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A LASER-ANEMOMETER FOR USE IN SHIP RESEARCH

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Abstract

In experimental ship model research the absence of a technique for taking accurate velocity measurements between propeller and hull on a driven ship has hindered design improvement. In this region a laser Doppler anemometer can provide measurements where conventional means such as pitot probes would fail to function. The present paper introduces a prototype anemometer, designed for ship science work, which will simultaneously measure two orthogonal components of velocity. The instrument combines two frequency shifted reference beam anemometers and utilizes a frequency shifting technique which is simple and inexpensive. Extension of the instrumentation to measure a third orthogonal component of velocity is also discussed. Results of preparatory tests with a model propeller contain time resolved pictures of the axial and radial components of velocity in front of and through the propeller plane. The final design of an instrument under construction for towing tank use is also shown.

Acknowledgments

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Nomenclature

f	Focal length of converging lens
f_d	Doppler frequency shift
Δf	Controlled frequency pre-shift
h	Distance measured above the propeller disc
ABCD, EFGH	Squares defining the planes of the converging lenses
D	Propeller diameter
L	Laser beam
O	Position of measurement volume
O'	Focal point in the frequency shifting module
R_1, R_2, R_3	Reference beams
U	Velocity component measured by one-dimensional anemometer
U_1, U_2, U_3	Orthogonal velocity components
θ	Angle between laser beam and reference beam for the one-dimensional anemometer
λ	Wavelength of the laser light

Introduction

Experimental research into ship hull and propeller designs involves rigorous scale model tests in towing tanks and cavitation tunnels. At present pitot tube measurements taken in the plane of the absent propeller in the wake of a model provide a velocity profile which the propeller sees when in position. In this way a propeller can be designed to meet an averaged fore-aft component of velocity which is peculiar to the shape of the ship hull and its operational speed. It is important that the designer has data available on which to base selection of the geometric properties of the propeller and to determine likely propeller efficiency. Due to the absence of techniques for investigating the flow between hull and propeller data has to be taken from methodical testing of propellers in open water. When the propeller is in operation on the ship, however, the water velocity varies in both magnitude and direction across the propeller disc thus introducing unavoidable error in design. Variation in wake across the propeller disc leads to a cyclic variation in thrust and torque. These variations are transmitted to the ship hull through the propeller shaft and cause troublesome vibrations. At present, due to the absence of information regarding flow between the propeller and hull little can be done to reduce these without lowering propeller efficiency. It is evident from the state of the art as mentioned that a technique of examining the flow between the ship hull and propeller could lead to a major improvement in their design.

A laser Doppler anemometer has the unique ability to take time resolved velocity information in this region without disturbing the flow. The measurement of fluid velocity using a laser beam and utilizing the Doppler effect was first demonstrated by Yeh and Cummins (1) and since then much effort has been put into developing the technique. Abbiss Chub and Pike (2) have written a concise review of L.D.A. in general and discuss the merits of different types of anemometers and signal processing techniques. The instrument to be described in this work is based on a simple one-dimensional reference beam anemometer which operates as follows:-

Consider figure 1. The light beam from the laser is split into two parts by a simple beamsplitter and the two beams are then focussed using a converging lens so that their point of intersection O is in the flow region. A neutral density filter is used to reduce the intensity of one beam (the reference beam) before it is collected by a photomultiplier tube. The intersection point of the two beams together with the aperture on the photomultiplier define the measuring volume in the flow at O from which velocity information is obtained.

Particles transported in the flow scatter light from the high intensity laser beam in the measurement volume at O. Some of this scattered light is directed along the reference beam and the two are heterodyned into the photomultiplier; the scattered light having a Doppler shifted frequency due to the velocity of the particles. The output current from the photomultiplier which is proportional to the incident light intensity is thus modulated at the Doppler shifted frequency which can then be measured. The frequency shift f_d can be expressed (2) in terms of the velocity component of a particle by

$$f_d = \frac{2U}{\lambda} \sin \frac{\theta}{2} \qquad \ldots.(1)$$

where λ is the wavelength of the light used, U is the particle velocity component and θ is the angle between the reference beam and laser beam as shown. The direction of U is in the plane of the two beams and bisects the compliment of the angle θ between them. Thus assuming the particles transported by the flow follow it exactly then measurement of the Doppler shifted frequency enables the velocity of the flow to be calculated. A detailed discussion of the validity of this assumption is beyond the scope of this paper. It is sufficient to state that in water flows particles of $\leq 5\mu$ are numerous and inherent in the supply. These scatter light well and for the frequencies of interest in ship research ($\approx 10^2$ HZ) follow the flow faithfully. A frequency tracker (3) processes the output from the photomultiplier and produces a voltage analogue of the changing Doppler frequency. Display of its output on an oscilloscope provides a time resolved picture of the flow velocity.

The reference beam anemometer, as described, cannot distinguish the sign of the local velocity U in the measurement volume. This is overcome by introducing a controllable frequency pre-shift into the reference beam before it intersects the laser beam. The consequent heterodyning of the scattered light from the measurement volume results in equation (1) being modified to

$$\Delta f \pm f_d = \frac{2U}{\lambda} \sin \frac{\theta}{2}$$

where Δf is the magnitude of the pre-shift. This technique also alleviates problems in low velocity signal excursions since for zero velocity in the flow i.e. $f_d = 0$ the range in which the Doppler frequency shift occurs can be chosen by adjusting Δf. The low frequency regions which are often noisy can thus be avoided.

Optical Geometry of the Instrument

The two orthogonal components of velocity are measured by a combination of two reference beam anemometers. Consider figure 2. Two converging lenses of equal focal length in the planes of the squares ABCD, EFGH share a focal point O which is at the centre of the measurement volume for the anemometer. The laser beam L and the two reference beams R_1, R_2 enter the first lens normal to its plane in the positions shown and are all focussed at O before emerging parallel from the second lens. The laser beam and reference beam R_1 form an anemometer in the inclined plane defined by DCEF and measure the velocity component U_1. Similarly the laser beam and reference beam R_2 combine to form an anemometer in the vertical plane defined by ADGF which measures the velocity component U_2. Both components are measured in the forward scatter mode since light is scattered towards the second lens in the square ABCD from the measurement volume at O.

The geometry can be extended to measure the third orthogonal component as shown in figure 3. A third reference beam R_3 enters the second lens normal to its plane at B. This is focussed at O before emerging parallel from the first lens at H. The laser beam and R_3 form an anemometer in the inclined plane BDFH and measure the velocity component U_3. Successful measure of this component relies on the intensity of backscattered light from O being sufficient to give a good signal to noise ratio when it is heterodyned with the reference beam. For small scattering angles the light intensity can be as much as two orders of magnitude less in backscatter than forward scatter. For practical reasons (due to ship model size) it is necessary to have a large separation ≃ 1m between the converging lenses and hence scattering angles are small. Methods of improving the signal quality (4) for the successful measurement of U_3 without resort to a high powered laser are under investigation.

Directional ambiguity in the measurement of U_1 and U_2 is removed by frequency pre-shifting the reference beams R_1, R_2. Figure 4 shows the necessary geometry for producing these. The technique is an extension of a method used by Ballantyne, Blackmore and Rizzo (5). Two converging lenses of 20cm focal length are arranged to share a common focus O' which is in the plane of a rotating perspex scattering disc. A mask containing four circular holes, positioned at the corners of a square ABCD, is placed adjacent to the second lens. The laser beam is directed perpendicular to the plane of the first lens so that it is focussed at O' before emerging parallel from the second lens through the hole at B. The scattering disc allows the laser beam to pass through it but some light is scattered onto the mask from particles on its surface.

The holes in the mask at A and C allow the lower intensity scattered light, which is frequency shifted due to the motion of the disc, to pass through. This forms two parallel reference beams R_1 and R_2 respectively in the correct configuration to match the geometry shown in figure 2. The third reference beam R_3 for extension of the instrument can be extracted from the hole at D. The amount of frequency pre-shift given to the reference beams is controlled by adjusting the speed of rotation of the disc and the position of the focal point $0'$ in its plane. This method of frequency shifting was chosen because of its simplicity and low cost when compared with more standard techniques such as rotating diffraction gratings (6) and electro optical modulation (7).

Optical System Testing

In order that the optical system could accomodate the differing stern widths of ship models the separation between the converging lenses had to be large. To this end the lenses were housed in the walls of a perspex tank which provided a separation of 0.84m of water. This then represented the actual separation distance and medium for the final instrument design. Lenses of 114mm in diameter were used so that the angles between the light beams could be as large as possible to reduce the measurement volume length. The distance AB shown in figure 2 was chosen to be $80\sqrt{2}$ mm. This corresponded to a measurement volume length of ≈3mm for light beams ≈ 2mm diameter. The signal weighting of the frequency tracker (3) could then resolve the point of velocity measurement to less than 1mm. A 20mW Scientifica and Cook He-Ne laser was used together with two E.M.I. 9658B photomultipliers for the initial testing. A schematic diagram of the apparatus used is shown in figure 5.

The frequency shifting module (figure 4) was aligned coaxially with the lenses in the tank walls so that the laser beam and reference beam were provided in the correct configuration for the optical geometry shown in figure 2. With this geometry the optical path lengths of the reference beams and laser beam are near equal. This is important so that the wave fronts in the beams have a well defined phase relationship when they re-combine in the measurement volume. This ensures a well defined interference and a corresponding good signal to noise ratio. If the path lengths differ by more than the coherence length of the laser (≈ 1m for He-Ne) then there is a random phase relationship between the wave fronts and clear heterodyning will not occur.

When a small screen was placed in the tank the spots of light from the beams were easily distinguished in a triangular array. The intersection of the beams at their common focus could be confirmed visually by moving the screen along the length of the tank and observing their convergence. With the screen removed two clear heterodyne signals could be observed from the photomultipliers when the scattering disc was rotating. The outputs from the photomultipliers were connected to a spectrum analyzer for this purpose. The measurement volume could be found electronically by moving a microscope slide through the point of intersection of the beams. A large increase in signal to noise ratio occurred as the slide passed through the measurement volume and caused an increase in the intensity of scattered light. With no artificial seeding of the water the signal to noise ratio achieved was ≈ 10 : 1 under normal conditions.

A small two bladed propeller (D = 55mm diam) was positioned in the tank so that the velocity components U_1 and U_2 (see figure 2) measured the radial and axial velocity components respectively. With the propeller rotating at 500 rpm these velocities were measured as the propeller was traversed vertically. Measurements of velocity were taken inside as well as above and below the propeller disc. The voltage analogues of the two changing Doppler frequencies were passed through two 30 second R.C. low pass filters before being recorded on digital voltmeters to give the mean velocity. The frequency tracker had a facility for setting zero output volts to correspond to zero flow velocity. The linear relationship between velocity and frequency (measured as a voltage from the tracker) meant that subsequent calibration was simple using a frequency meter. Figure 6 shows a plot of the axial and radial flow through the propeller disc at a radius of 0.25 D. The acceleration of the axial component through the disc is clearly defined. Measurements taken inside the latter were too low due to the frequency tracker losing the Doppler signal as the propeller blade chopped a light-beam. The tracker would hold the last value of the Doppler frequency it was following when the signal disappeared until a new signal appeared again. In this case a simple digital voltmeter reading does not give an accurate measure of the mean velocity. Flow statistics inside the disc can still be retrieved, however, by computer analysis of the time resolved signal. Gating of the signal would allow only those parts containing fluid information to pass through for analysis. The larger experimental scatter for the radial flow can be attributed to "wall effects" due to the finite size of the test tank.

Figure 7 (a) - (d) shows time resolved pictures of the two velocity components displayed on an oscilloscope. The dotted line represents a common zero for the two voltage analogues of the changing flow velocity. The upper and lower trace represent the axial and radial flow components respectively. Figure 7 (a) represents the two components at a position h/D = 0.2 (h is the distance from the top of the propeller disc). The negative voltage for the radial component represents an inflow into the propeller axis whilst the larger axial flow (positive volts) shows a constant flow towards the disc. At a position h/D = 0.02 (see figure 7 (b)) strong pulsing of the axial flow is present. The pulsing occurs at the blade passage frequency. Slight pulsing of the radial flow is also present at this position. The trace of figure 7 (c) represents the components when the propeller blade is just clipping the measurement volume of the anemometer. As the blade replaces the fluid in the latter the two velocities are shown to jump towards zero. The blade was transparent, to an extent, and this explains why zero velocity was not always obtained. The anemometer will measure the speed of the propeller rotation as the leading edge enters the measurement volume. Sharp increases in the signal to noise ratio occurred as the blade passed and caused a higher intensity of scattered light. Figure 7 (d) shows the two components below the propeller disc at $h/D = -0.2$. The mean axial component is increased as expected and the pulsing of the blade passage frequency is not as evident.

Ship Research Applications

The laser anemometer (as shown in figure 5) can be readily used in cavitation tunnel work for propeller design. The glass walls of the tunnel allow the light beams easy optical access to the flow region. It was found in practice that the alignment of the optics is quite sensitive and to this end it is preferable to arrange a support system so that the optical apparatus can be traversed as one unit.

The design of the anemometer for use in a ship towing tank is shown in figure 8. Possible extension of the instrument to measure the third orthogonal (athwartships) component of velocity has been included. This takes the form of the extra reference beam and photomultiplier R_3 and P_3 respectively. Two hydrofoils straddle the stern of the ship model such that the distance between them is twice the focal length of the converging lenses shown in figure 2. The hydrofoil cross sections are specially designed in that their presence does not affect the magnitude of the velocity at a point mid-way between them. The converging lenses are housed in the walls of the hydrofoils and periscopes permit access of the light beams via the lenses to the flow region. Small, high quality, mirrors are used to direct the light beams to the periscopes. In this way the optical geometry shown in figure 3 can be reproduced in the propeller region. Adjustment of the hydrofoils in unison fore-aft, vertically and athwartships allows the whole flow region to be examined. The frequency shifting module (see figure 4) is situated equidistant from each hydrofoil to create an equal light path length design (see Optical System Testing). All ancillary equipment laser, photomultipliers, frequency trackers etc. are carried on a trolley which is towed along with the ship model. This prototype anemometer (figure 8) is under construction at Southampton University prior to testing in a towing tank and the National Physical Laboratory (ship division) are building the anemometer shown in figure 5 for propeller testing in a 42" cavitation tunnel.

References

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(3) Wilsmhurst, T., Rizzo, J.E.,Journal of Physics, E: Scientific Instruments, Vol. 7, 1974, pp 924-930

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(5) Ballantyne, A., Blackmore, C., Rizzo, J.E., Optics and Laser Technology, Vol. 6, 1974, pp 170-173

(6) Oldengarm, J., van Krieken, A.H., Raternik, H.J., Optics and Laser Technology, Vol. 5, 1973, pp 249-252

(7) Drain, L.E., Moss, B.C., Opto-Electronics, Vol. 4, 1972, pp 429-439

List of Figures

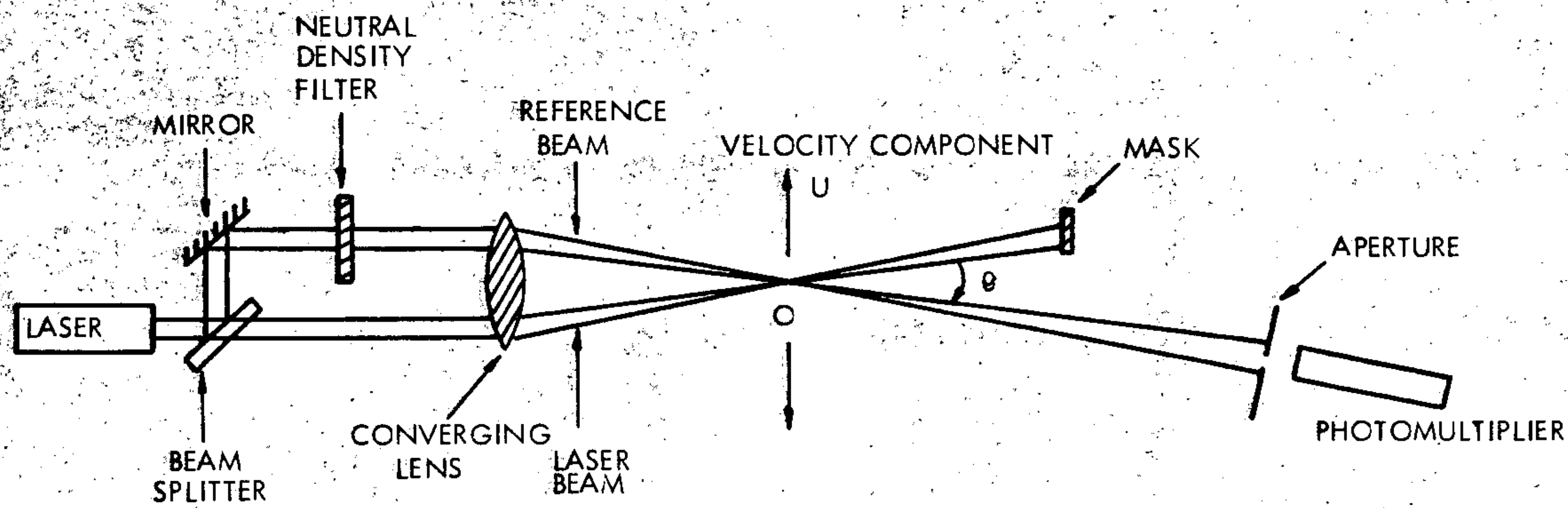

FIG. 1.
REFERENCE BEAM ANEMOMETER.

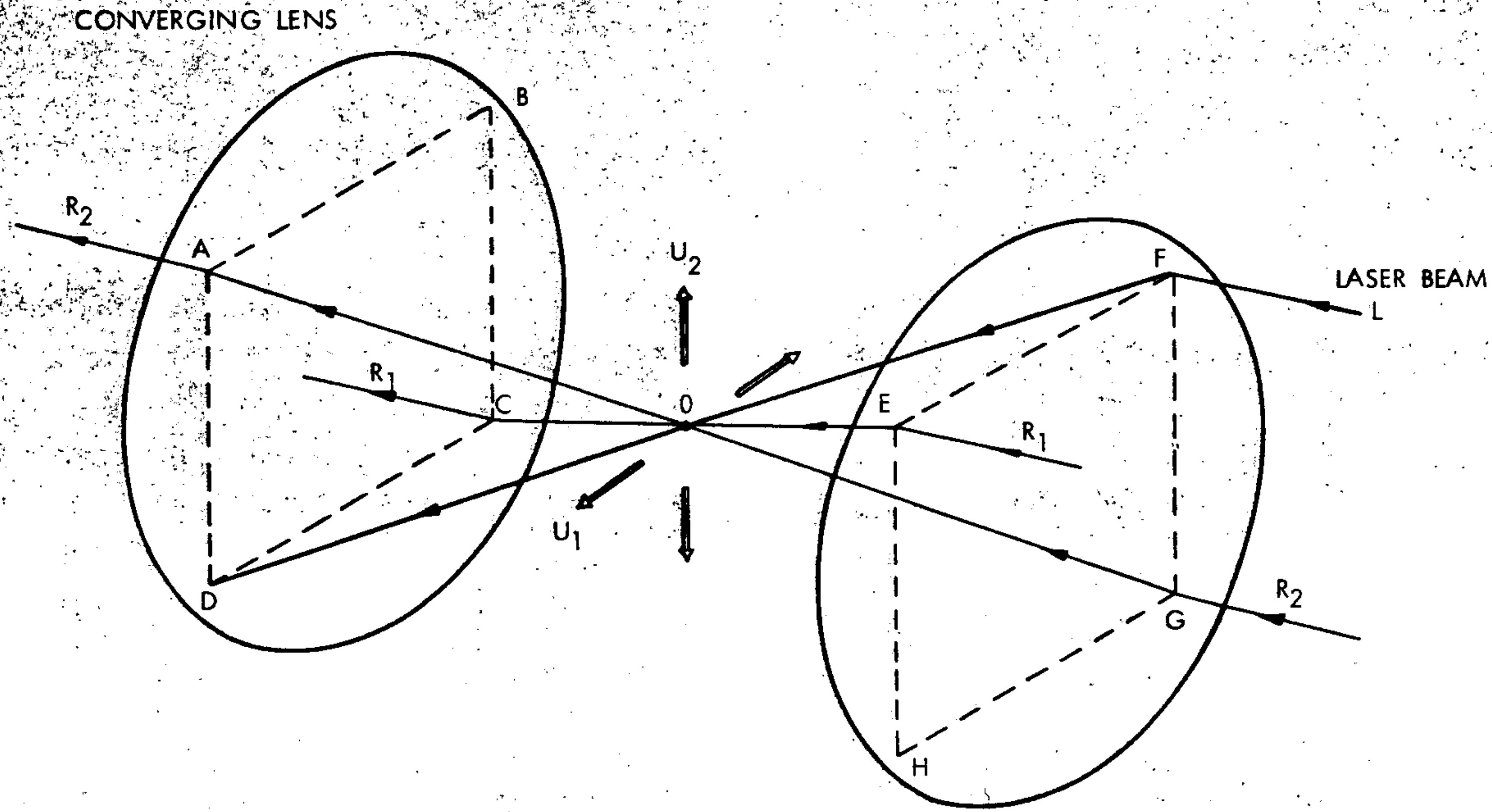

FIG. 2.

2 COMPONENT MEASUREMENT MODULE.

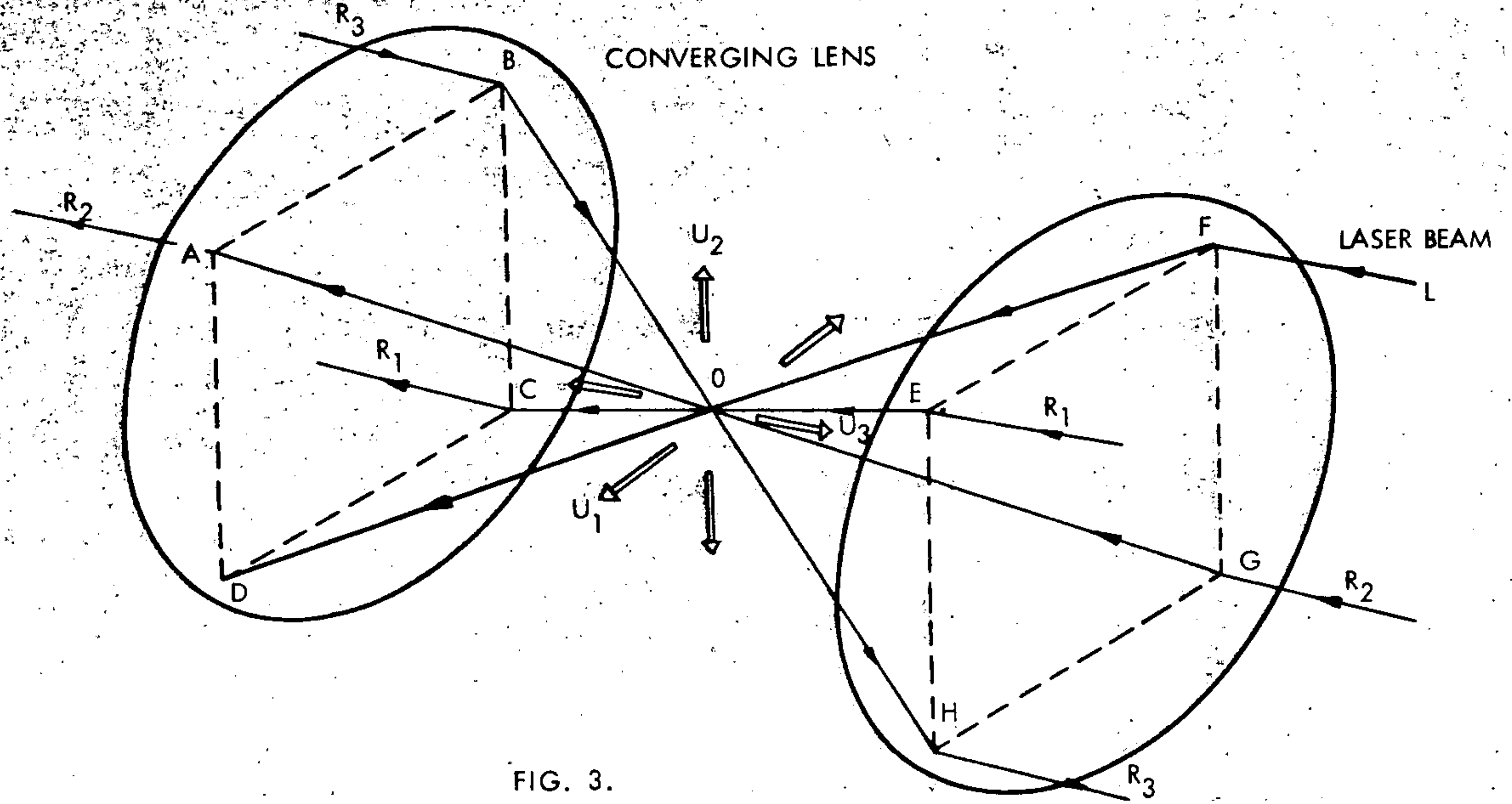

FIG. 3.

3 COMPONENT MEASUREMENT MODULE.

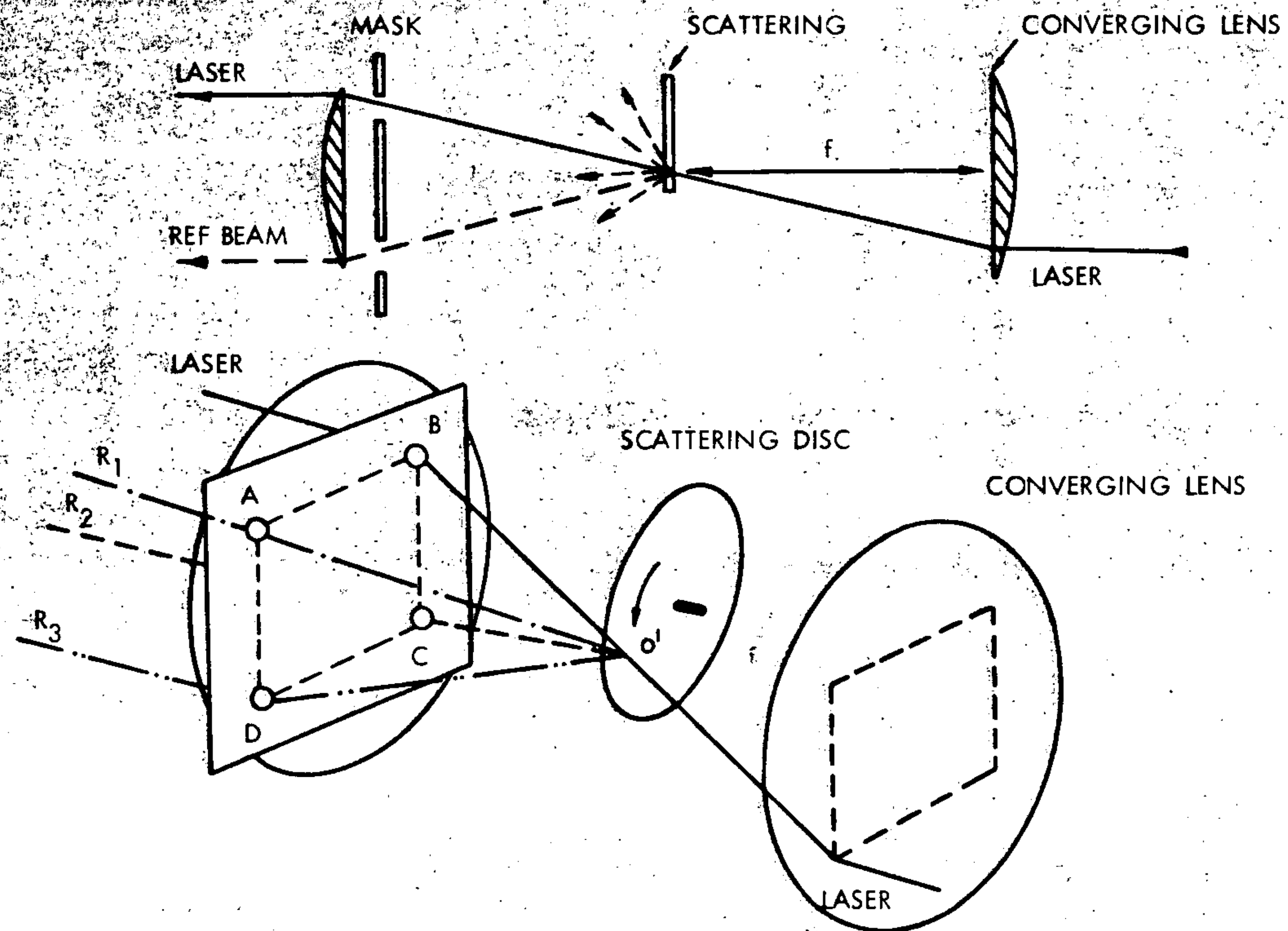

FIG. 4.
FREQUENCY SHIFTING MODULE.

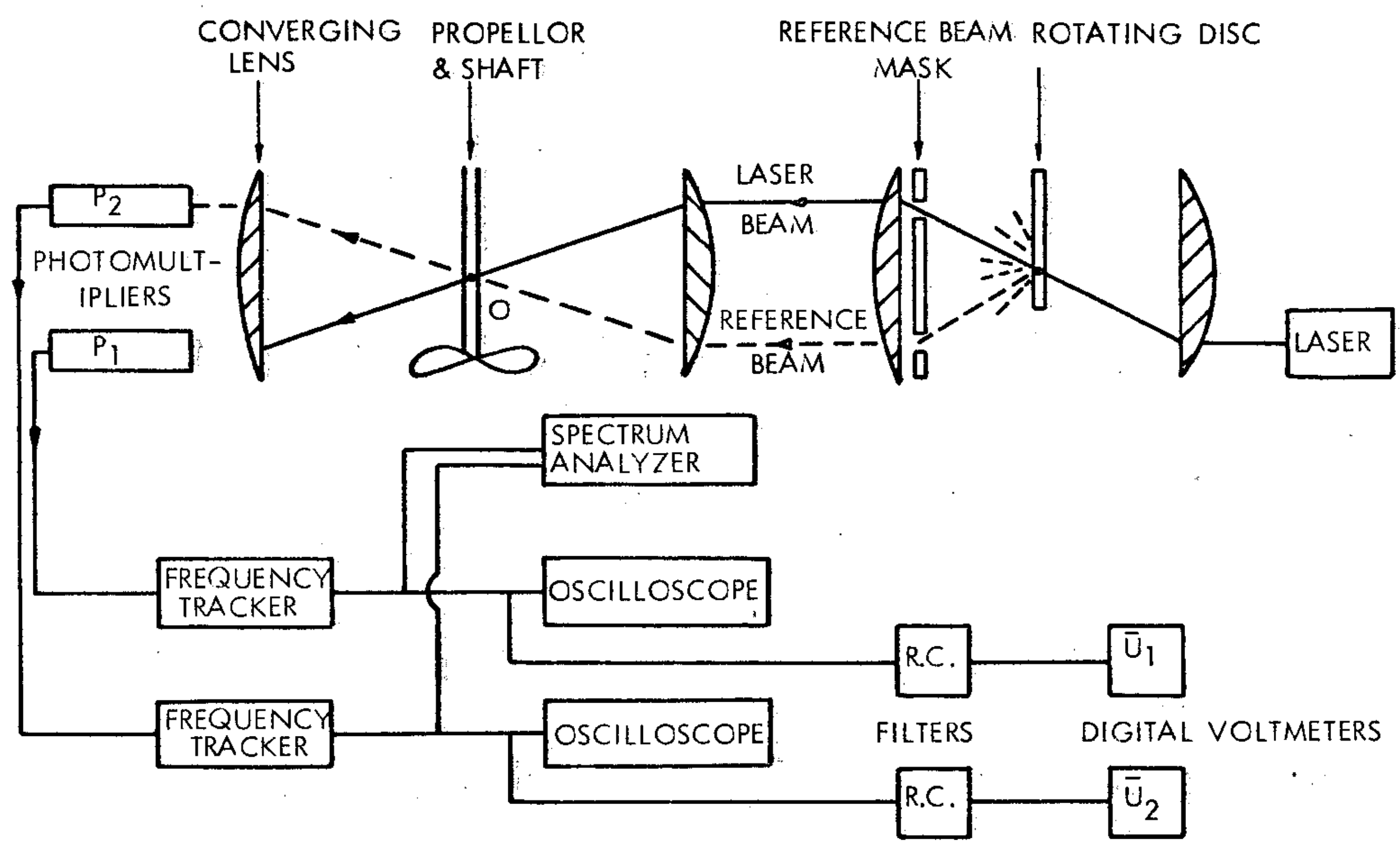

FIG. 5.
SCHEMATIC DIAGRAM OF LABORATORY TEST APPARATUS.

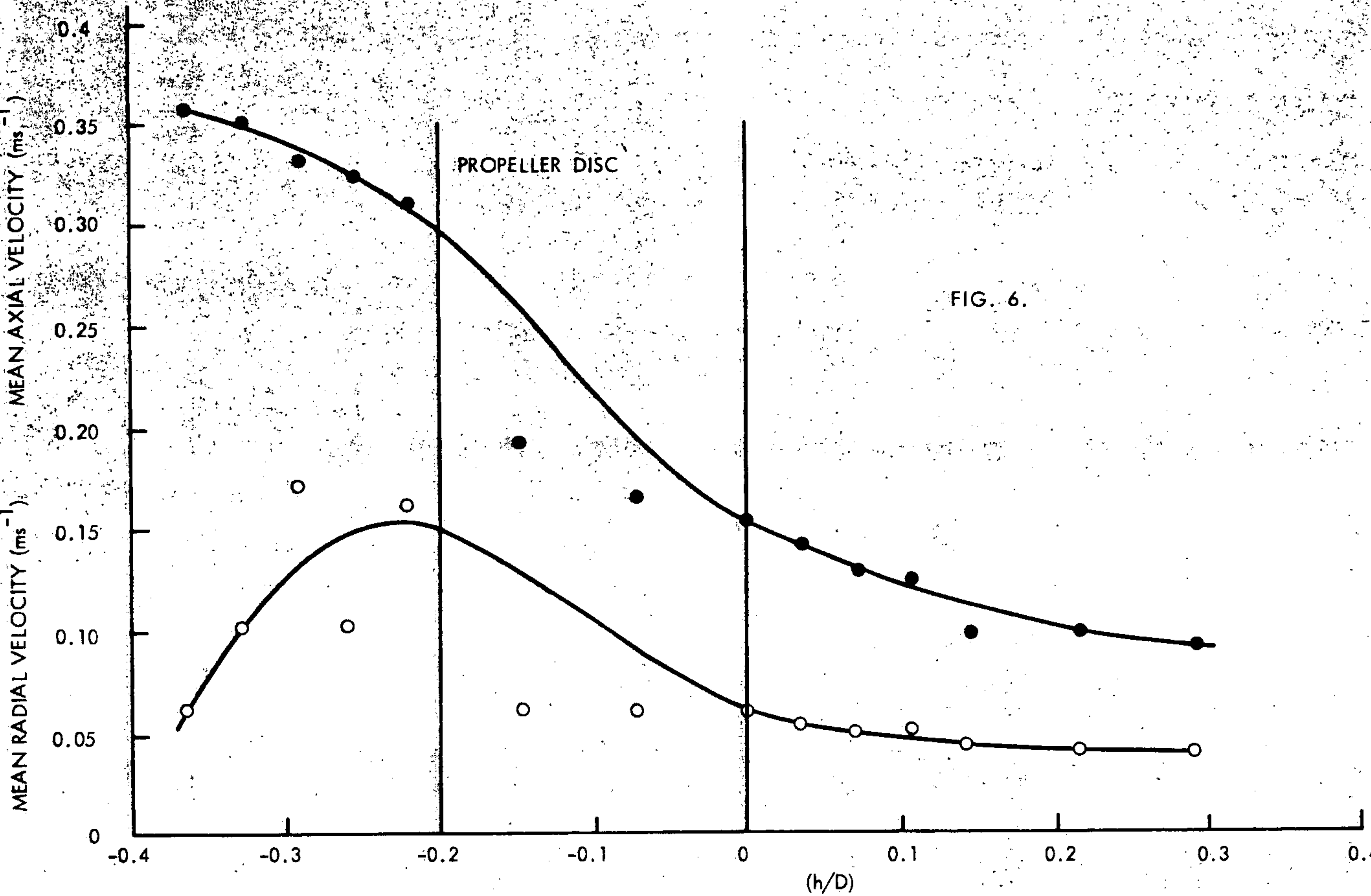
MEAN AXIAL VELOCITY (ms⁻¹)
MEAN RADIAL VELOCITY (ms⁻¹)
PROPELLER DISC
0.4
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
(h/D)

FIG. 6.

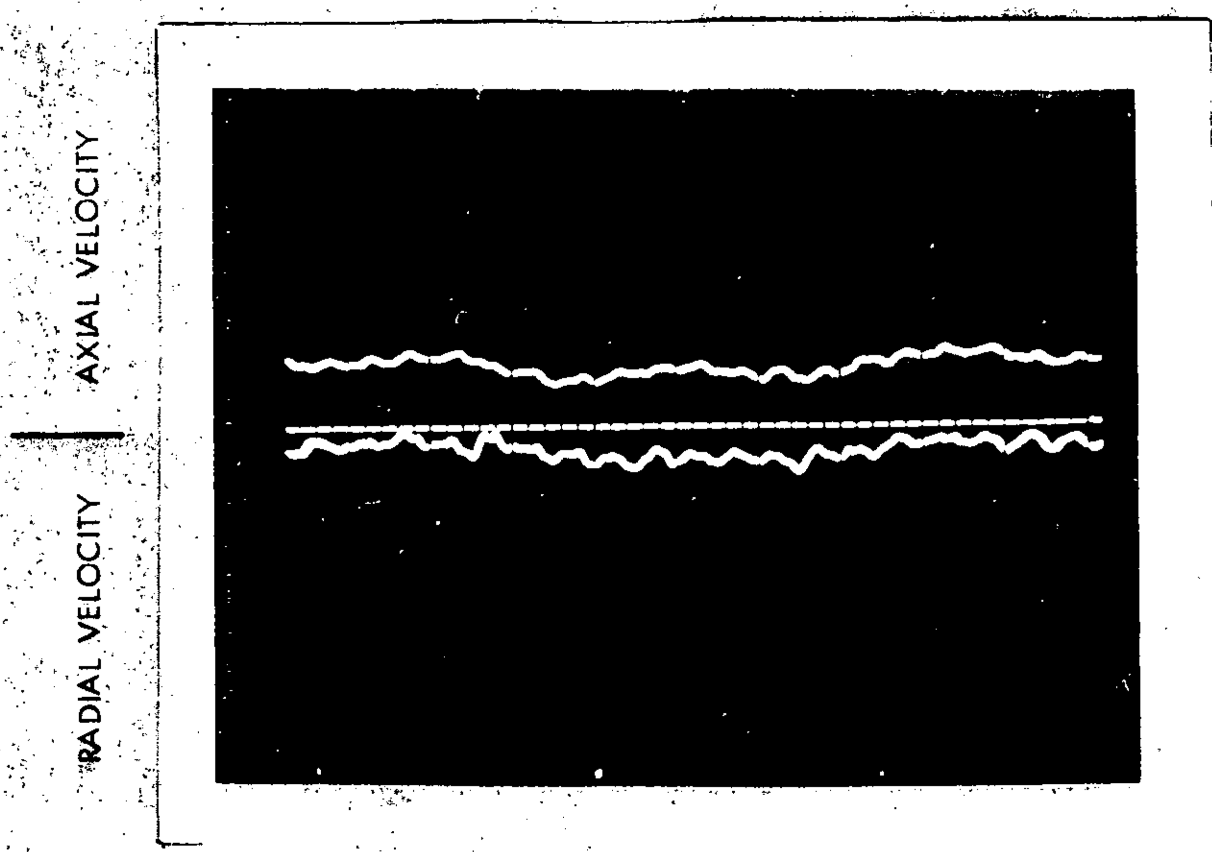

FIG. 7(a). h/D = 0.2

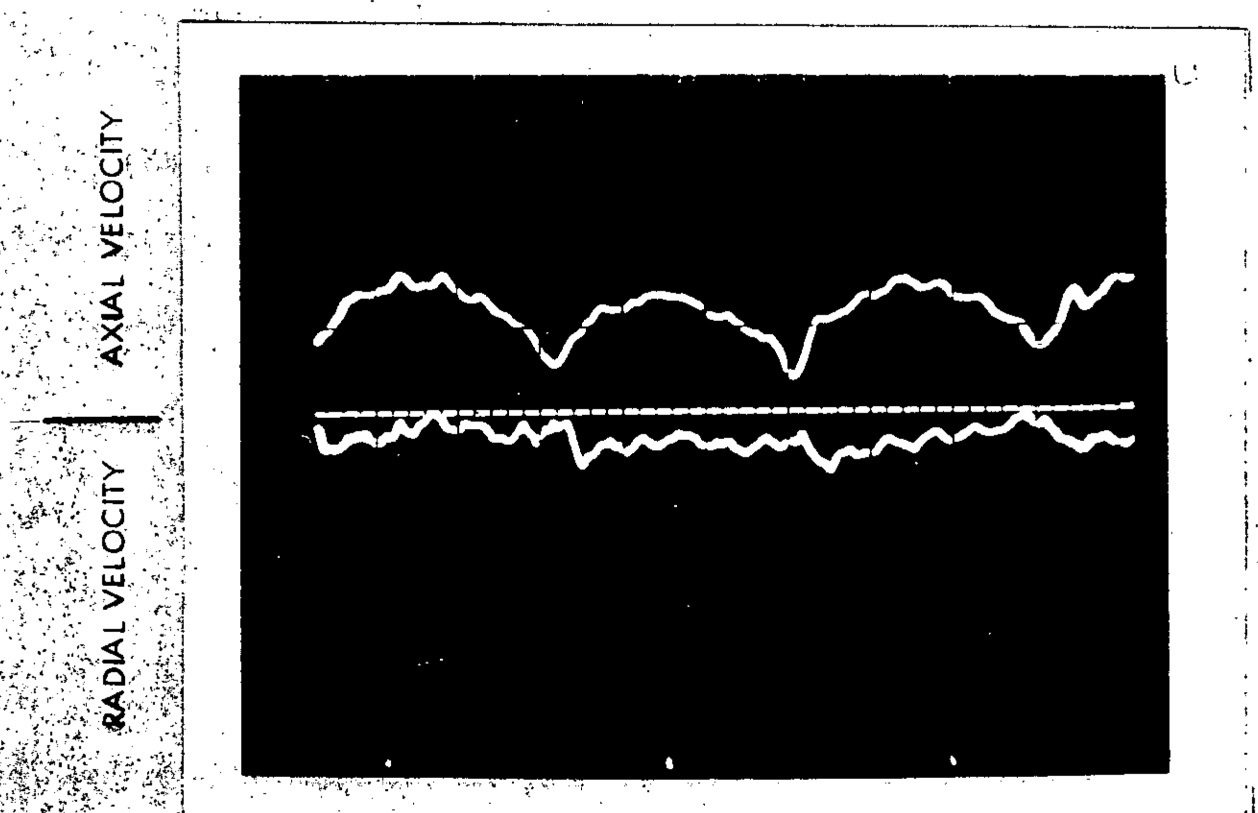

FIG. 7(b). h/D = 0.02.

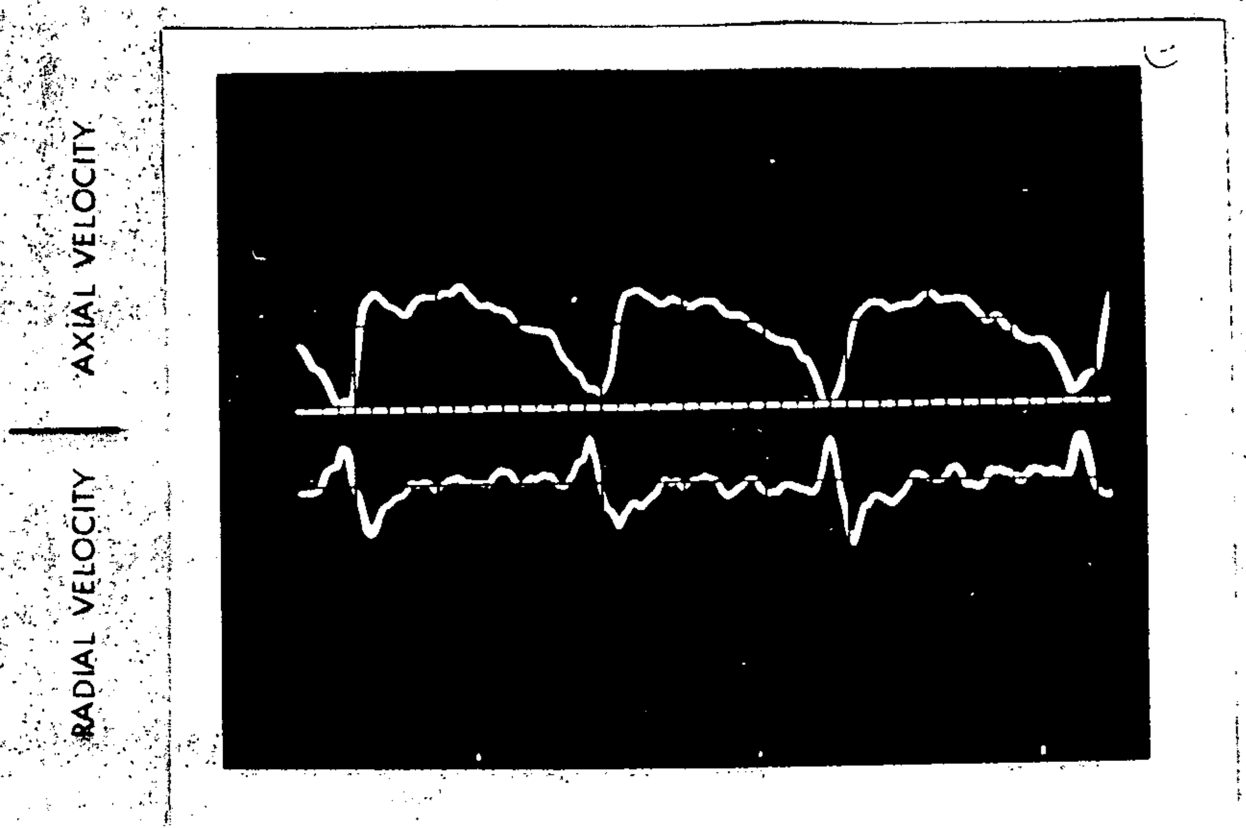

FIG. 7(c). h/D = 0

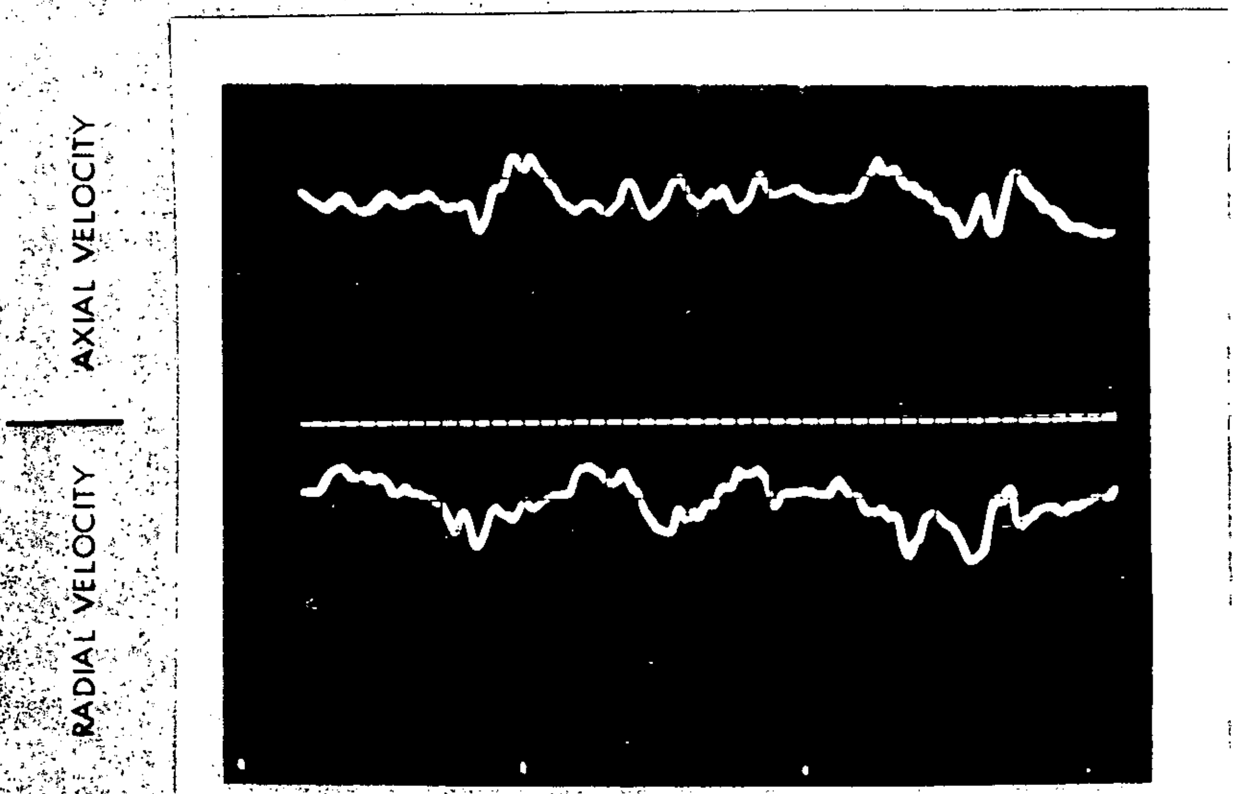

FIG. 7(d). h/D = - 0.2

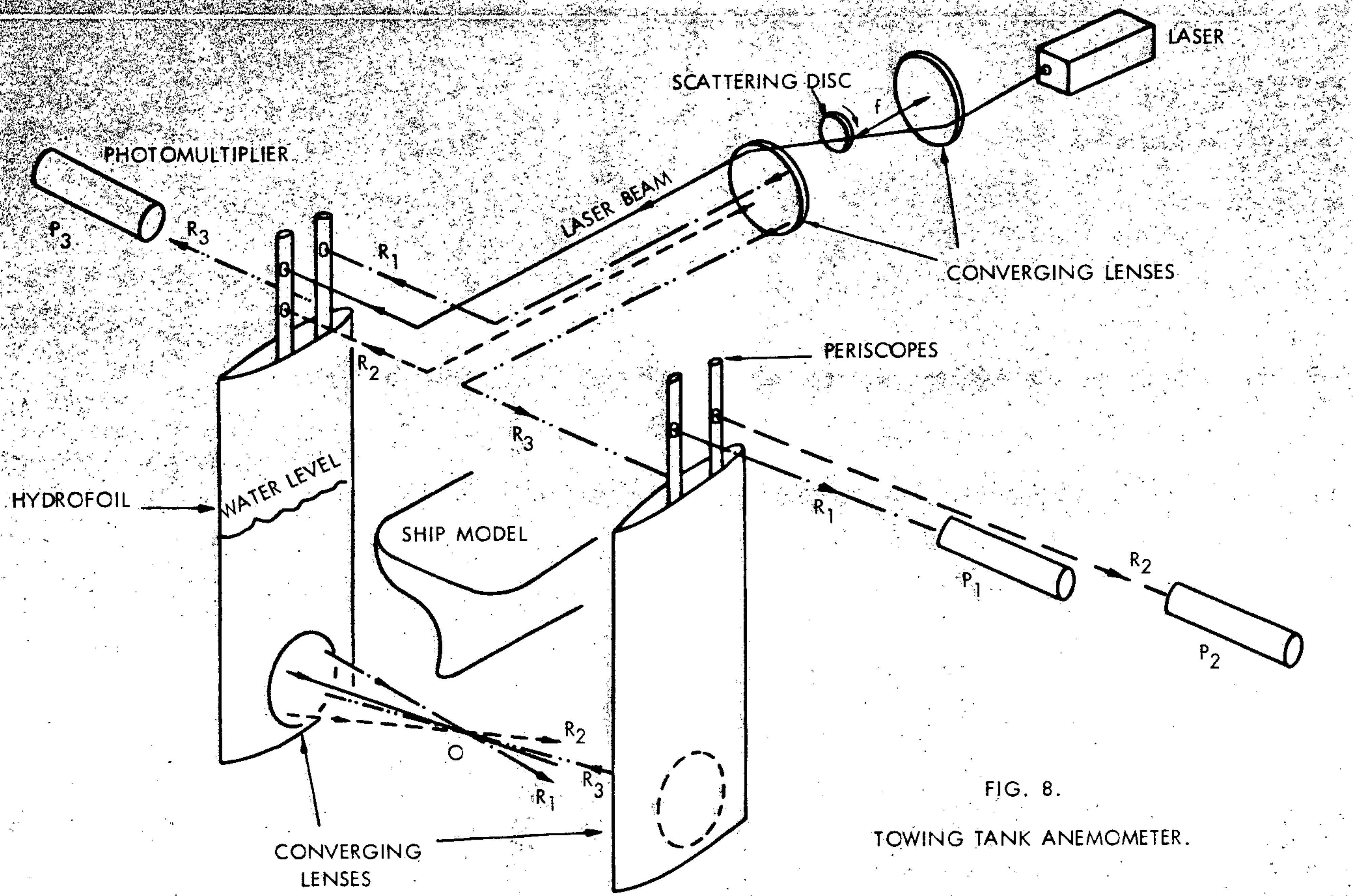

FIG. 8.

TOWING TANK ANEMOMETER.