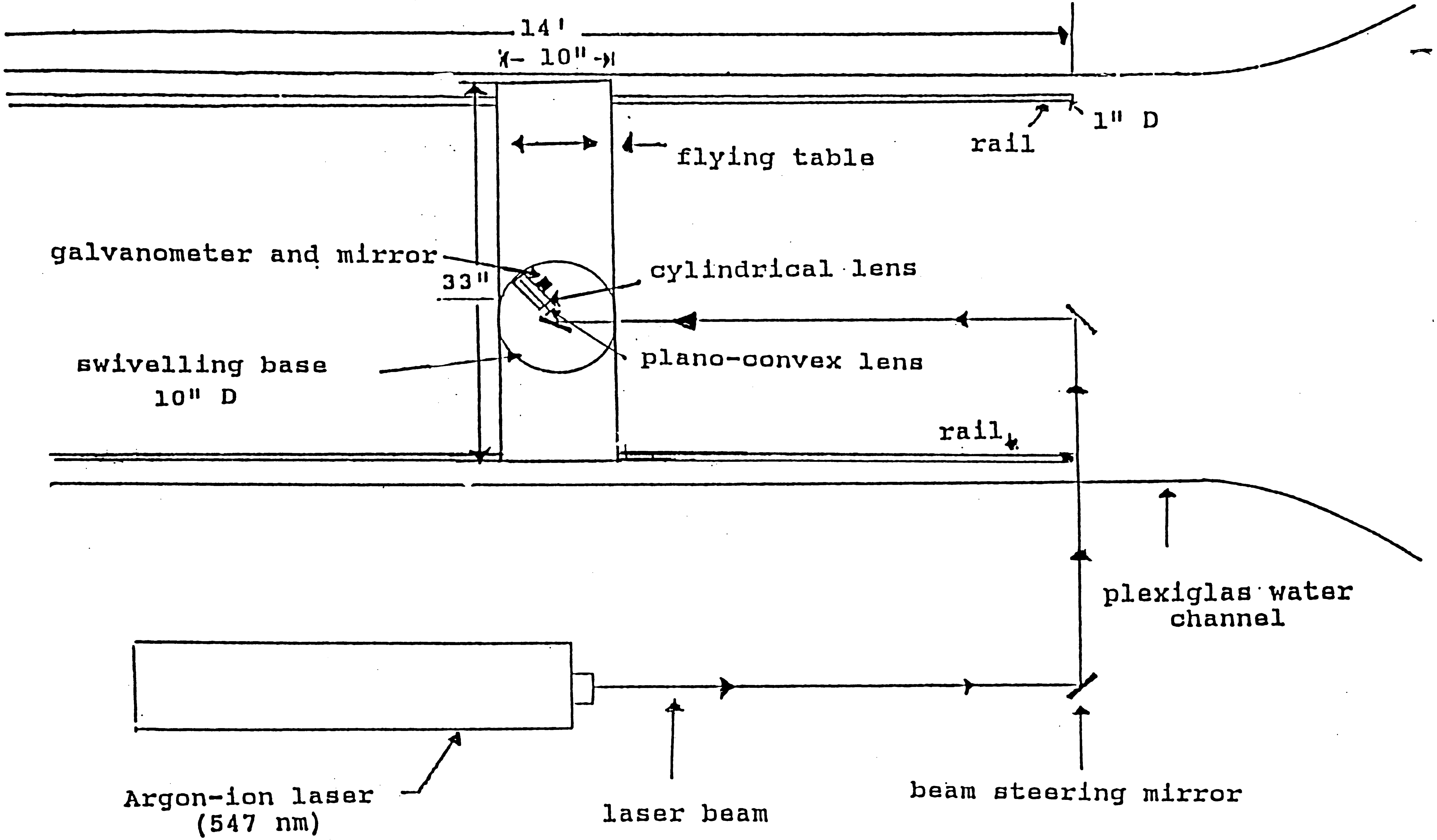


Fig. 2-1

SIDE VIEW OF LASER SCANNING SYSTEM

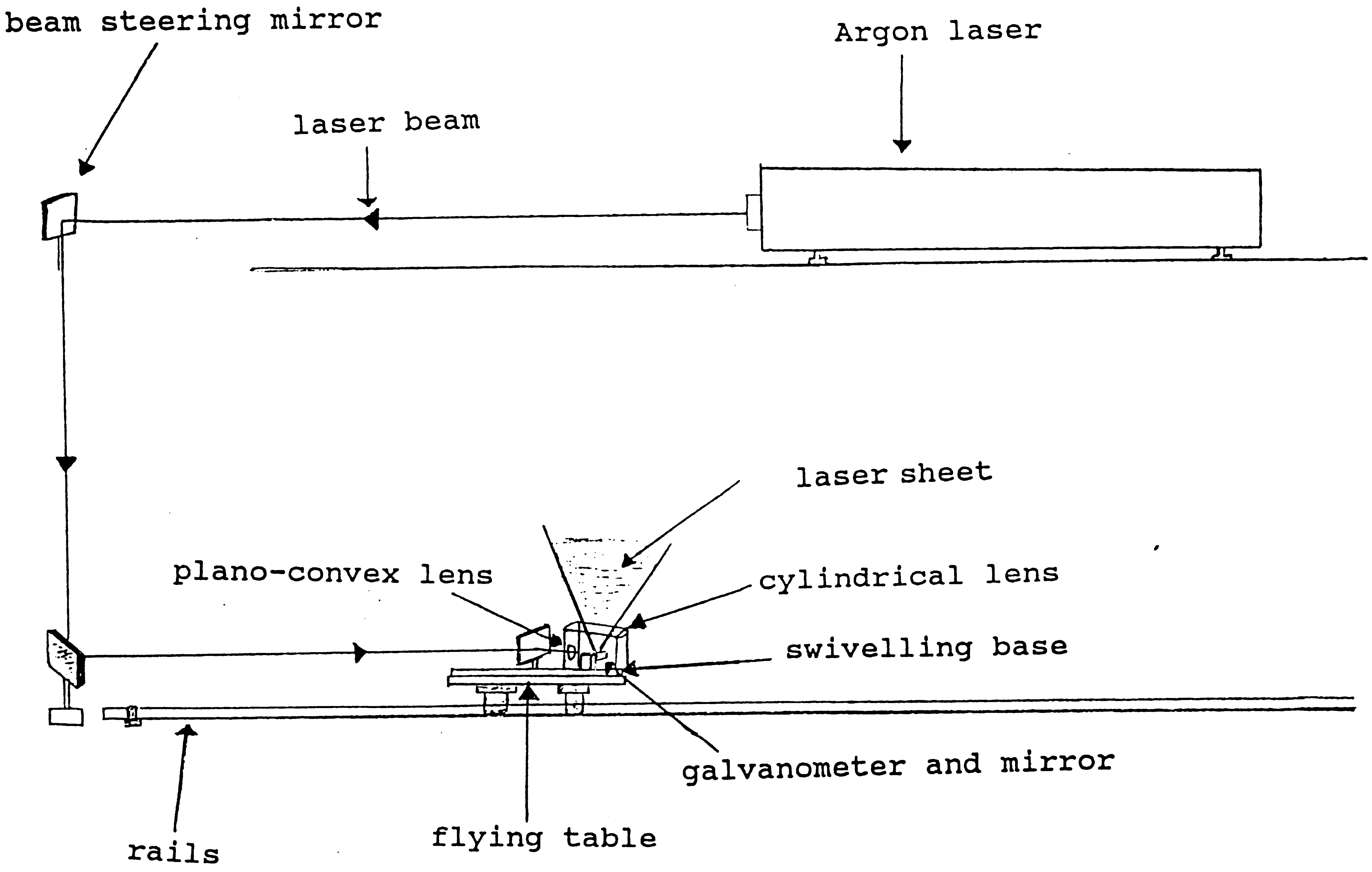


Fig. 2-2

FRONT VIEW OF LASER SCANNING SYSTEM

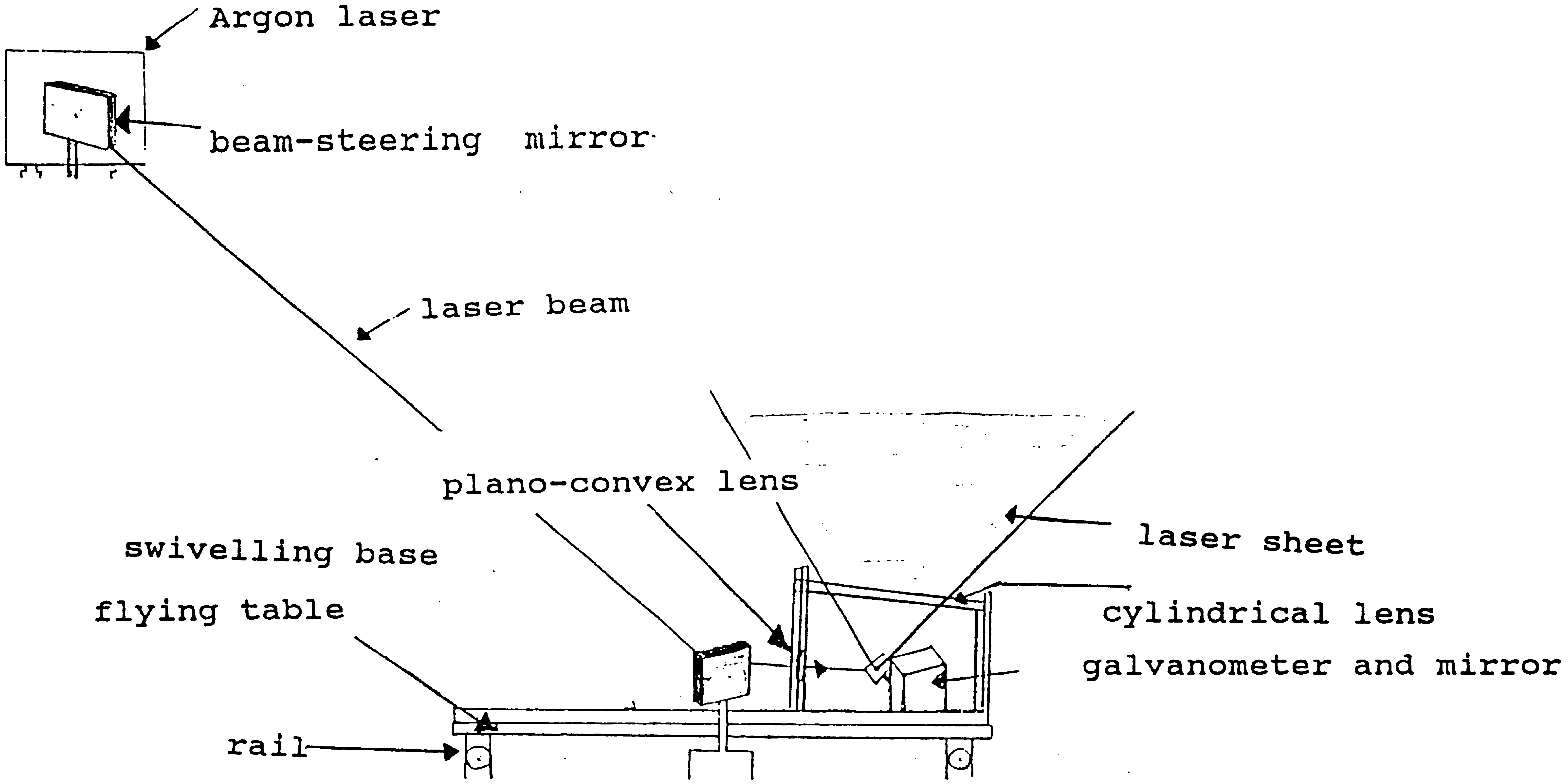
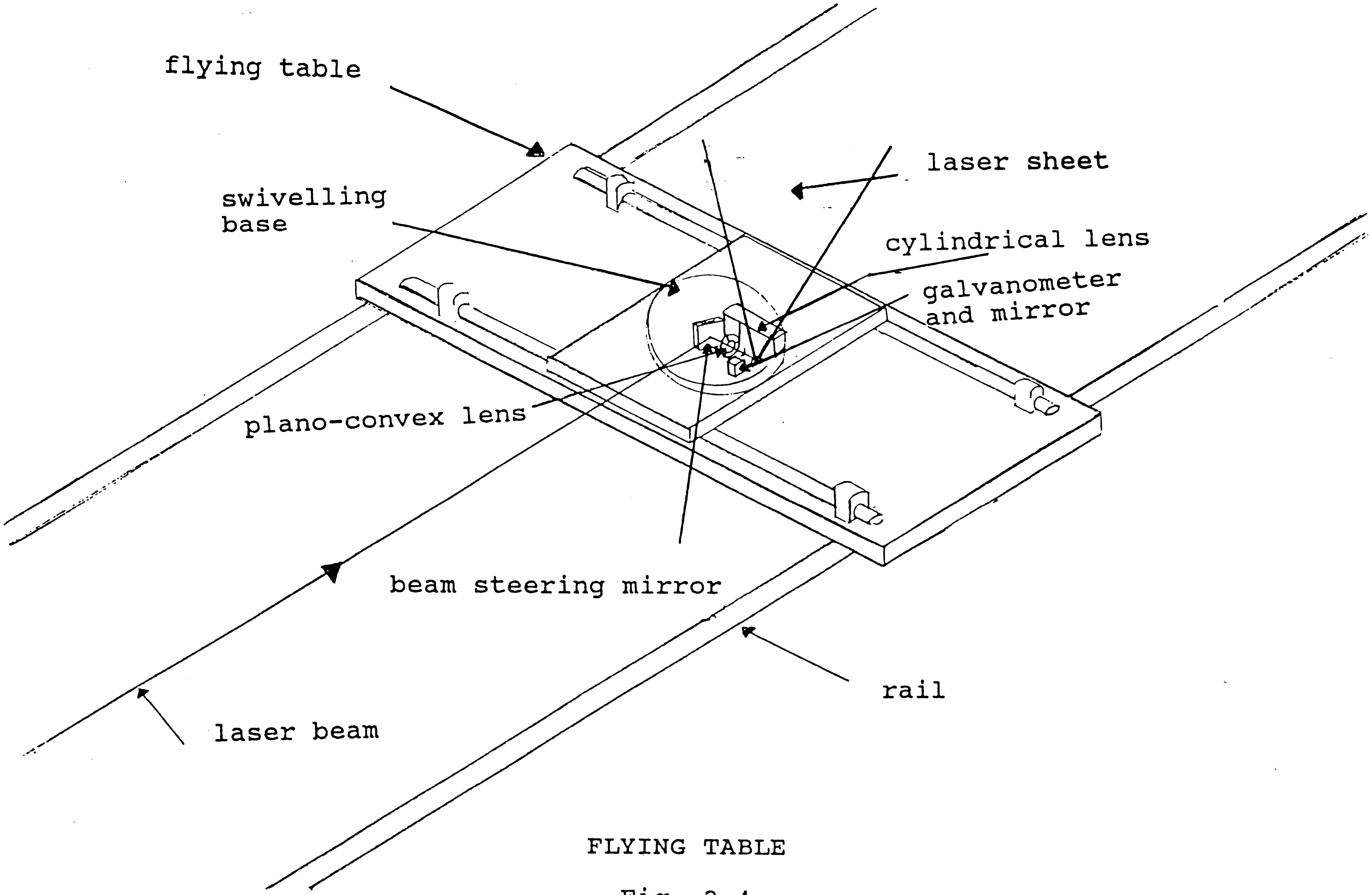
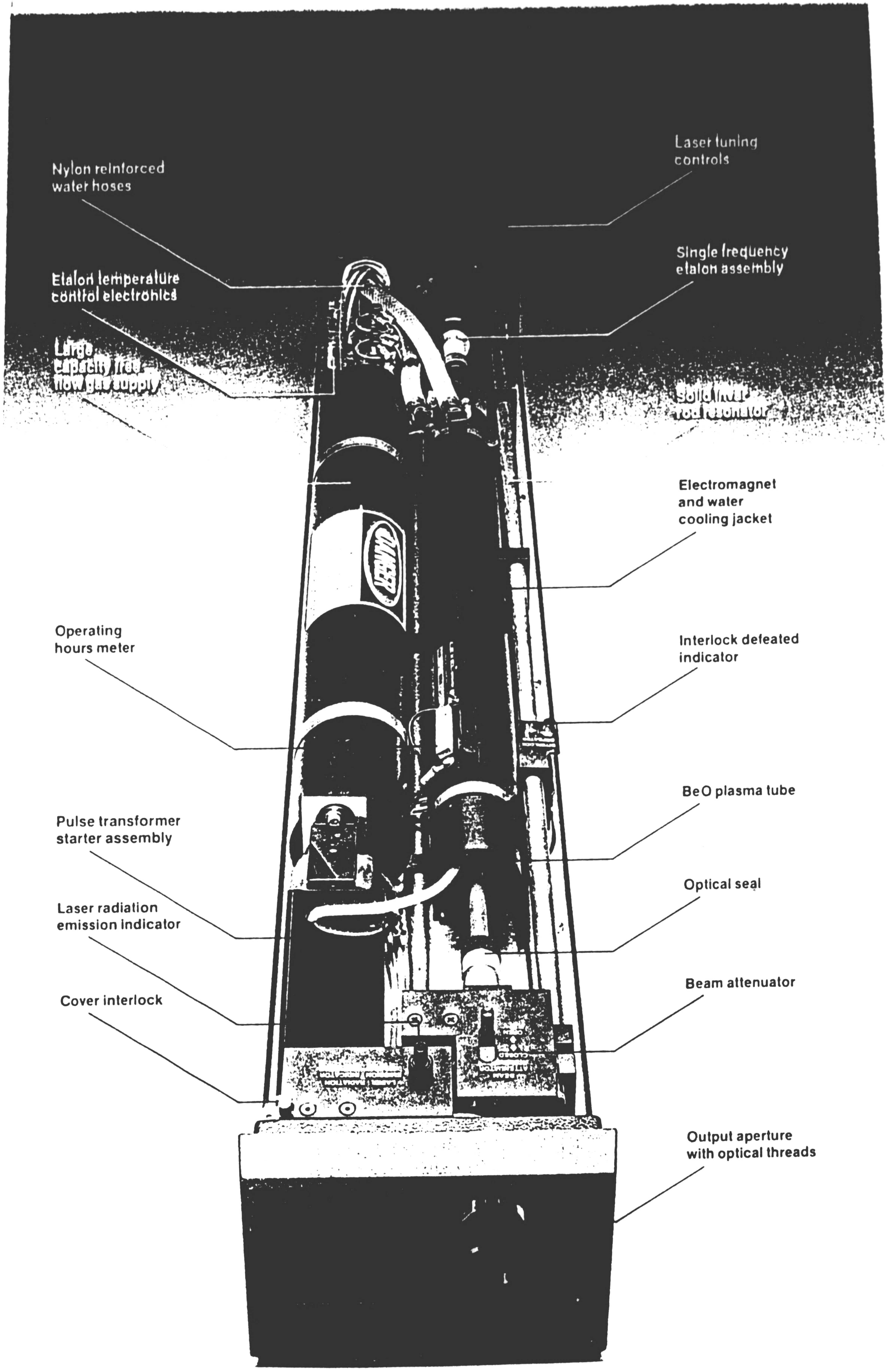


Fig. 2-3



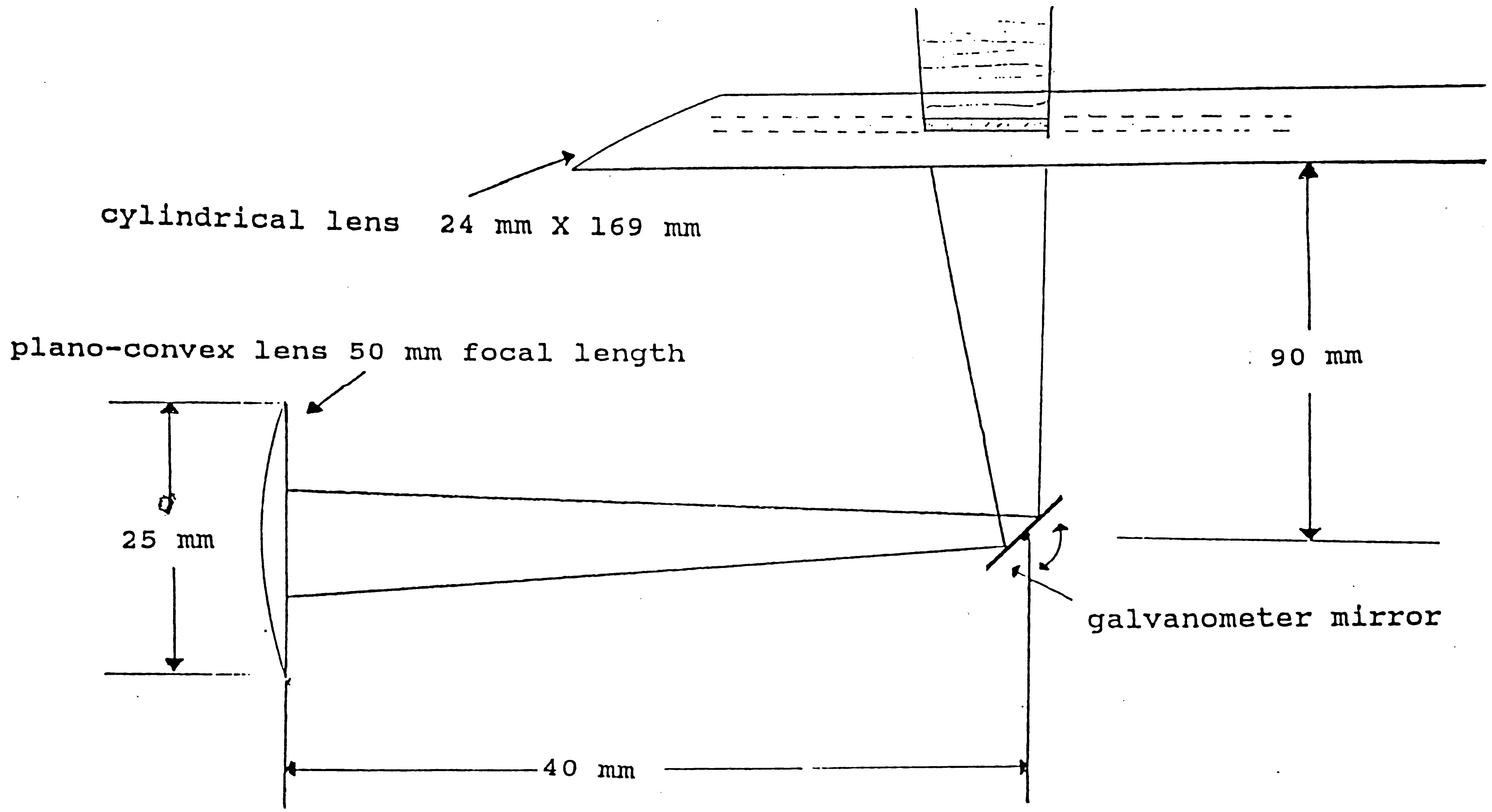
FLYING TABLE

Fig. 2-4



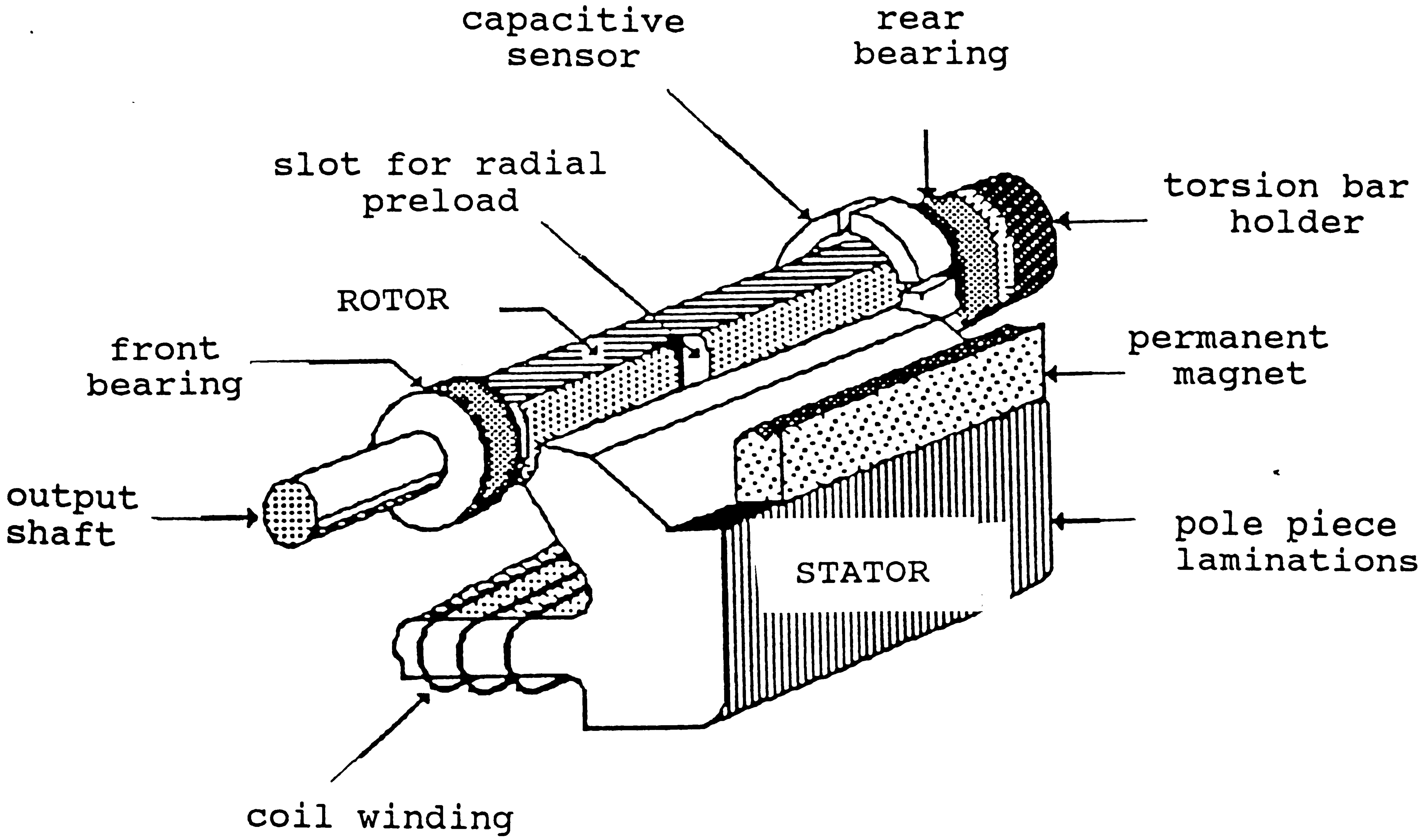
LASER HEAD COMPONENTS

Fig. 2-5



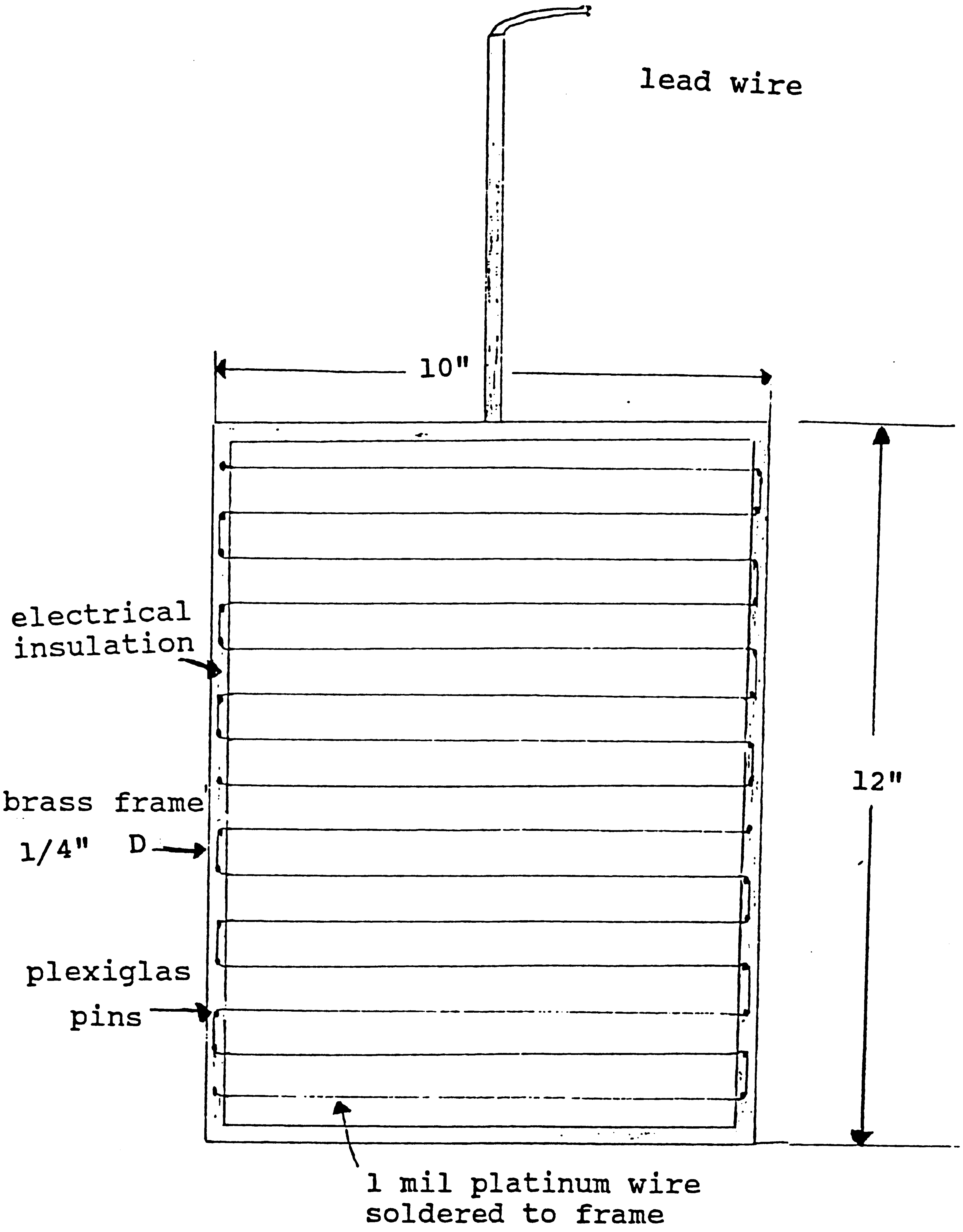
PLACEMENT OF LENSES RELATIVE TO GALVANOMETER

Fig. 2-6



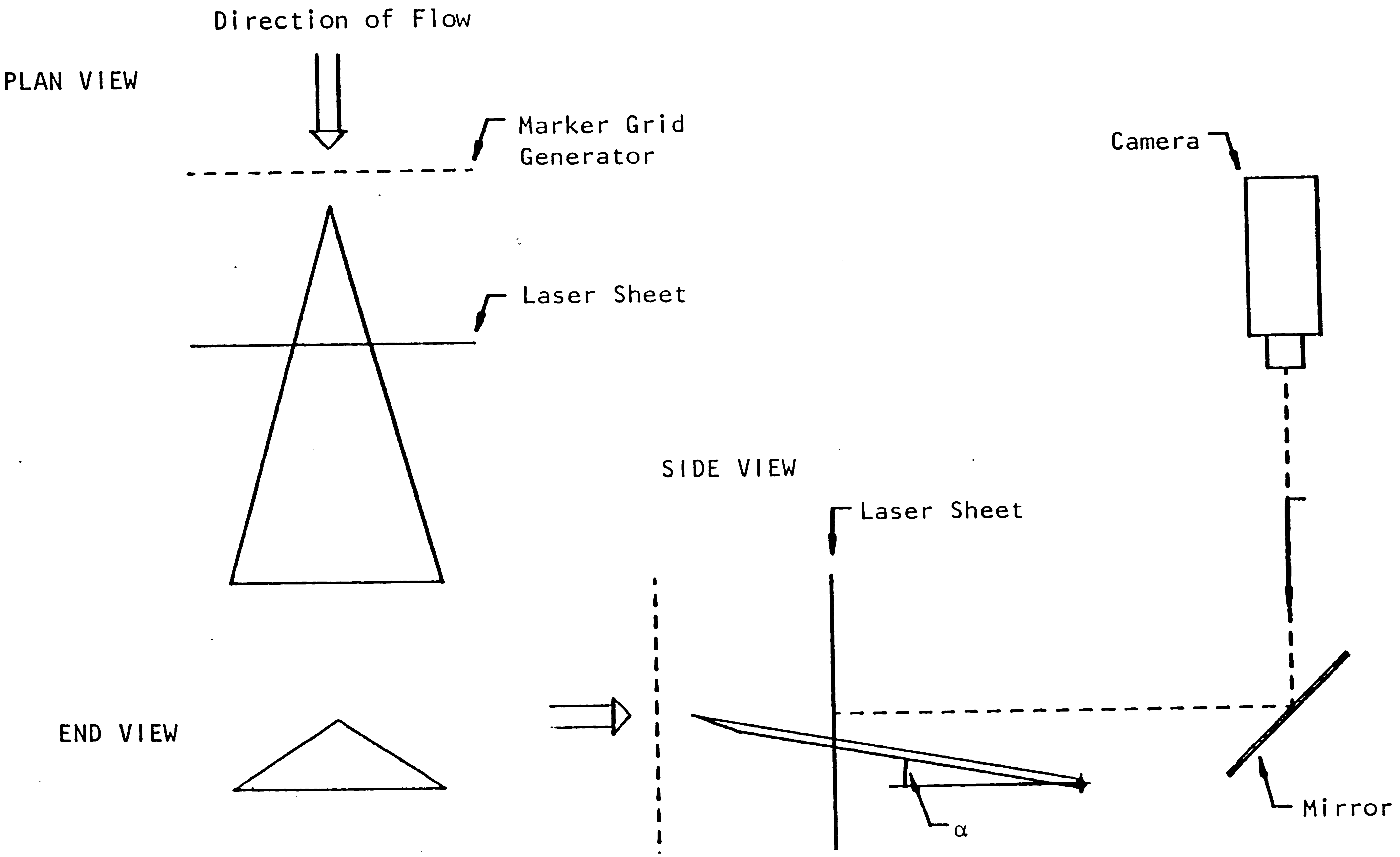
MAIN STRUCTURAL FEATURES OF GALVANOMETER

Fig. 2-7



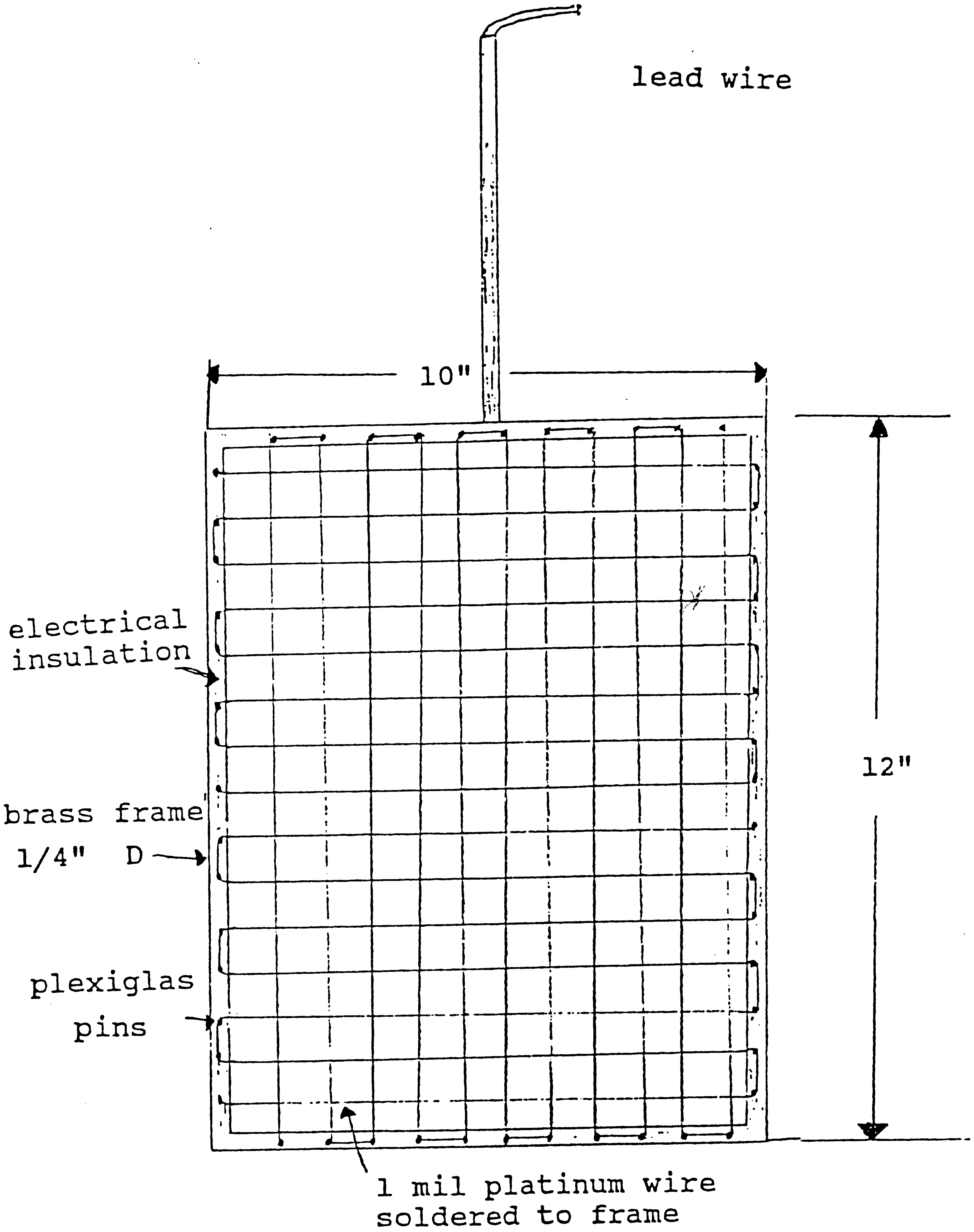
MULTIPLE WIRE PROBE

Fig. 2-8



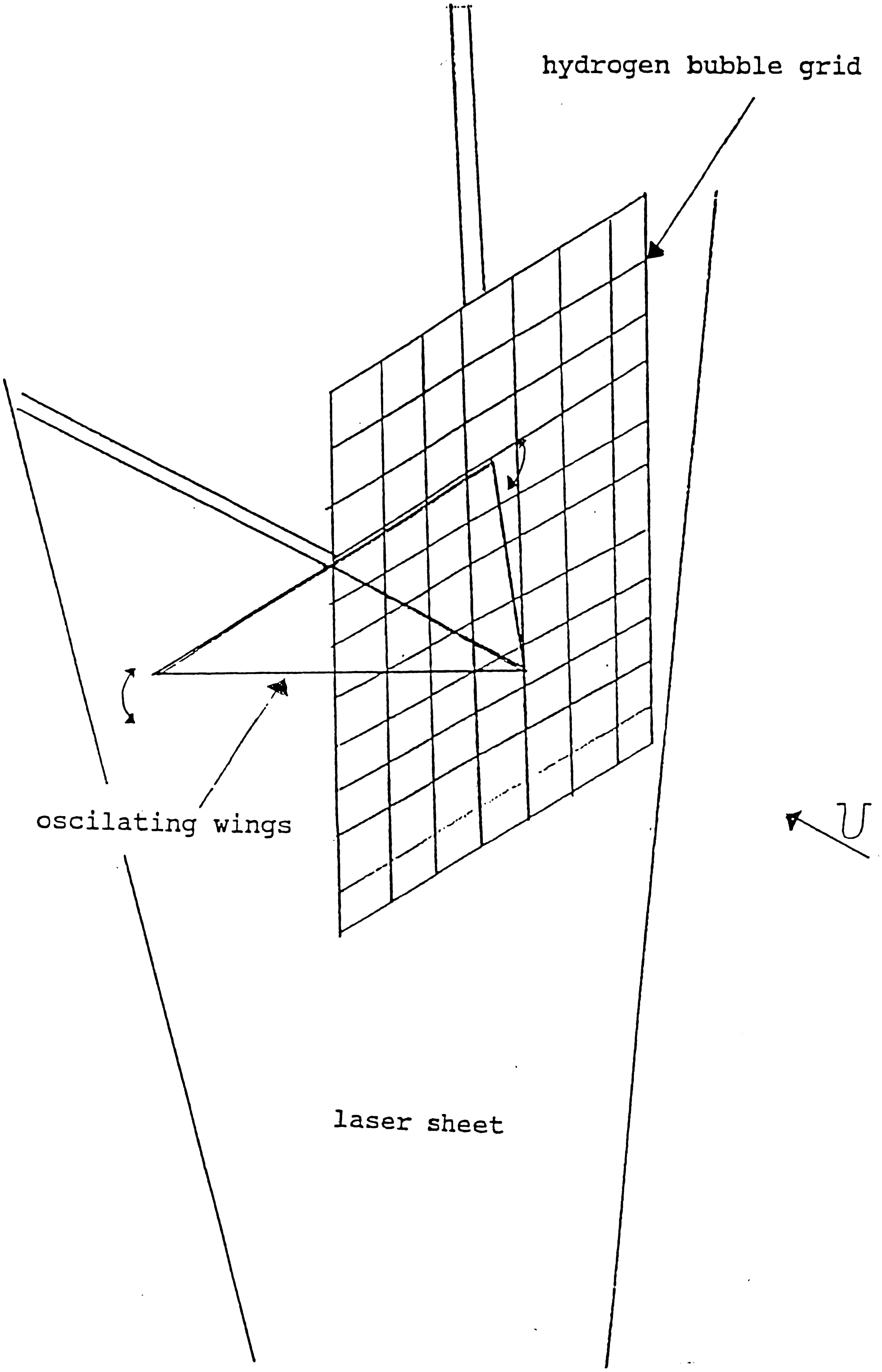
SCHEMATIC OF DELTA WING WITH MIRROR AND CAMERA
(Rockwell 1987)

Fig. 2-9



OMNI PROBE

Fig. 3-1



OSCILLATING WING SEGMENT SCHEMATIC

Fig. 3-2

OSCILLATING WING SEGMENTS
(Rockwell 1987)

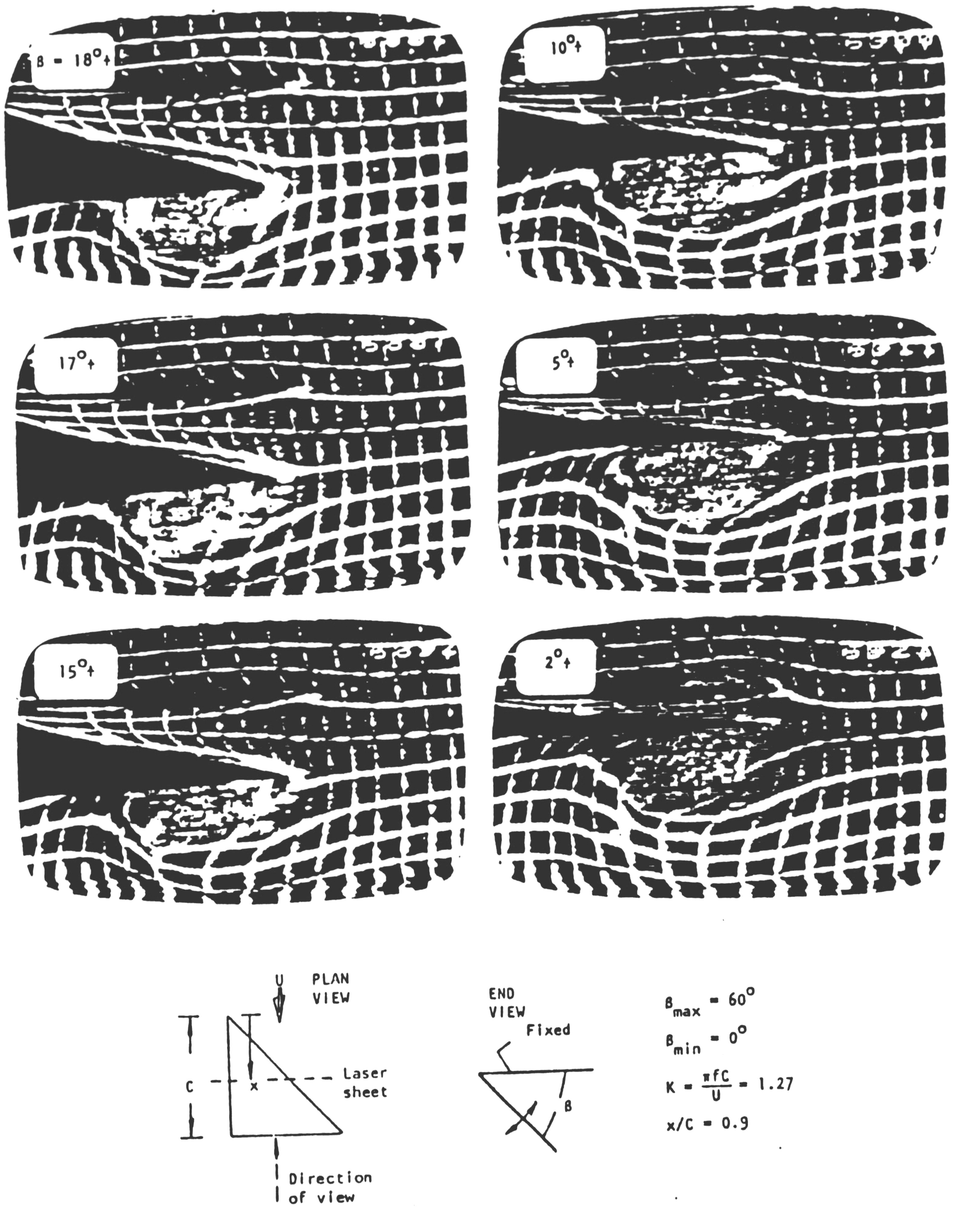
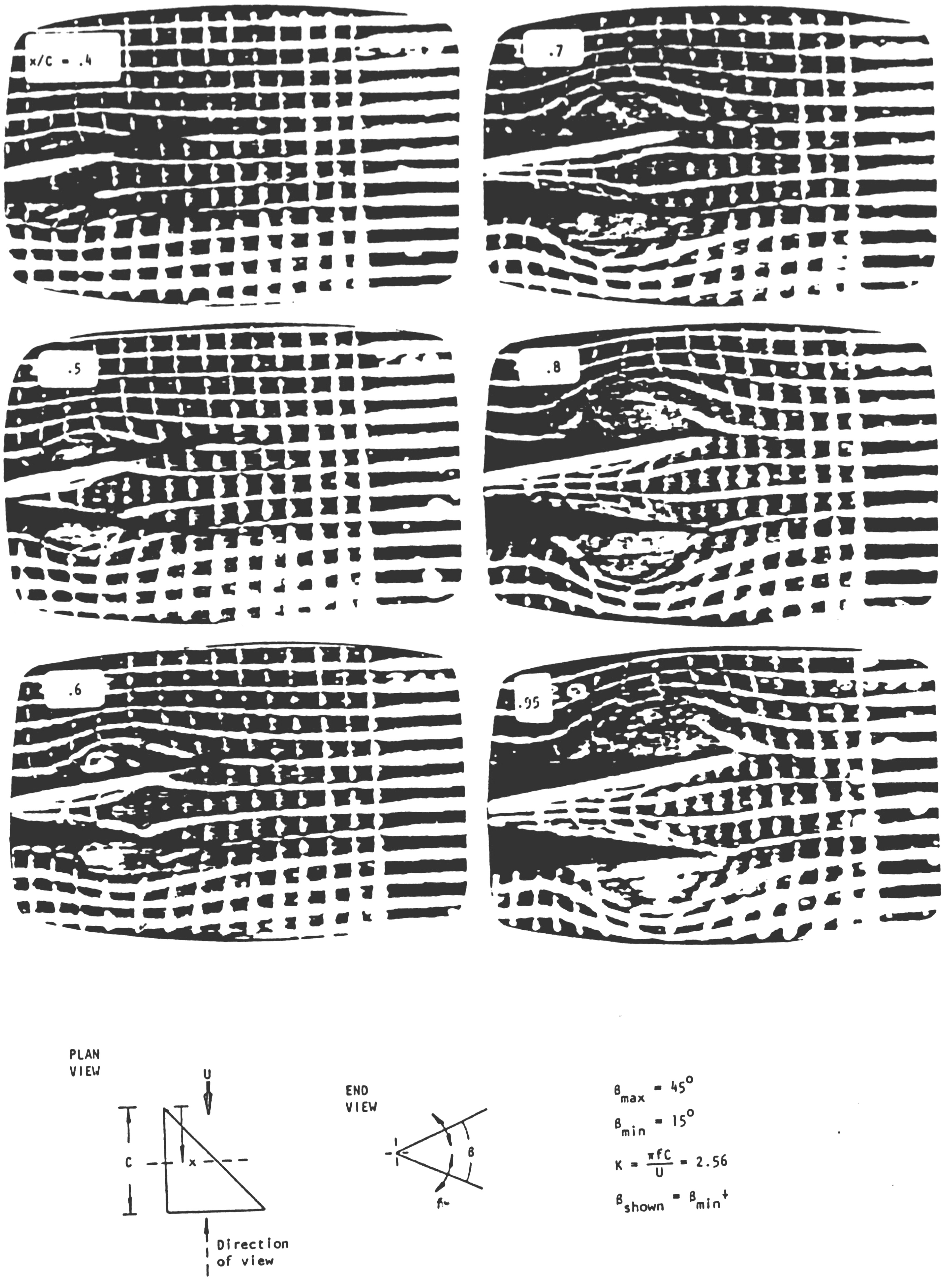


Fig. 3-3

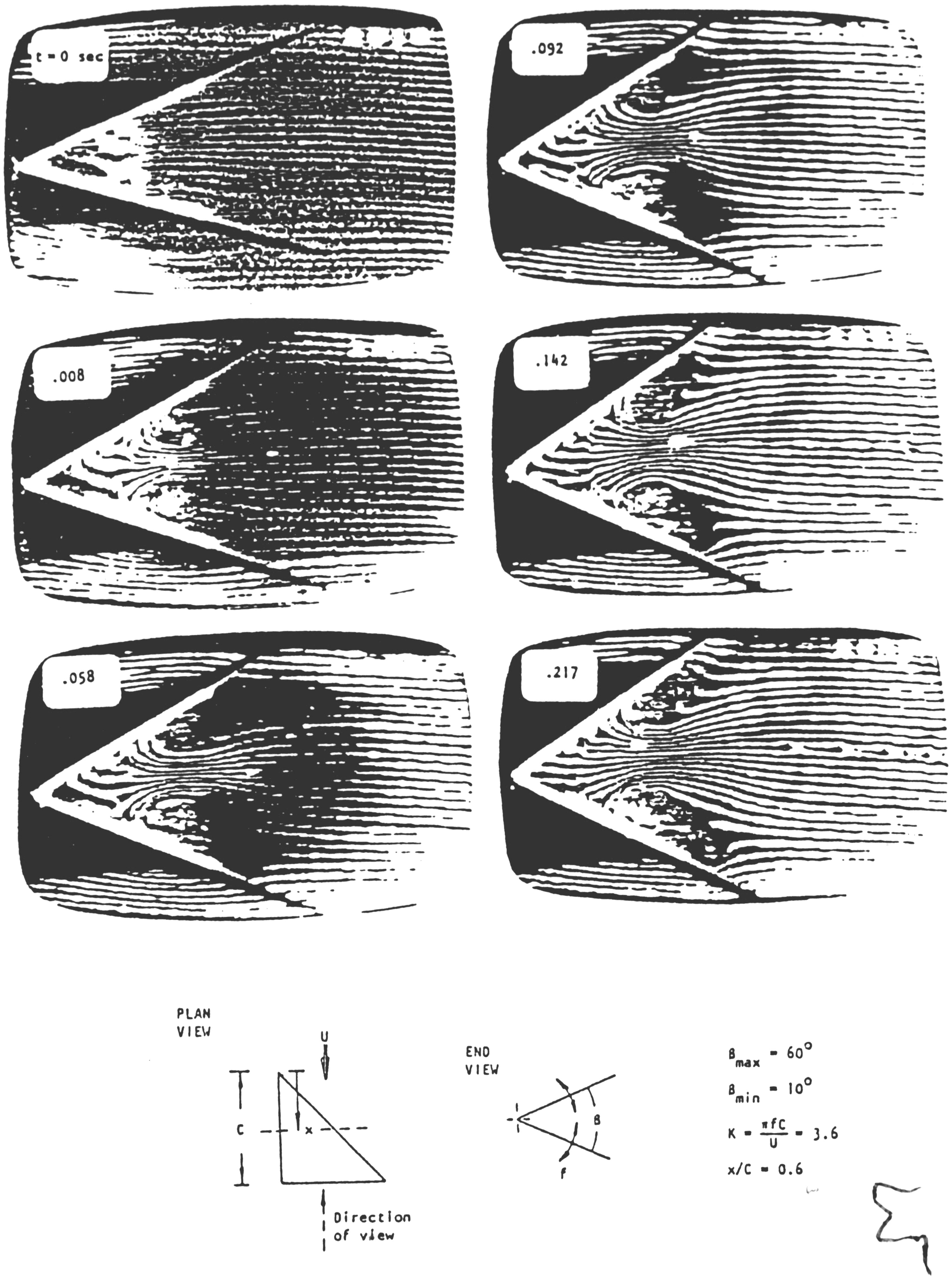
OSCILLATING WING SEGMENTS
(Rockwell 1987)



OMNI PROBE FLOW VISUALIZATION

Fig. 3-4

OSCILLATING WING SEGMENTS
(Rockwell 1987)



HORIZONTAL PROBE
IMAGES

Fig. 3-5

OSCILLATING WING SEGMENTS
(Rockwell 1987)

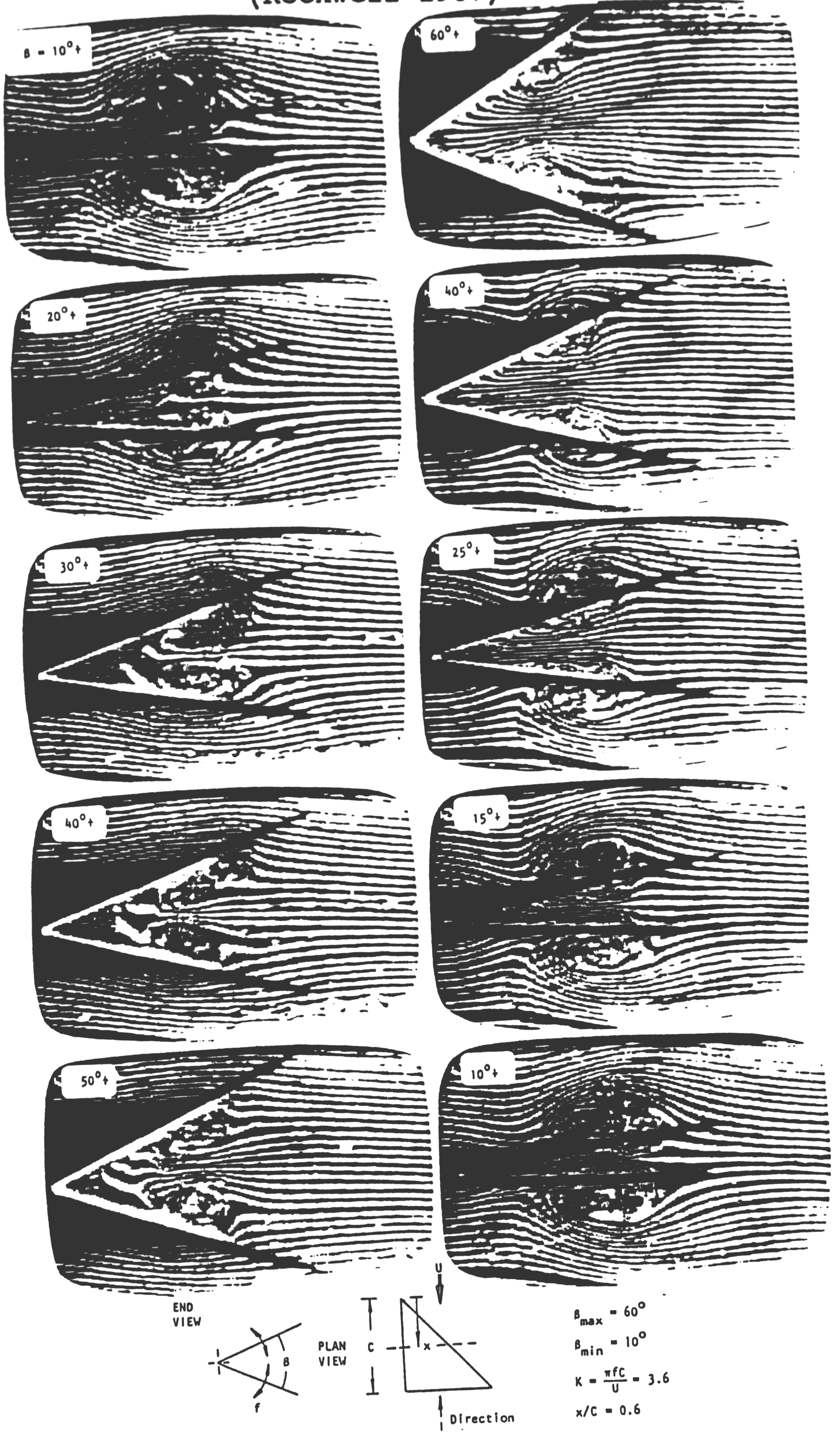
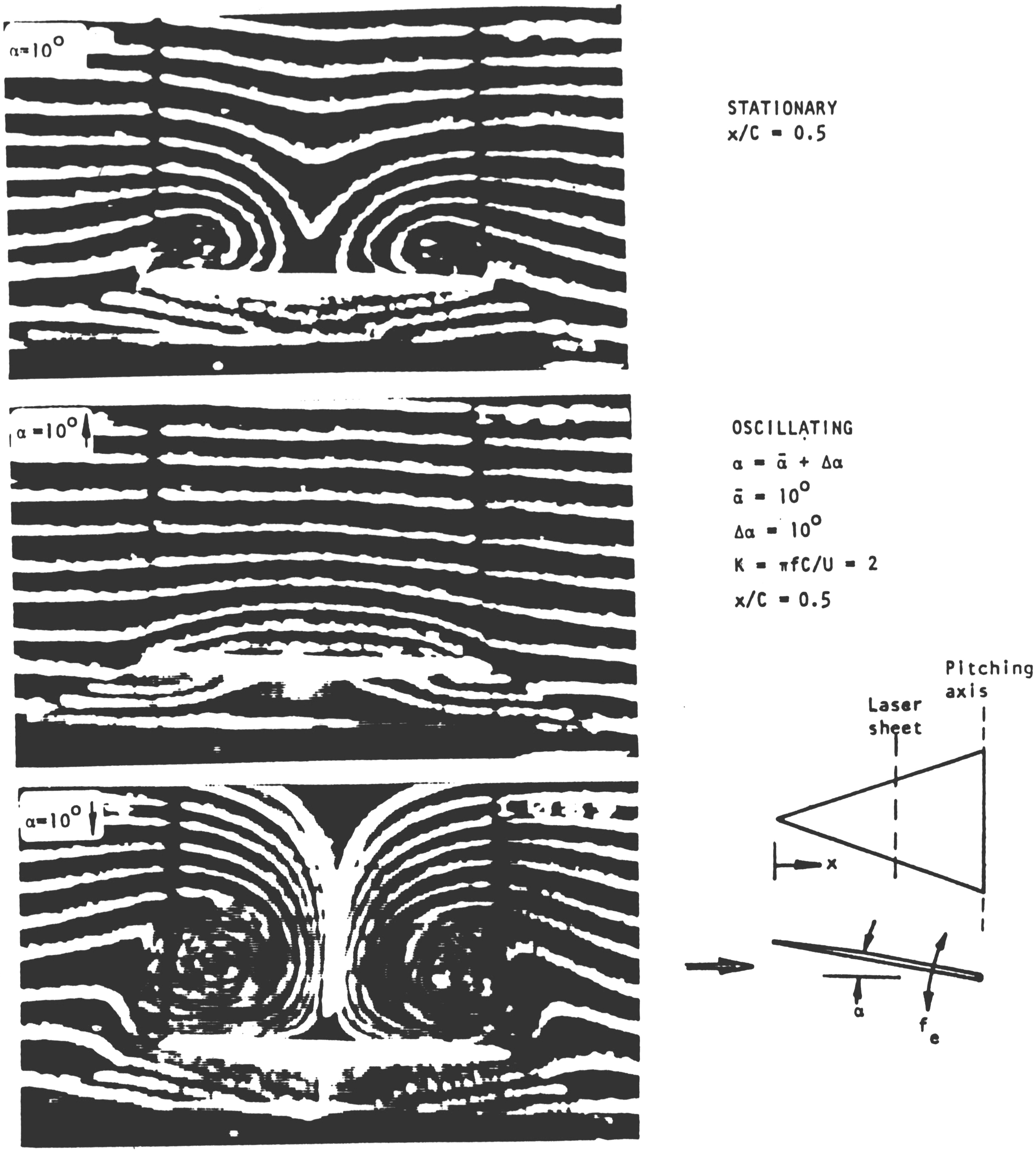
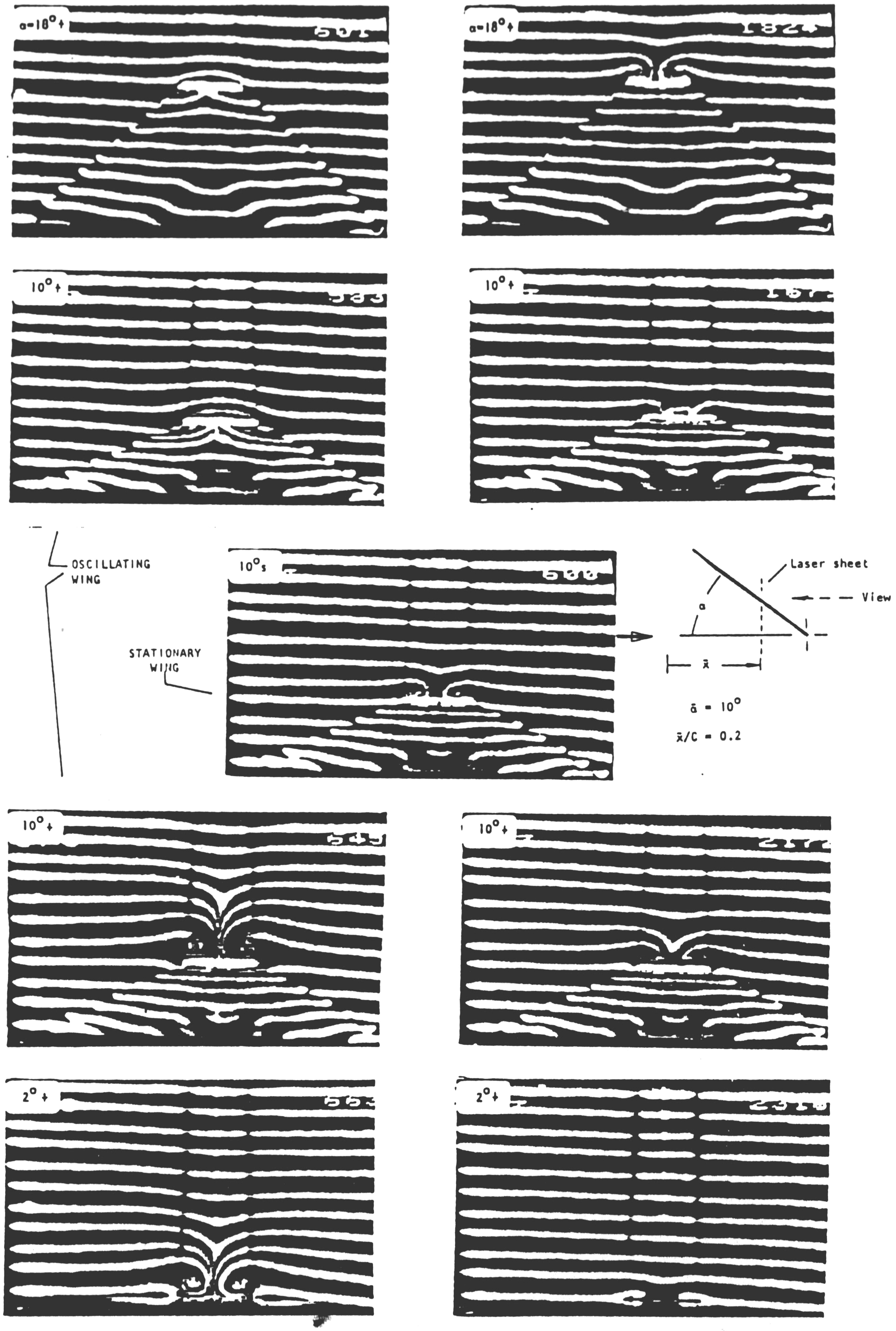


Fig. 3-6



FLOW STRUCTURE ON PITCHING DELTA WING
WITH LASER INDUCED BUBBLE REFLECTION
(Magness and Rockwell 1986)

Fig. 3-7



k=1.95

k=0.24

PITCHING DELTA WING LASER CROSS SECTIONS

Fig. 3-8 (Rockwell 1987)

TURBULENT BOUNDARY LAYER AT BLUNT TRAILING EDGE

SCHEMATIC DIAGRAM

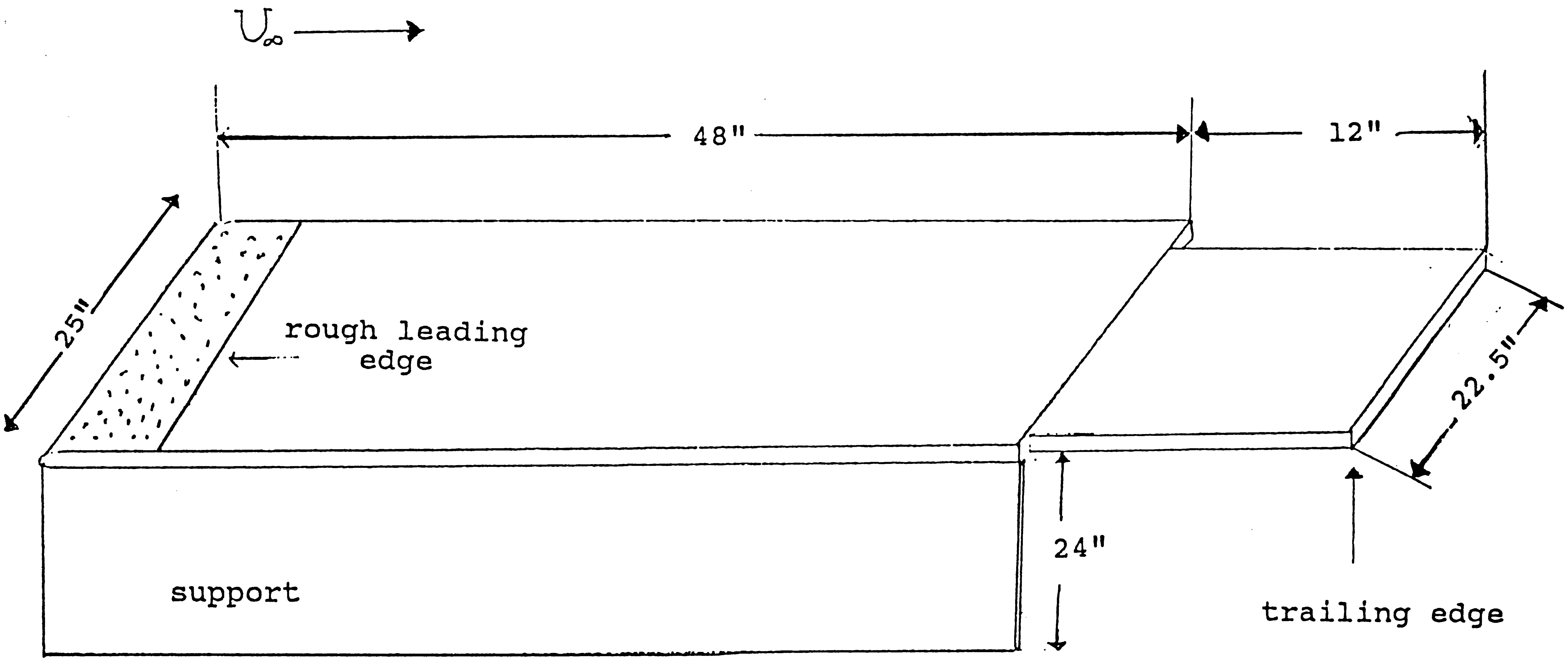
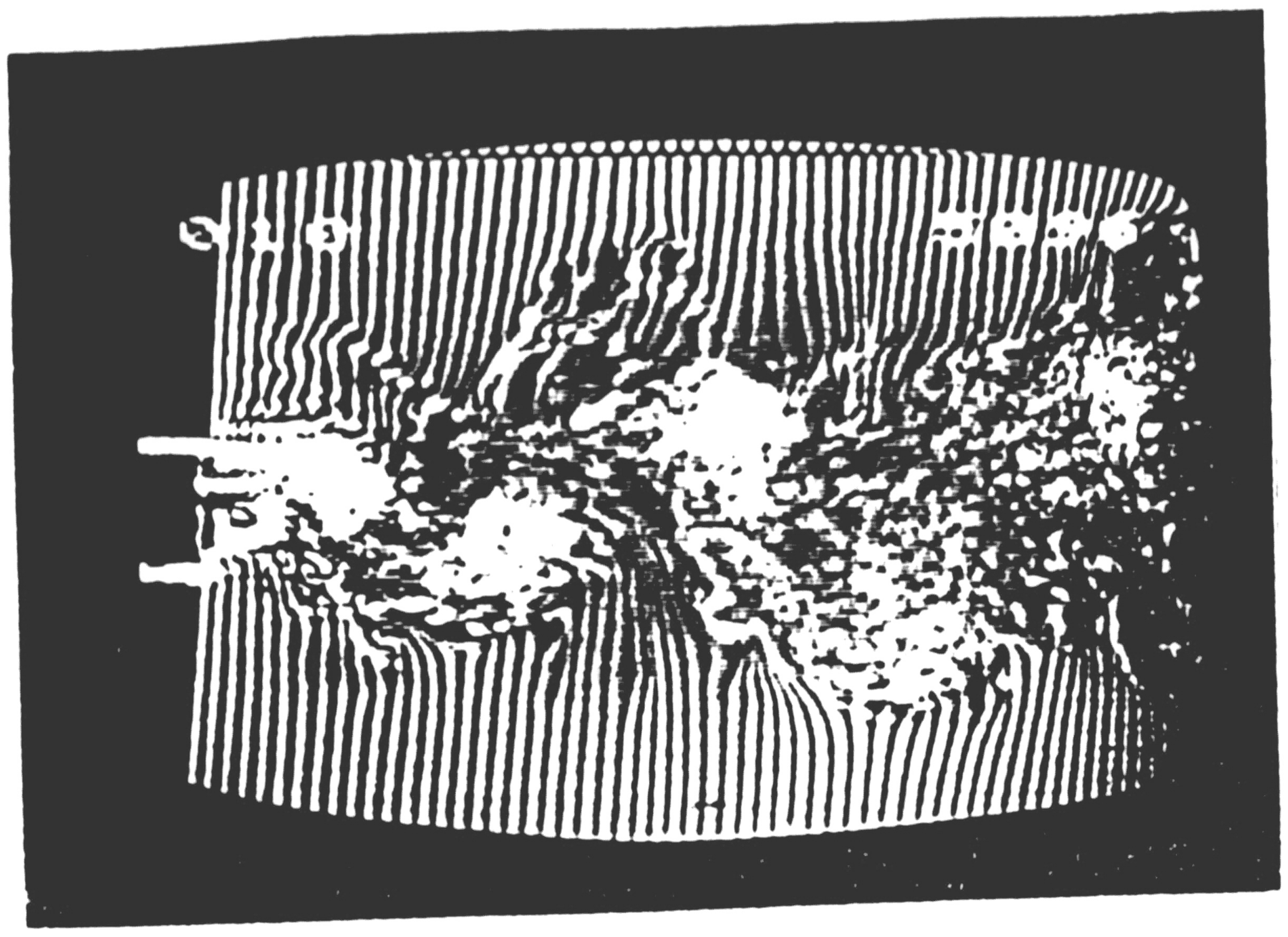
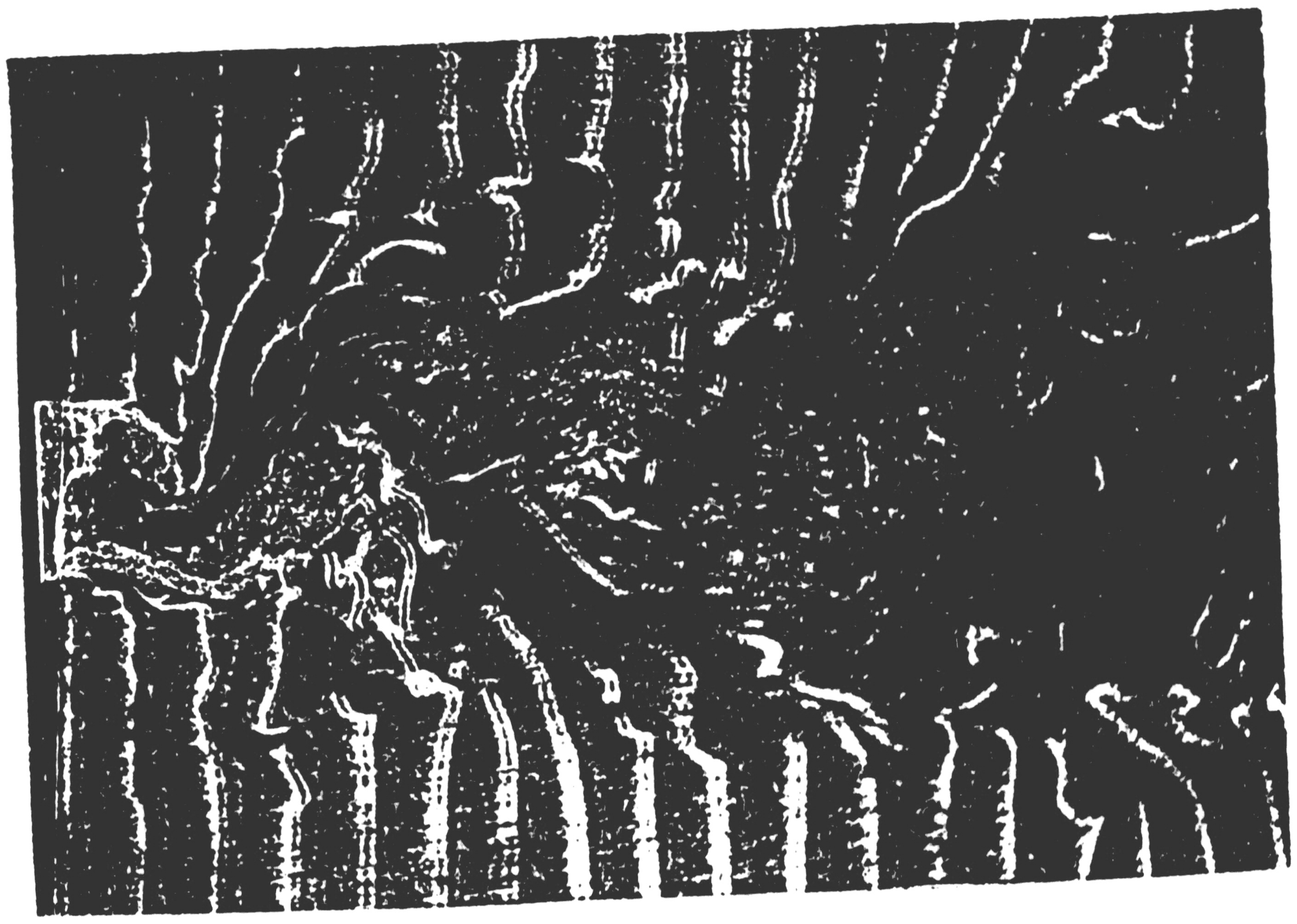


Fig. 3-9

STATIONARY BLUNT TRAILING EDGE IMAGES

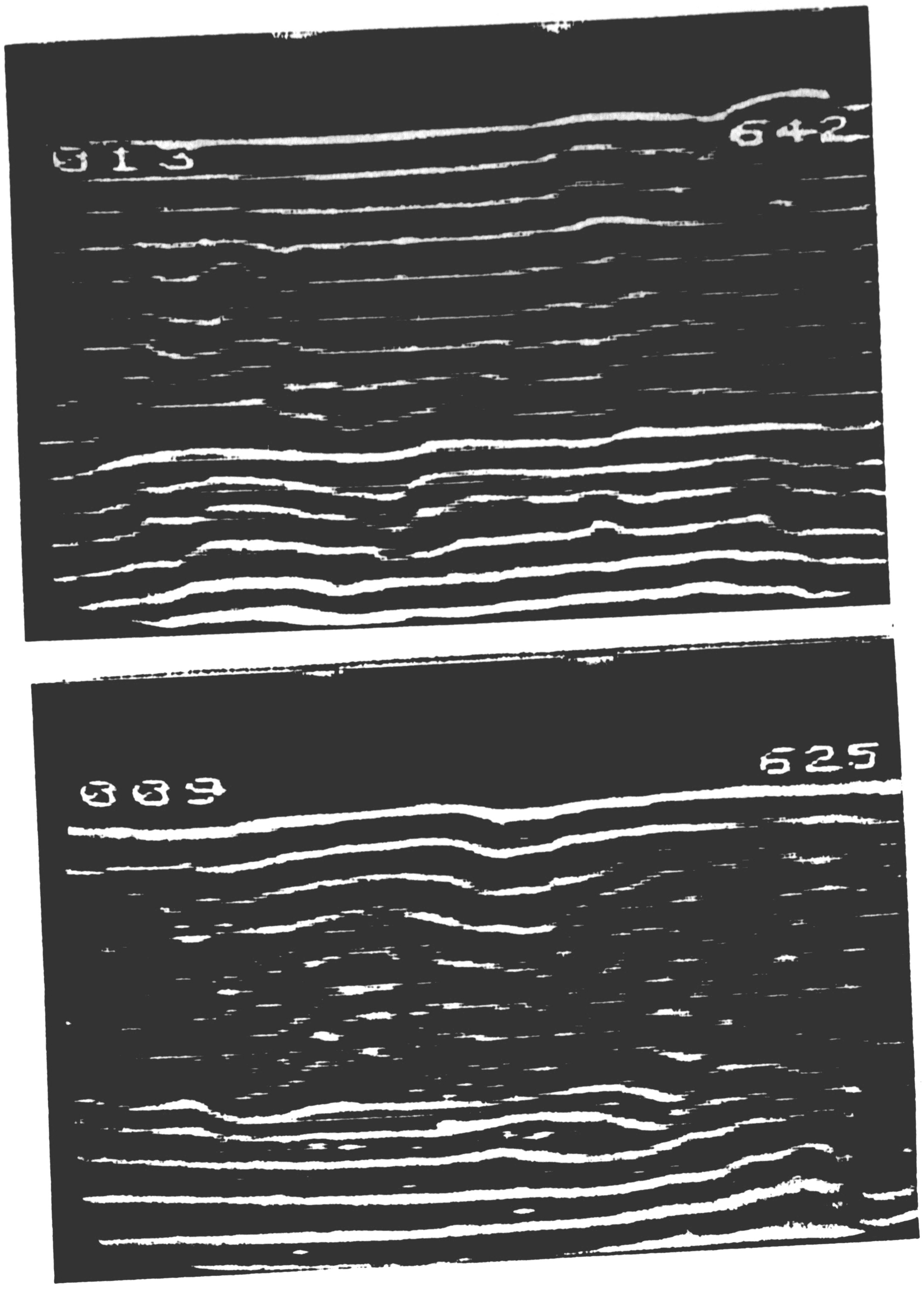


2-D strobe light illumination
of vortex shedding U = 1 ft./sec.



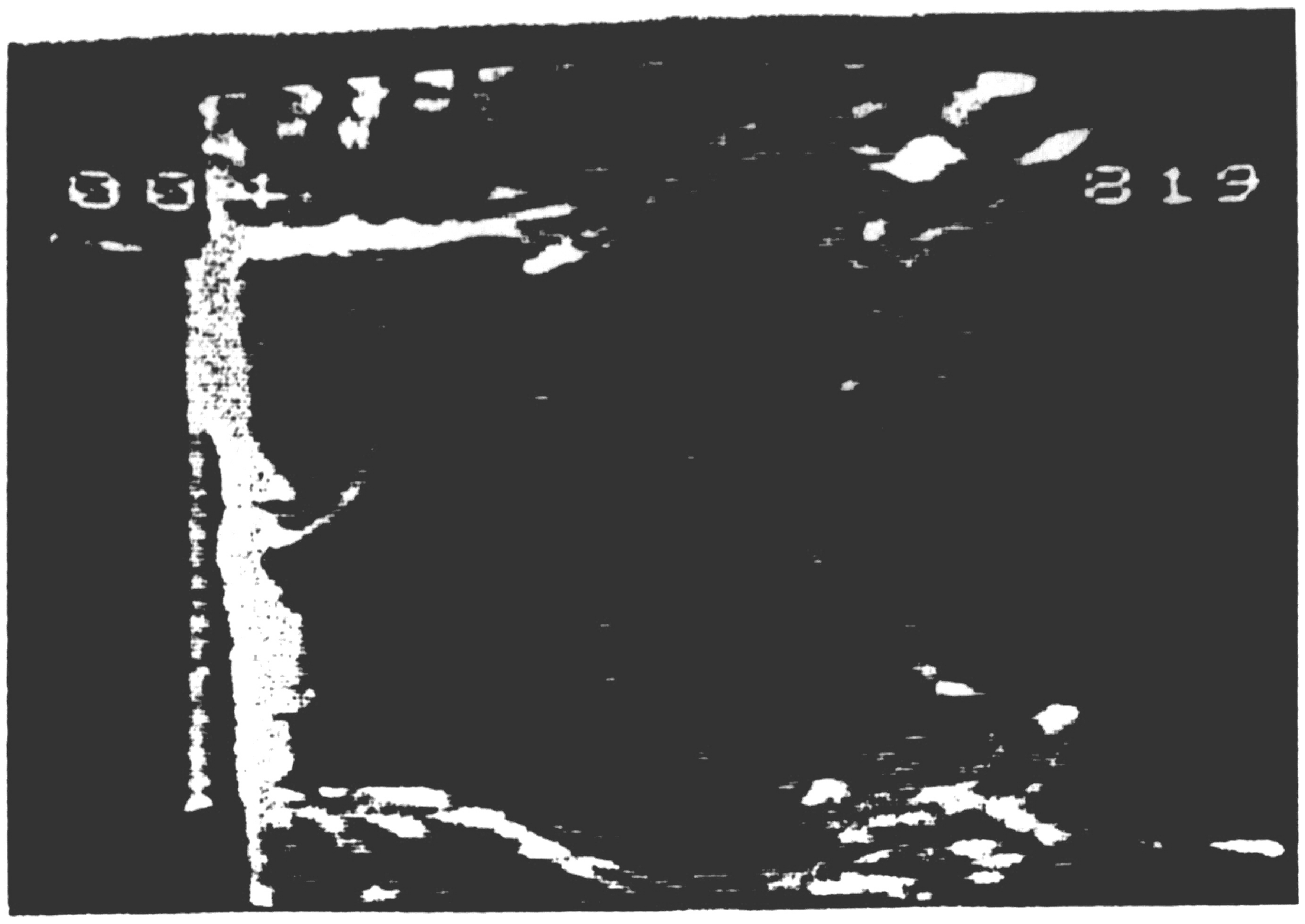
Laser sheet illumination in streamwise plane
of vortex shedding U = 1 ft./sec.

Fig. 3-10

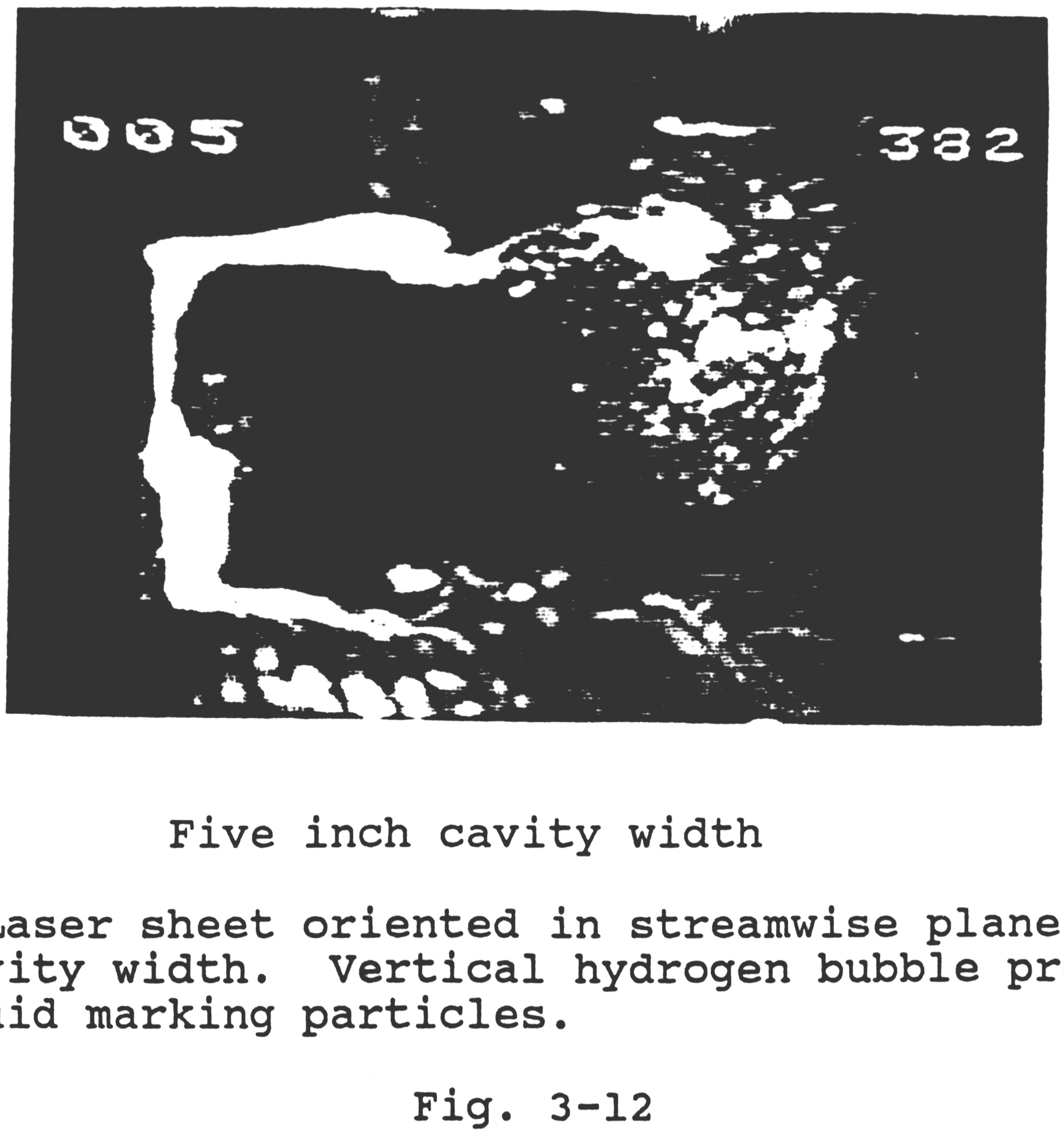


Images of cross-stream laser scanning with laser sheet three inches downstream from a stationary blunt trailing edge. The laser sheet illuminates a cross section of hydrogen bubble sheets emanating from a horizontal multiple-wire probe.

Fig. 3-11



Four inch cavity width



Five inch cavity width

Laser sheet oriented in streamwise plane illuminating cavity width. Vertical hydrogen bubble probe provides fluid marking particles.

Fig. 3-12

VITA

The author was born in Mineola, N.Y. on November 6, 1961, eldest son of Dr. Arthur E. and Marilyn G. Klink. After obtaining the B.S. in Mechanical Engineering from Rutgers University in May 1983 he worked as an Analytical Engineer at Pratt and Whitney Aircraft until August 1985. He married Rebecca L. Kight and has one son. Upon completion of the requirements for the M.S. degree, he will be employed by Exxon Co. U.S.A in Thousand Oaks, California.