SSSU 4/77
ISSN 0140 3818

UNIVERSITY OF SOUTHAMPTON

DEPARTMENT OF SHIP SCIENCE

FACULTY OF ENGINEERING AND APPLIED SCIENCE

LASER-DOPPLER ANEMOMETRY IN SHIP HYDRODYNAMICS

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Ship Science Report No. 4/77

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Summary

Since the advent of laser-Doppler anemometry (L.D.A.) as a new tool in experimental fluid mechanics much effort has been devoted to developing practical instrumentation for engineering applications. A non-interfering velocity measurement technique which provides high spatial resolution, directional sensitivity and time resolved information can provide measurements in ship hydrodynamics which hitherto were unobtainable. This paper describes an L.D.A., constructed at Southampton University to take axial velocity measurements in a ship-model towing tank. The optical geometry used is versatile and is readily applicable to cavitation tunnel work. An appendix is included which describes the extension of the instrument to measure three orthogonal components of velocity simultaneously. Results from the wake of a ship model showing mean wake fraction and wake spectra are presented. Three dimensional presentation of the wake power as a function of frequency is also included. Measurements taken in the wake of a circular cylinder towed along the tank verify the periodic vortex shedding at a Strouhal number of 0.2 and demonstrate the real-time measurement capability of the instrument. It is hoped that this paper will promote the use of L.D.A. in ship science research. If further progress in the problems of propeller-hull interactions, wake scaling, bilge vortex convection, cavitation and propeller induced vibration is to be made then time resolved velocity information provided by this instrument is required.

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1. 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. Variation in wake across the propeller disc leads to cyclic variation in thrust and torque. These variations are transmitted to the ship hull through the propeller shaft and can cause troublesome vibrations. For example, if large bilge vortices are shed off a ship stern it is important to detect the shedding frequency and avoid use of a propeller whose blade passage frequency (or a harmonic of it) has the same value. At present, due to the absence of time resolved information regarding flow between the propeller and hull little can be done to reduce such problems without lowering propeller efficiency. It is evident from the state of the art as mentioned that a technique of examining a wake in real time could lead to a major improvement in ship hull and propeller 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. Description of optical system tests in the development of the towing tank anemometer can be found in two earlier works by the author, Refs. (3), (4).

1.1 A Reference Beam Anemometer

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. 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

$$f_d = 2\mu U \sin(\theta/2)/\lambda \qquad (1)$$

where λ is the wavelength of the light used, μ is the refractive index of the medium, 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 complement 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 $\lessapprox 5\mu$ are numerous and inherent in the supply. These scatter light well and for the frequencies of interest in ship research ($\lessapprox$ 100 Hz) follow the flow faithfully. A frequency tracker[5] 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 (within the time constant of the frequency tracker).

1.2 Frequency Shifting

The reference beam anemometer, as described, cannot distinguish the sign of the local velocity U in the measurement volume. This problem is overcome by introducing a controllable frequency pre-shift into the reference beam before it heterodynes with the scattered light from the measurement volume. The resulting frequency-velocity relationship (1) becomes

$$\Delta f \pm f_d = 2\mu U \sin(\theta/2)/\lambda \qquad (2)$$

where Δf is the magnitude of the frequency pre-shift. Frequency shifting alleviates problems in low velocity signal excursions since for zero flow velocity ($f_d = 0$) the photomultiplier produces a current output modulated at Δf and the range in which this occurs can be selected. In this way low frequency regions which are often noisy can be avoided. There are several means of introducing the pre-shift into the reference beam.[6,7] The technique used for the towing tank anemometer is an extension of that used by Ballantyne, Blackmore and Rizzo[8], and utilizes a rotating scattering plate.

2. Optical Geometry

This is best understood by considering it as the combination of a frequency shifting and measurement module. The former is shown in Fig. 2. Two converging lenses L_1 and L_2, on the same axis, are arranged to have a common focus O' which is in the plane of a rotating scattering disc.[8] A mask M containing two holes A and B at a distance 2d apart is placed adjacent to L_2 in the position shown. The laser beam is positioned so that it enters L_1 perpendicular to its plane and is focussed at O' before passing through the hole in M at B and emerging parallel from L_2. The scattering disc whilst allowing most of the laser beam to pass through it unaffected scatters a small fraction of light forward from O' onto the surface of the mask M. The circular hole at A allows some of this light to pass through which is then formed into a parallel beam by L_2.

When the scattering disc is rotated at a constant speed the scattered light undergoes a Doppler frequency shift and in this way a frequency pre-shifted reference beam is formed by the light emerging from the hole A. Equation (1) is applicable. The amount of frequency pre-shift Δf is controlled by the speed of rotation of the disc, the position of O' on the disc surface, the separation (2d) of the holes on the mask M and the focal length of L_2. The laser beam and frequency shifted reference beam are thus presented in a horizontal plane for combination by the measurement module. Intensity of the scattered light reference beam is low enough to avoid the need of the neutral density filter shown in Fig. 1.

The measurement module, shown in Fig. 3, consists of two converging lenses L_3 and L_4 which share a common focus at O in the flow region of interest. The laser beam and reference beam are focussed by L_3 at O and their intersecting waists form the measurement volume for the anemometer as described in section 1.1. The reference beam heterodynes with scattered light from O and emerges from L_4 as a parallel beam before being directed via a pin-hole shutter onto the surface of the photomultiplier tube. A schematic diagram of the complete optical geometry together with the subsequent electronics is shown in Fig. 4. Extension of this system for multi-orthogonal component measurement is described in the Appendix. Precautions and practical suggestions in aligning the two modules for use other than in a towing tank can be found in an earlier work by the author, Ref. (9).

3. Instrument Description

A schematic diagram of the towing tank anemometer is shown in Fig. 5 and the photographs in Figs. 6(a) and 6(b) show the completed instrument. Fig. 6(a) is a close-up of the optical components of the L.D.A. and Fig. 6(b) shows the ship model in position. Consider Fig. 5. The laser, photomultiplier and frequency shifting module are all fixed to a horizontal plate which can be traversed axially along the tank, vertically and athwartships. Two surface piercing hydrofoils, fixed to the same plate, straddle the stern of the ship model and these complete the anemometer. The latter contain periscopes which permit optical access of the light beams to the wake of the ship model.

Light from the laser is reflected into the frequency shifting module which produces the laser beam and reference beam parallel and in a horizontal plane ready for convergence by the measurement module. Two periscopes, each containing a right angled prism and square mirror top and bottom respectively, transmit the beams down the middle of the hydrofoil and present them, still parallel, to the lens L_3 of the measurement module which is housed in the base of the hydrofoil. This lens acts as a window and converges the two beams to form the measurement volume of the anemometer. The lens L_4, housed similarly in the other hydrofoil, receives the reference beam and transmits it parallel to the photomultiplier via a periscope running down its centre. It follows that the hydrofoils are separated by a distance equal to twice the focal length of the lenses L_3 and L_4 in water. The lenses used are plano-convex and mounted flat face outwards to give as little discontinuity in the outer surface of the hydrofoil as possible. The latter were chosen so that their size and separation did not interfere with a velocity measurement mid-way between them. A mask similar to that used in the frequency shifting module (Fig. 2) was fixed adjacent to the lens L_3 inside the hydrofoil to act as a guide for the laser beam and reference beam. This ensures that the beams are presented in a horizontal plane across the diameter of the lens. Fine adjustments were possible by tilting the prisms and the mirrors at the top and bottom of the periscopes respectively. Table I gives the complete specifications of the various components of the instrument.

TABLE I

Component Specification

Component	Description
Laser	20 mW, He-Ne, Scientifica & Cook Ltd.
Photomultiplier	Type 9658B, selected red response, E.M.I. Ltd.
Frequency Tracker	High frequency type, Communications & Electronics Ltd.
Lenses:	
Frequency Shifting Module	Plano-convex, diam. = 0.11 m, focal length = 0.2 m
Measurement Module	Plano-convex, diam. = 0.12 m, focal length = 0.31 m
Periscopes:	Aluminium, adjustable mountings
Top	Right-angled prism, side = 12 mm, reflecting surface silvered, Optical Works, Ealing
Bottom	Square mirror, front surface silvered, side = 25.4 mm, Optical Works, Ealing
Hydrofoils	Fibre glass with aluminium ribs Type N.A.C.A. 0010-64 cross-section chord = 0.4 m, span = 0.6 m, max. thickness = 0.04m
Scattering Disc	Perspex, diam. = 0.08 m, thickness = 1.5 mm
Scattering Disc Motor	Synchronous, 375 rpm, El-Remco Ltd. Type D7
Mask	Aluminium plate thickness = 1 mm, circular holes, laser beam = 3 mm, ref. beam = 6 mm, distance d = 25 mm

Miscellaneous

Frequency Pre-Shift (Δf)	Δf = 320 kHz
Flow Scattering Angle (θ)	$\theta \simeq 7^o$
Doppler Shift for flow of 1 m/s (f_d)	f_d = 250 kHz
Measurement Volume[10]	length $\simeq$ 3 mm width $\simeq$ 0.17 mm

4. Calibration and Operation

The initial calibration of the anemometer is carried out without the presence of the ship model. It is convenient to use the speed of the ship towing tank carriage over a measured section as a calibration. The anemometer is fixed to the ship carriage and towed along the tank with the hydrofoils immersed. When the water in the towing tank is still and the carriage stationary the output voltage of the frequency tracker is linearly proportional to the speed of the frequency shifting disc according to equation (2). Initial frequency-voltage calibration of the tracker[5] is conducted with a signal generator. The tracker has the useful facility of an output voltage offset so that the output voltage corresponding to the frequency pre-shift Δf can be adjusted to zero volts. In this way a negative voltage represents a reverse flow.

For a constant speed of the anemometer over the measured test section of the tank the output voltage of the tracker can be recorded or acquired on-line to a computer. Knowing the frequency-voltage calibration, equation (1) gives the carriage speed predicted by the anemometer. Owing to the fact that the angle $\theta \simeq 7^{o}$ and taking into account any alignment errors which may occur, it is preferable to calibrate by the towing tank speed, i.e. the carriage is run down the tank at several known speeds and the linear voltage-velocity relationship with the anemometer is established.

When the ship model is in position the anemometer is traversed in the wake by changing the position of the horizontal plate to which the hydrofoils are attached. The whole optical geometry is thus traversed in unison and as such remains aligned. The low intensity of the reference beam is such that the intersection point with the laser beam, which forms the measurement volume of the anemometer, is not visible to the naked eye. Initial location is performed electronically. Consider Fig. 7. Given the ship model for investigation a microscope slide is fixed to the stern, below the water level, so that part of the slide protrudes into the wake. The slide is painted black except for a 1 mm square which allows the waist of the laser beam, which is clearly visible in the water, to pass through it. The position of the transparent square is noted relative to the stern of the model.

For no flow in the towing tank the anemometer measures the speed of the frequency shifting disc and if the amplified output of the photomultiplier is displayed on a spectrum analyzer a clear Doppler signal at frequency Δf (see section 1.2) is observed. The anemometer is initially positioned by eye so that the laser beam waists through the slide which is approximately mid-way between the hydrofoils. When the measurement volume coincides with the latter, the light scattered from the laser beam is of a higher intensity than that scattered by the water alone. This provides a sudden increase in the signal to noise ratio of the Doppler signal observed on the spectrum analyzer. In this way the measurement volume is detected electronically by accurately traversing the anemometer athwartships. The microscope slide is then removed and the reference point is noted on the traverse scales. The measurement volume can then be moved to the wake plane of interest. For a mean velocity measurement it is possible to have the voltage from the tracker integrated and measured on a digital voltmeter whilst the ship model is in motion. This depends on the time available over the measured section of the tank and the oscillatory nature of the flow of the wake position. The alternative is to tape record the voltage or acquire it on-line to a computer.

From experience, it is recommended that the voltage is tape-recorded and analysed by computer at a later time. This not only preserves real time information but considerably shortens the time required to measure the wake. It is useful, however, to have a digital display of the velocity voltage as this enables a check to be made that the water in the tank is stationary before repeating a run. When large models are tested it is possible that after several runs a net circulation exists in the tank which would invalidate results. The time allowed for the water to settle in the past has largely been decided on experience. The anemometer showed that this usually overestimated the time necessary to wait between runs, especially considering the accuracy of the pitot-tube water-manometer arrangement normally used. The steps to be followed in operation of the anemometer are as follows:

(i) Calibrate the frequency tracker.[5]

(ii) With the hydrofoils immersed and the water still, track the scattering disc velocity and adjust the output offset to zero volts.

(iii) Couple the anemometer to the towing tank carriage with no ship model present.

(iv) Establish the voltage-velocity linear relationship between the anemometer and carriage speed.

(v) Fix the microscope slide to the ship stern and establish the exact position of the measurement volume.

(vi) Remove the slide and traverse the measurement volume to the wake plane of interest.

(vii) Record the velocity-voltage over the measurement length.

(viii) Check between runs that the digital display of the tracker voltage returns to zero corresponding to no circulation in the tank.

5. Results

5.1 General

Visual display of the tracker voltage, measured over the whole towing tank determines how smoothly the ship carriage is controlled in acceleration and retardation. The power spectrum of a test run without a model will identify the frequency of any vibration transmitted to the anemometer by the towing arrangement. In an ideal case there should be no significant peaks in the power spectrum. For no flow the anemometer measures the speed of the rotating scattering disc. Any variations in this speed due to the motor or unsteadiness in the disc contribute a background noise level. Fluctuations of this order are usually very small (< 20 dB) compared with those measured in the flow and occur at the mains frequency of 50 Hz and harmonics of this. This noise, if troublesome, can be removed by suitable filtering of the tracker output.

The dynamic range of the instrument is decided by the voltage-frequency calibration of the frequency tracker. For small velocities the small frequency fluctuations can be arranged to produce large voltage variations with the tracker at its most sensitive. The absolute limit is decided by the unsteadiness of the rotating scattering disc. For the calibration used in the results to be presented the smallest voltage measurable, allowing for fluctuations, corresponded to a velocity of 10 mm/s. The corresponding limit for a Pitot-tube inclined water-manometer arrangement is 70 mm/s if the manometer can be read to within a head of 0.5 mm of water. Theoretically, the upper limit of the dynamic range is infinite as the scattering angle in the flow can be reduced to maintain the Doppler shift within the limits of the frequency tracker. The upper limit for the scattering angle used and the frequency shift added corresponded to a velocity of 12 m/s.

The initial calibration of the instrument showed that the anemometer-carriage speed relationship was linear and readings were repeatable to less than one per cent. (no ship model present).

5.2 Ship model tests

The ship model used for the wake tests was of a twin-screw motor yacht CRINIERA d'ORO. Figure 8 shows the wake plane chosen for measurement and this corresponds, as indicated, to all the three- and two-dimensional plots of the wake which are presented.

Figure 9 shows a plot of the Taylor wake-fraction defined as (model speed-wake speed)/model speed. Owing to the small size of the towing tank the model length was restricted to 1.8 m and it was towed at a speed of 1 m/s. Practical problems of vibration, weight limitation and accessibility were all enhanced by use of the instrument in a small tank. It is anticipated that use in a large tank will alleviate problems in the engineering design. Figure 10 shows where in the wake the maximum fluctuations are occurring. As expected, these occur close to the ship hull where the turbulent boundary layer separates. The last two figures are perhaps easier to interpret when shown in three dimensions in Figs. 11 and 12.

Figure 11 shows a histogram plot of the Taylor wake fraction whilst Fig. 12 is a standard three-dimensional computer output. Although Fig. 12 shows the distribution of the total fluctuating energy in the wake it is necessary from considerations of propeller induced vibration to search for significant frequencies in this plot. This is achieved by computing a power spectrum of each velocity record in the wake and examining the energy in a given frequency band. Figure 13 shows the wake energy in the frequency band 4.5-6 Hz. The model did not have any significant frequencies as the measurable energy was evenly distributed in the range 0-12 Hz. Some spurious energy was present at a frequency of 6.25 Hz (1/8th mains frequency), however, and this is the cause of the ripple discernable in the frontage of Fig. 13.

5.3 Cylinder wake tests

In order to demonstrate the ability of the anemometer to measure boundary layer separation and vortex convection an experiment was devised to take measurements in a cylinder wake. An aluminium cylindrical bar of diameter 2 cm was positioned horizontally between the hydrofoils and towed by the ship carriage at 1 m/s. The bar was immersed in the water so that a vertical traverse across the essentially two-dimensional wake was possible. Measurements were taken at a distance of 5 cm behind the cylinder axis.

When a circular cylinder is towed through a fluid the nature of the flow is largely decided by the Reynolds number (Re) based on the cylinder diameter. ($Re = Vd/\nu$, V = flow velocity, d = cylinder diameter, ν = kinematic viscosity.) For $Re \cong 60$ oscillations in the wake occur and appear as alternate shedding of lumps of fluid from the top and bottom of the cylinder. Vorticity is concentrated in these lumps which move downstream to form the well known 'Karman Vortex Street'. This phenomenon continues until Re $\simeq 10^4$. The periodicity of the vortex shedding determined by the Strouhal number (nd/V, n = shedding frequency) depends upon Re to some extent but maintains a value close to 0.2. For the cylinder under test the predicted shedding frequency is 10 Hz at Re $\simeq$ 11,000.

Figure 14 shows a plot of the mean velocity and R.M.S. fluctuations across the cylinder wake. The sudden increase in mean velocity is shown to occur across the path of the convected vortices where the maximum R.M.S. fluctuations are reached. At a point two cylinder diameters off the axis of the wake the flow oscillations are induced by this convection. Figure 15 shows a power spectrum of the velocity at this point and proves that all the power is indeed concentrated at the shedding frequency of 10 Hz predicted by the Strouhal number of 0.2. Figure 16 is a tracing of an oscilloscope display of the velocity fluctuations at this position showing this 10 Hz oscillation. From examination of time-resolved pictures from the wake it is possible to identify the path of the centre of a vortex and its approximate size. This information is important in considering the effect of bilge vortices convected off a ship hull passing through the propeller plane.

6. Conclusions

The expense of commercially available equipment and the 'black box' attitude towards L.D.A., shared by the unfamiliar, has hindered its widespread use in engineering applications. In rarefied or high speed gas flows, etc. application can be difficult and considerable expertise is required. In water flows, however, where scattering particles are plentiful and inherent in the supply, L.D.A. is generally easy to use and frequency tracking demodulation is now an accepted and standard means of Doppler signal processing. Problems in experimental ship hydrodynamics (towing tank or cavitation tunnel) are particularly suited for laser investigation given the correct design of optical geometry.

The instrument described in this paper is robust, easy to use and can be manufactured from readily available materials and laboratory parts. A commercially available anemometer for towing tank use does not exist and for the more straightforward use in a cavitation tunnel modification of existing systems can be difficult and costly. Given the essentials of laser, photomultiplier, frequency tracker, etc, and the facilities of an engineering workshop, construction of this instrument is straightforward. The optical geometry is versatile and finds easy application in a cavitation tunnel. Multi-orthogonal component measurement is an additive facility. The prototype described was tested in a small towing tank at the Department of Ship Science at Southampton University. The restriction of size caused extra problems in engineering design, such as inaccessibility, weight limitations and vibration. Indeed, the author's main worry was that vibration, through suspension of the whole instrument from the moving carriage, would cause the hydrofoils to move and destroy the coincidence of the laser beam and reference beam which waist to a diameter of $\simeq$ 0.2 mm. The final structure was, however, rigid and physically shaking the anemometer did not destroy the Doppler signal. It is expected that in a large tank application will be easier as many of these problems will not be present.

It should be noted that optical access across the wake between the hydrofoils for the laser beam and reference beam is necessary for the instrument to function. Interference by propeller shafts or the ship hull, if they cross the wake plane of interest, will prevent some measurements. Measurements in the wake where optical access is from one side only can be taken but these require a different signal processing system and are outside the scope of the present paper. In conclusion, the advantages of the towing-tank L.D.A. compared with the 5-hole Pitot probe or Pitot-rake are as follows:

(i) Non-interference with the flow.

(ii) Excellent spatial resolution.

(iii) Directional sensitivity.

(iv) Time-resolved velocity information.

(v) Large dynamic range.

(vi) Accuracy to less than 1%.

(vii) Constant monitoring of water flow (tank circulation, etc.).

(viii) Shortened wake measurement time.

(ix) Automatic check of carriage acceleration and retardation.

(x) Simultaneous orthogonal component information.

Acknowledgements

The author wishes to thank Dr. J.E. Rizzo for many helpful discussions and criticisms at the design stage of the instrument. Thanks are also due to Messrs. A. Gomm, D. Baxter, N. Powell, A. Tuck and V. Judd for technical assistance and to Mrs. B. Guerrera for preparation of the manuscript. The work presented forms part of a continuing research project at Southampton University and financial assistance of the Science Research Council is acknowledged.

7. Appendix

Extension for Multi-Component Measurement

The optical geometry as described in section 2 measures the axial component of velocity in the wake of the ship model. Extension of this geometry for simultaneous measurement of the vertical component can be achieved by modifying the measurement and frequency shifting modules as follows.

The two orthogonal components of velocity are measured by a combination of two reference beam anemometers. Consider Fig. 17. The lenses L_3 and L_4 as in Fig. 3 share a common focus at O which is the position of the measurement volume for the anemometer. They are each co-planar with the squares ABCD and EFGH respectively. The laser beam L and two reference beams R_1 and R_2 enter L_3 normal to its plane in the positions shown and are focussed at O before emerging parallel from L_4. The laser beam and R_1 form an anemometer in the inclined plane defined by ABHG and measure the axial component of velocity U_1. Similarly, the laser beam and reference beam R_2 combine to form an anemometer in the vertical plane defined by BCEH which measures the vertical component U_2.

Figure 18 shows the modification necessary for the frequency shifting module (Fig. 2) to produce the correct configuration of light beams to complement the measurement module. The mask M contains 3 circular holes at the corners of the square A'B'C'D' (= ABCD) which is co-planar with the lens L_2 as shown. The laser beam is directed perpendicular to L_1 so that it is focussed at O' before passing through the mask at B' and emerging parallel from L_2. As described in section 2 the circular holes at A' and C' allow scattered light from O' to pass through which is then formed into two parallel reference beams R_1 and R_2. In this way the laser beam and reference beams are presented in the correct configuration for combination by the measurement volume.

Modification of the towing-tank anemometer involves the addition of an extra periscope to each hydrofoil to cater for the extra reference beam as well as an extra photomultiplier and frequency tracker for signal processing. Description of the testing of the two component system in the laboratory is described in Refs. (4) and (11). Results are shown from measurements taken near a rotating propeller. The system was aligned to measure the axial and radial flow through the propeller disc and into the axis respectively. Discussion of the alignment of the system as a two-component self-aligning instrument for general use is given in Ref. (9).

The geometry can be extended further to measure the third (athwartships) component by utilizing the light scattered back from O towards the lens L_1. The completed 3-component orthogonal geometry is shown in Fig. 19. A third reference beam R_3 perpendicular to L_4 enters the lens at F and is focussed at O before emerging parallel from L_3 at D. This, together with the laser beam form a third anemometer which measures the athwartships component U_3. Successful measurement 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 R_3. Backscattered light in this geometry can be as much as two orders of magnitude less than in forward scatter. An alternative means of signal processing (photon correlation[2]) can be used. Tests to establish this third component are described in Ref. 4.

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Figure Captions

Fig. 1	One-dimensional reference beam laser Doppler anemometer
Fig. 2	Frequency shifting module
Fig. 3	Measurement module
Fig. 4	Complete optical geometry with ancillary electronics (Plan View)
Fig. 5	Schematic layout of the towing-tank anemometer
Fig. 6(a)	Close-up of the optical components
Fig. 6(b)	Towing-tank anemometer with the ship model in position
Fig. 7	Initial location of the measurement volume
Fig. 8	Position of the wake plane of measurement
Fig. 9	Taylor wake fraction, Min. level = 0.05, Max. level = 0.4, contour intervals = 0.05
Fig. 10	R.M.S. fluctuations in the wake plane, Min. level = 0.0225 Max level = 0.04, contour interval = 0.0025 m/s
Fig. 11	Histogram representation of the Taylor wake fraction, Max. value = 0.46
Fig. 12	Three-dimensional representation of R.M.S. fluctuations in the wake, Max. = 0.04 m/s, Min. = 0.01 m/s
Fig. 13	Three-dimensional representation of the wake power in the frequency band 4.5-6 Hz, Max. = 0.006 $(m/s)^2$
Fig. 14	Mean velocity and R.M.S. fluctuations in the cylinder wake
Fig. 15	Cylinder wake power spectrum showing concentration of energy at $\approx$ 10 Hz
Fig. 16	Time-resolved display of wake velocity
Fig. 17	Two-component measurement module
Fig. 18	Two-component frequency shifting module
Fig. 19	Three-component measurement module

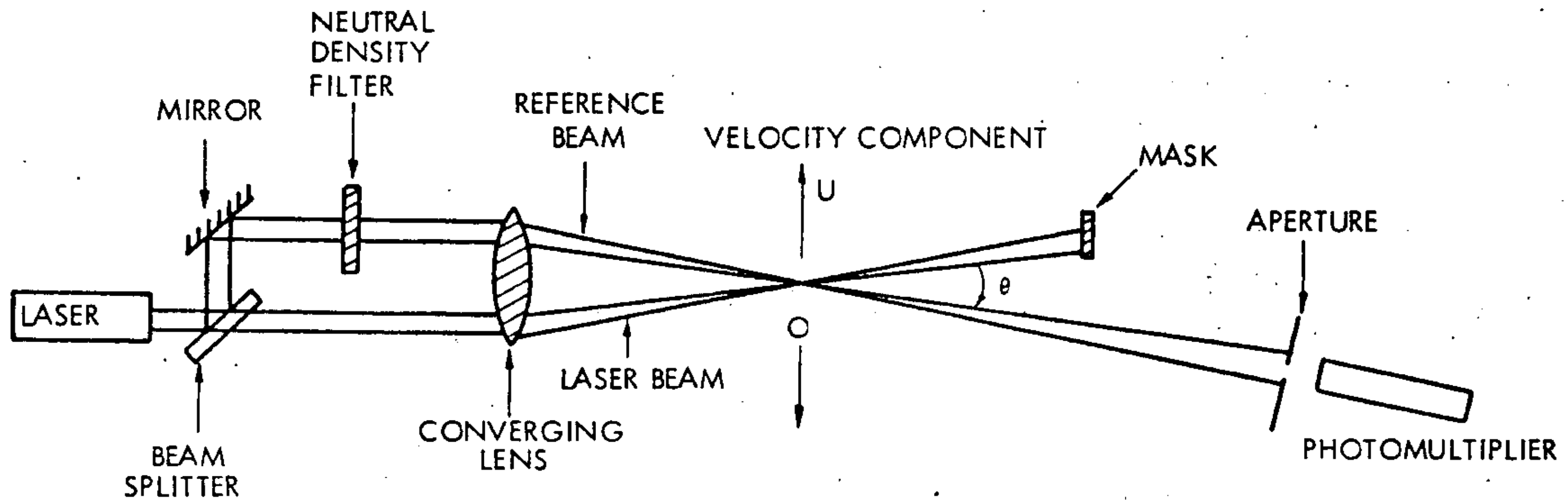
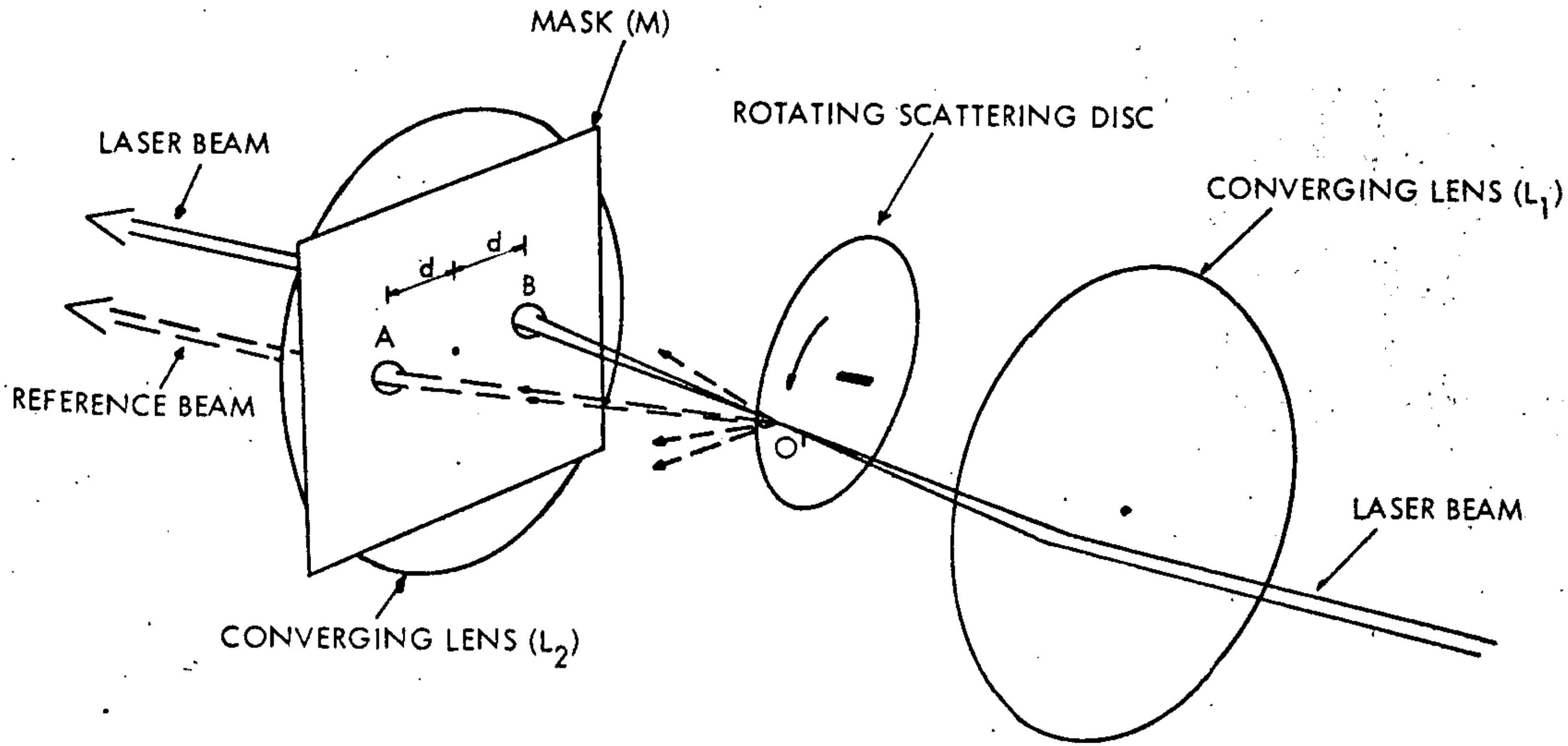
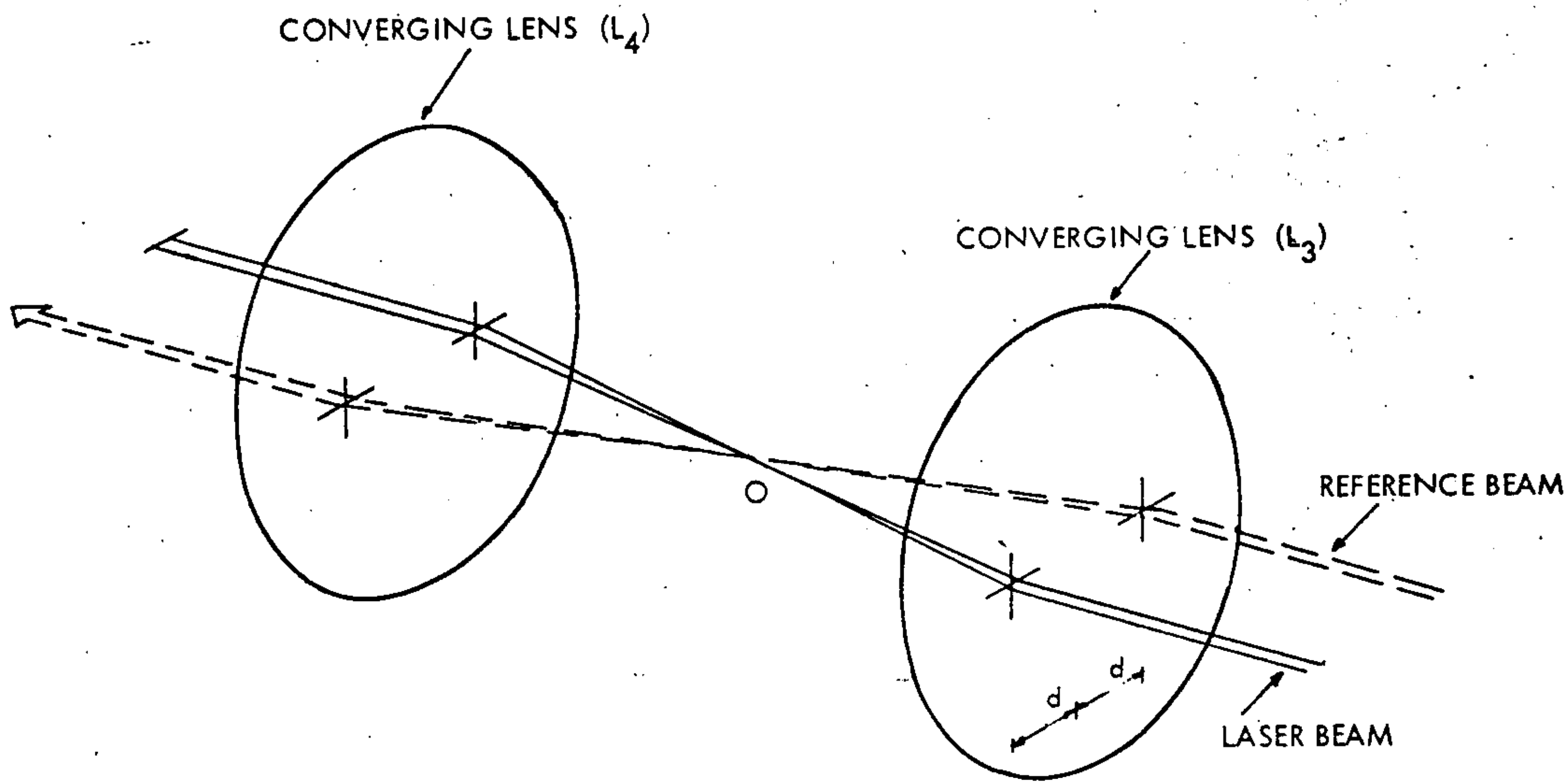


FIG. 1. REFERENCE BEAM ANEMOMETER.



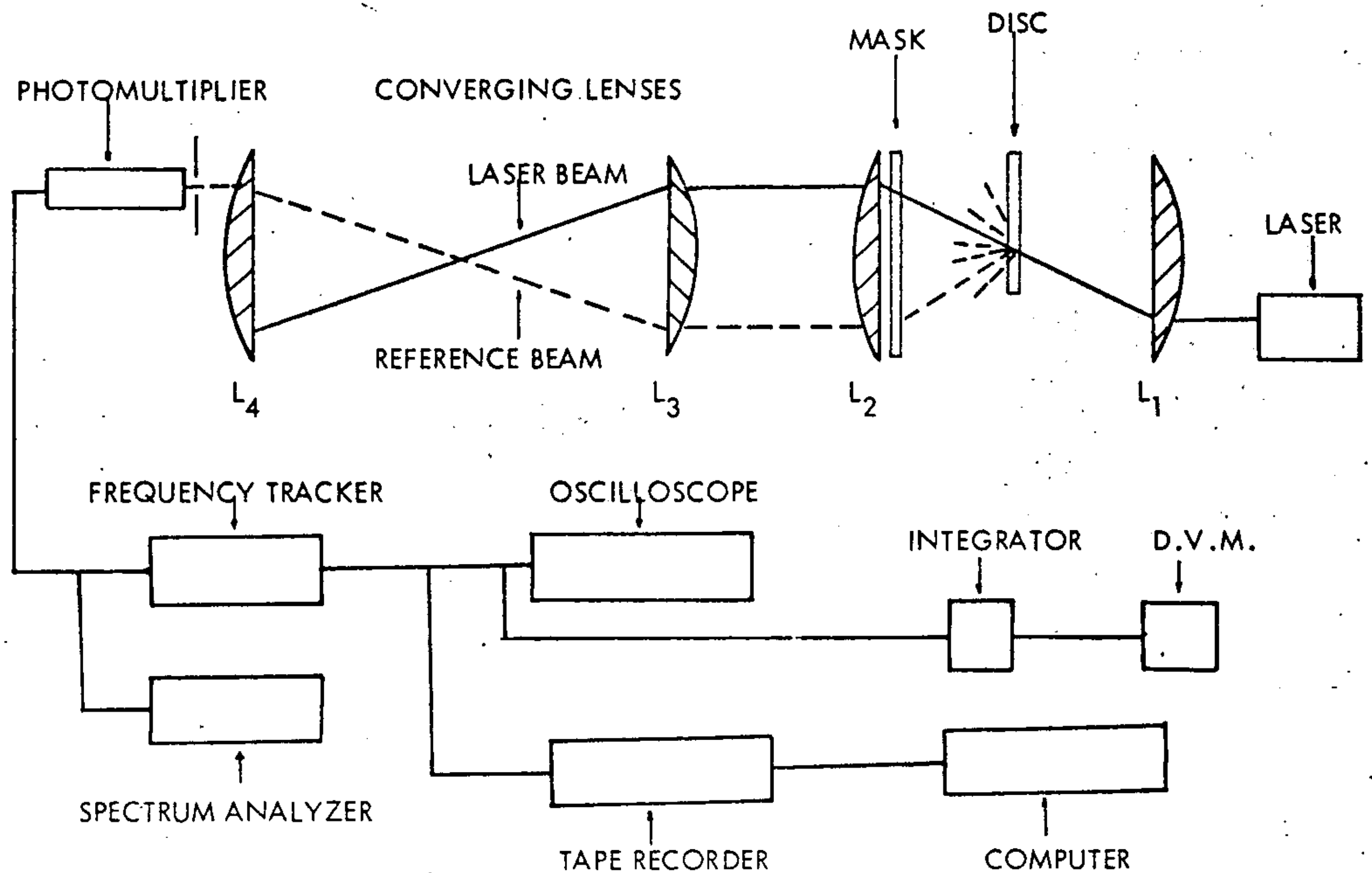
FREQUENCY SHIFTING MODULE

FIG. 2



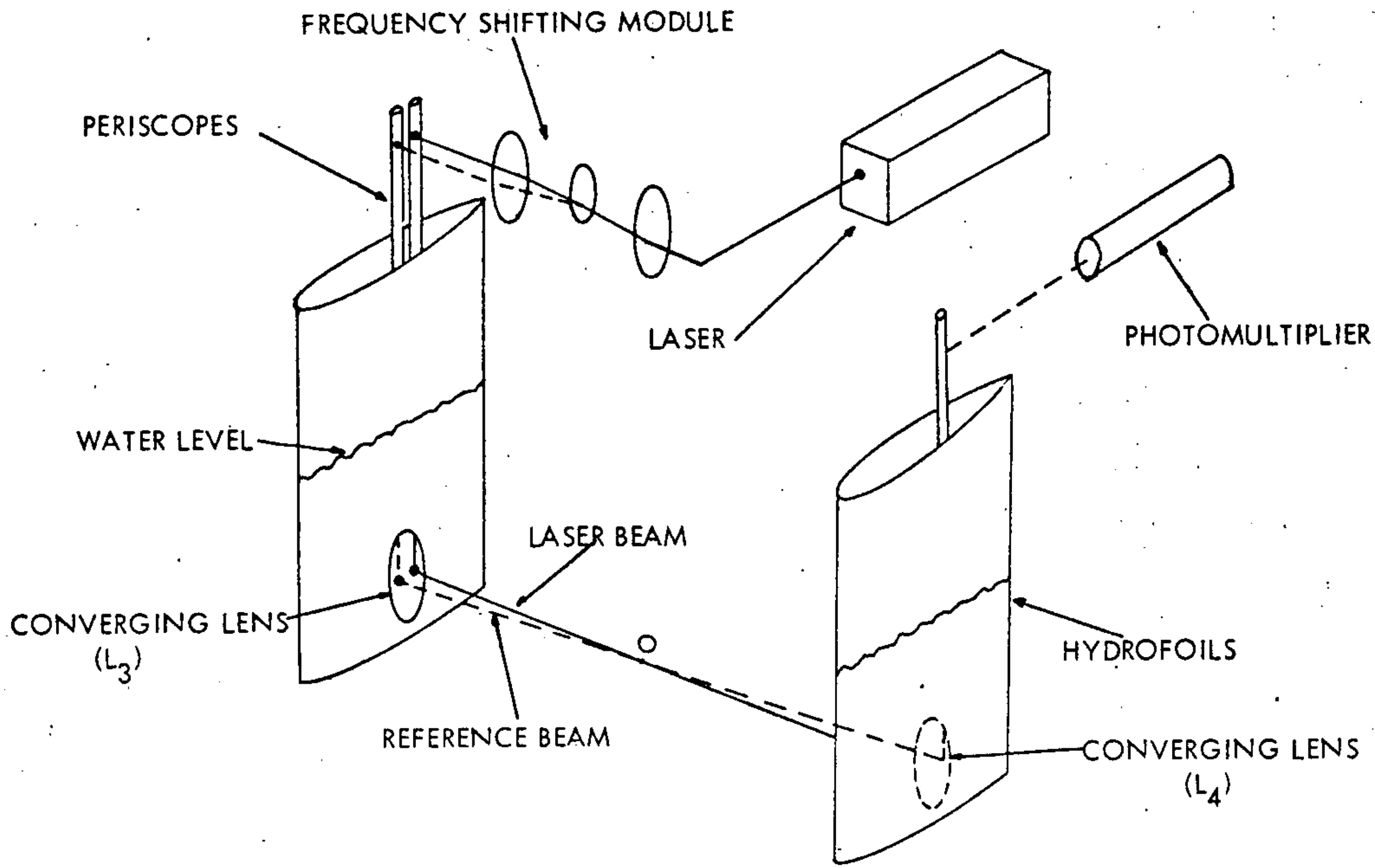
ONE-COMPONENT MEASUREMENT MODULE

FIG. 3

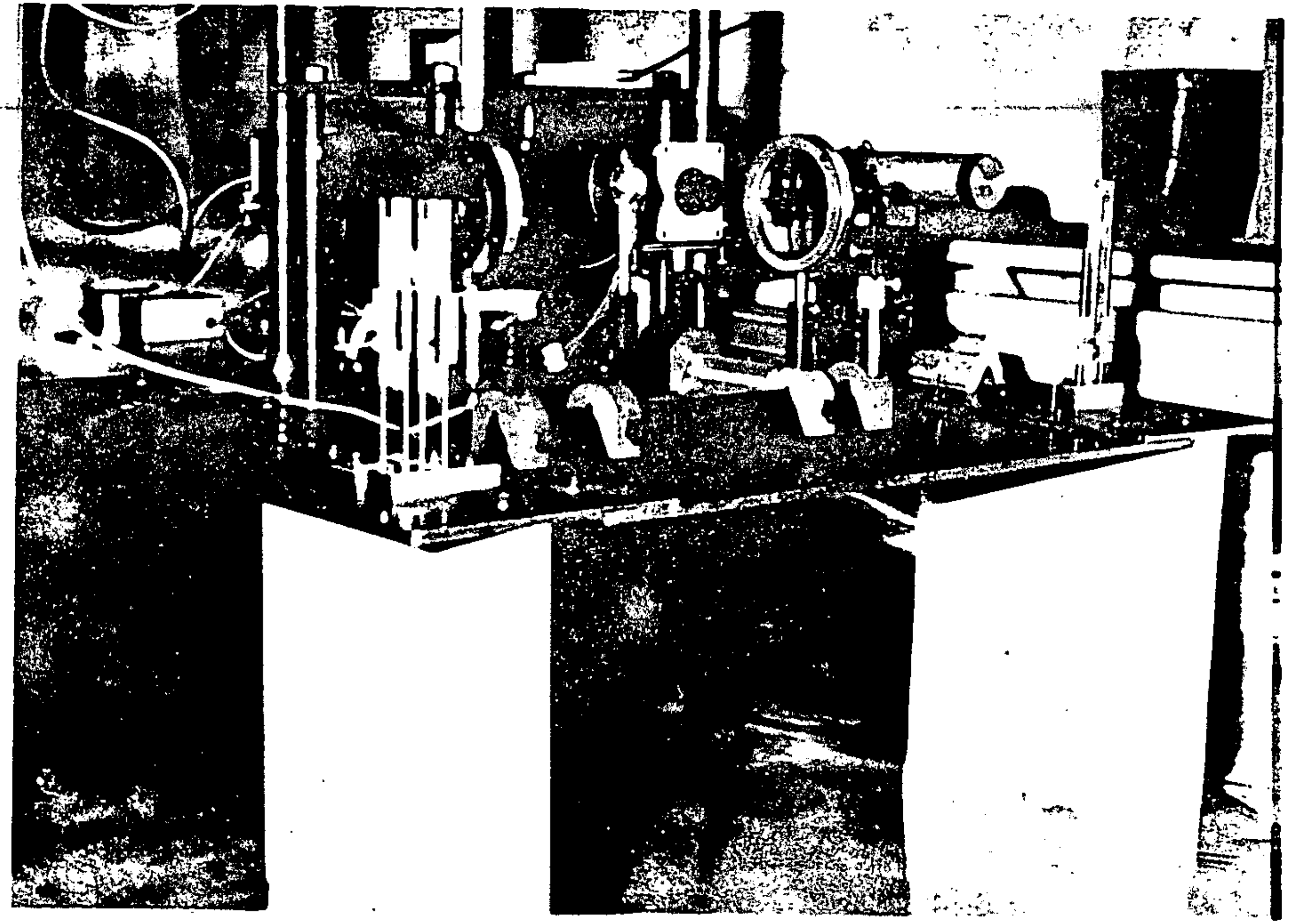


OPTICAL GEOMETRY AND SUBSEQUENT ELECTRONICS

FIG.4

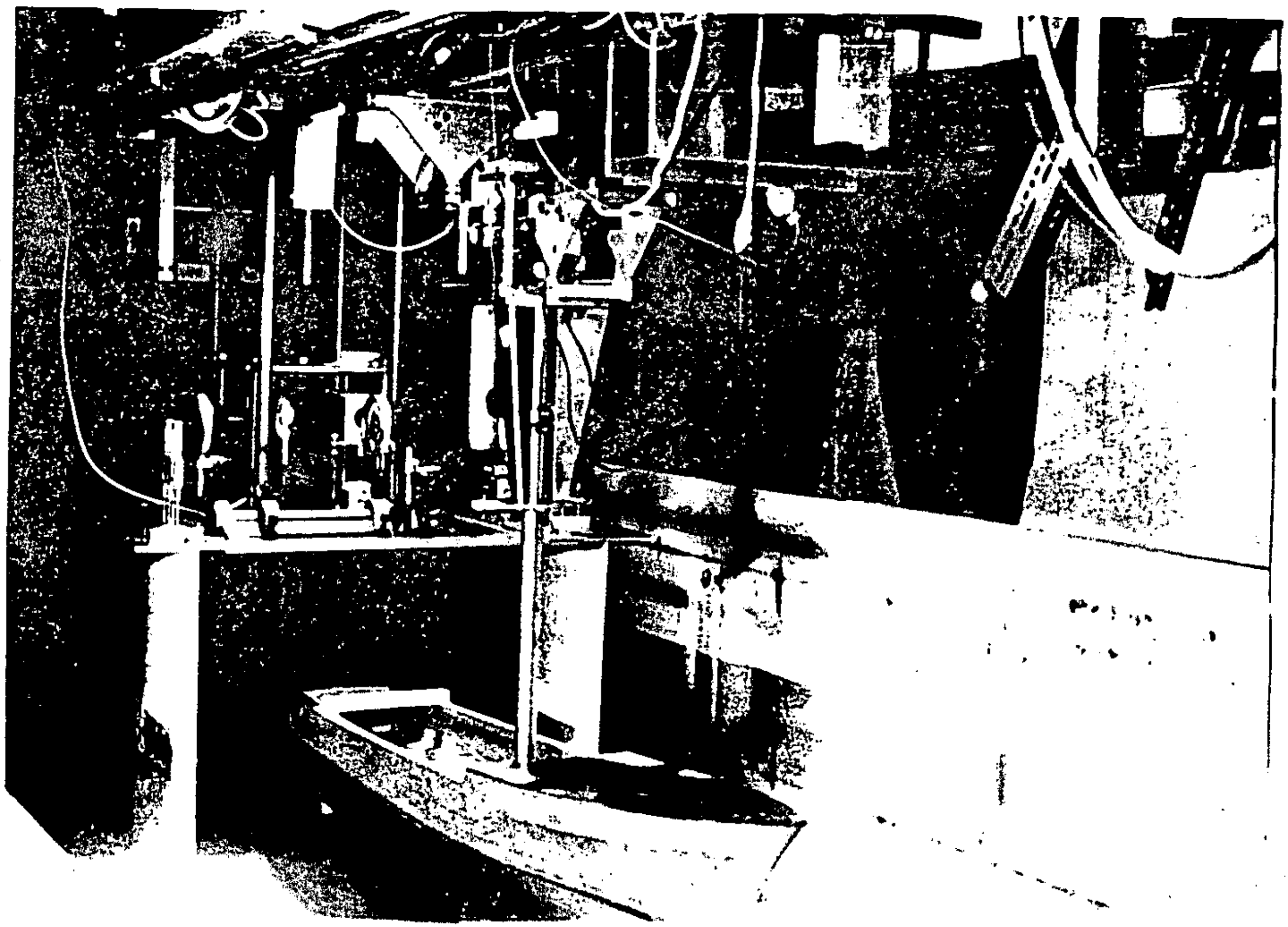


TOWING-TANK ANEMOMETER
FIG.5



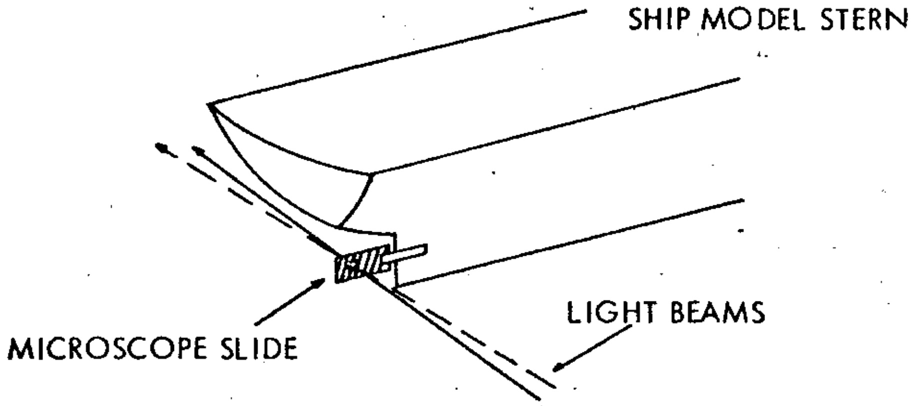
OPTICAL COMPONENTS OF THE L.D.V.

FIG. 6(a)

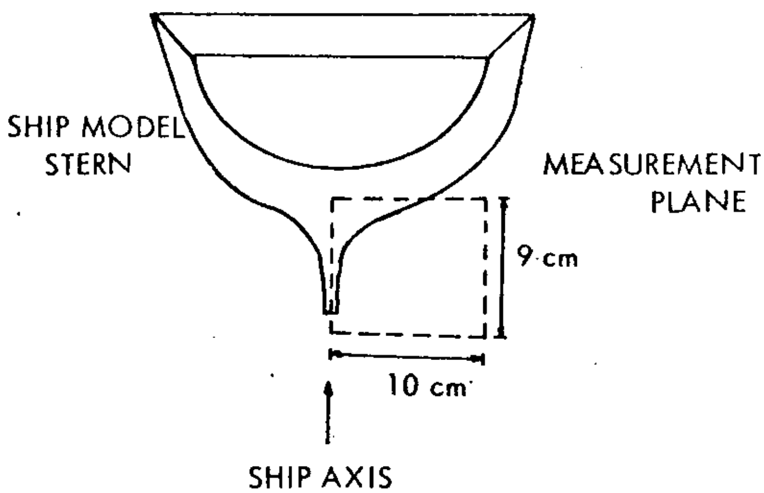


L.D.V. WITH THE SHIP MODEL IN POSITION

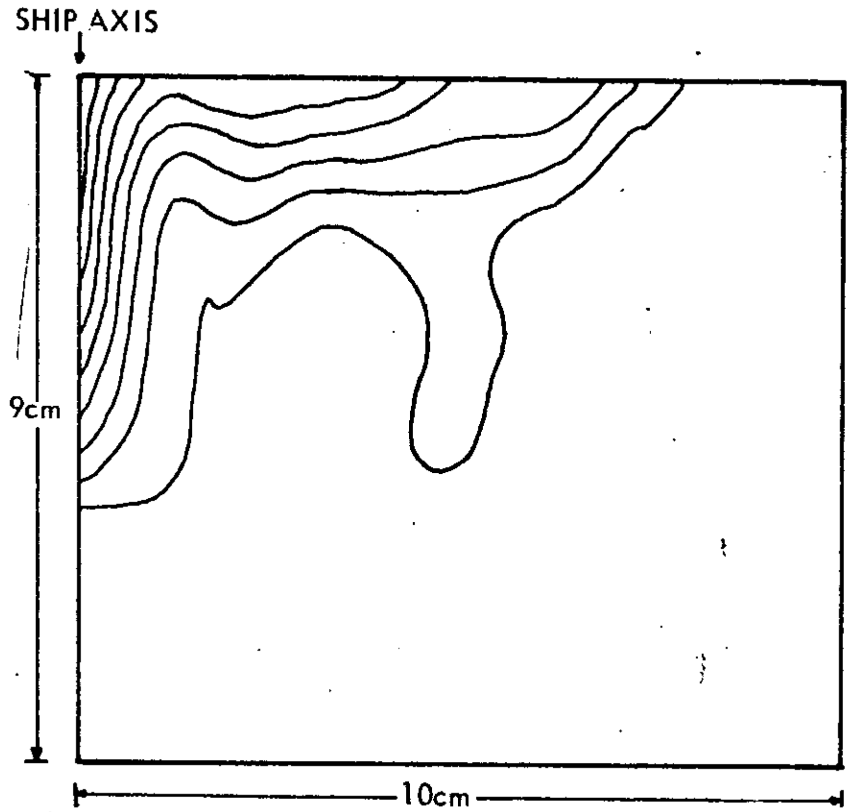
FIG. 6(b)



INITIAL LOCATION OF MEASUREMENT VOLUME
FIG.7



POSITION OF MEASUREMENT PLANE
FIG.8



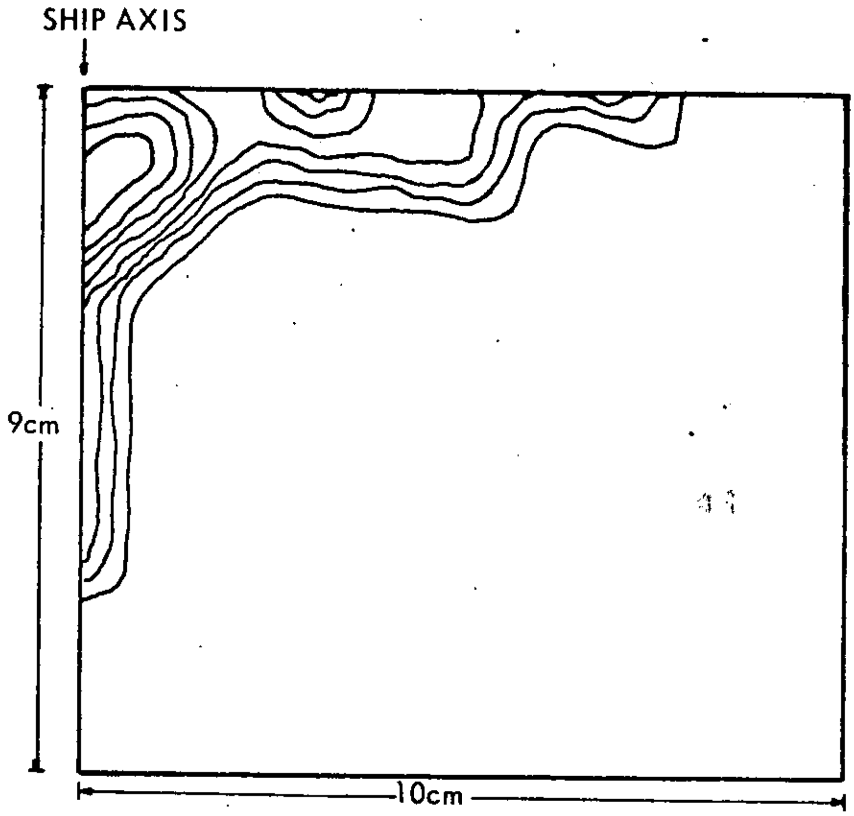
2 - D PLOT OF THE TAYLOR WAKE FRACTION
FOR THE SHIP CRINIERA D'ORO

MIN LEVEL = 0.05

MAX LEVEL = 0.4

CONTOUR INTERVALS = 0.05

FIG.9



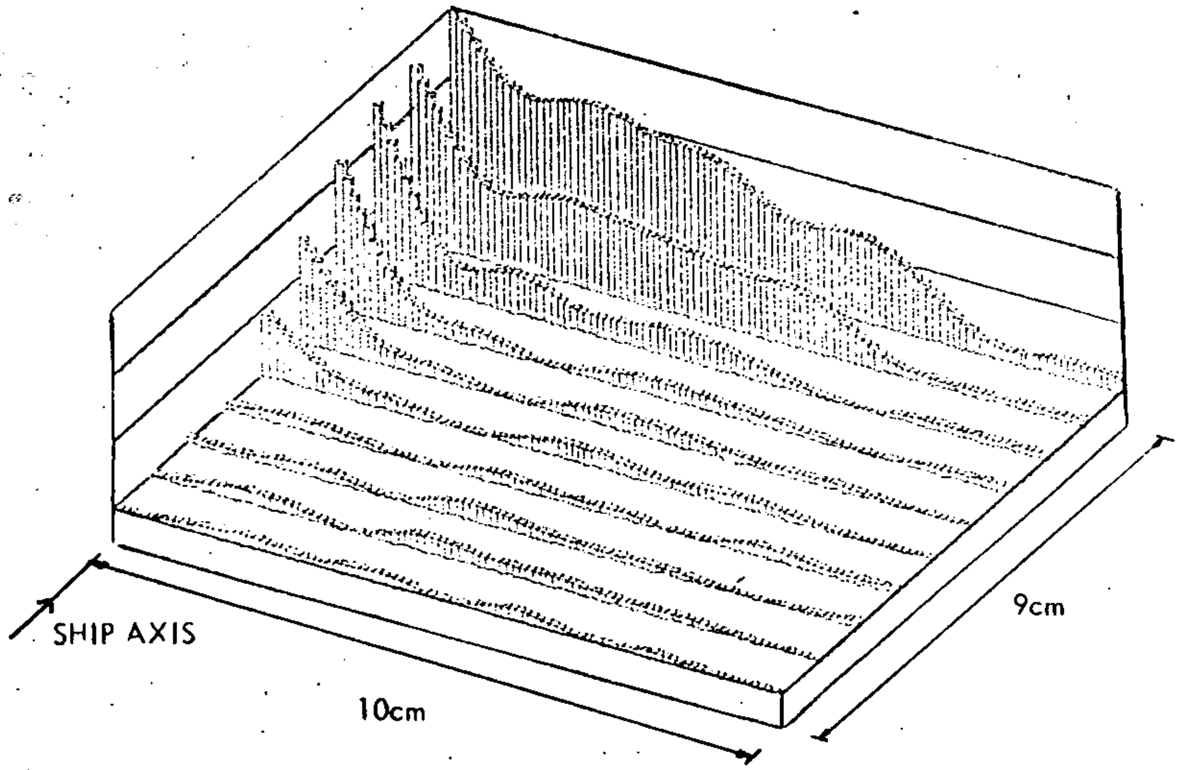
2-D PLOT OF THE RMS VELOCITY FLUCTUATIONS IN THE WAKE OF THE SHIP CRINIERA D'ORO

MIN LEVEL = 0.0225

MAX LEVEL = 0.04

CONTOUR INTERVALS = 0.0025 M/S

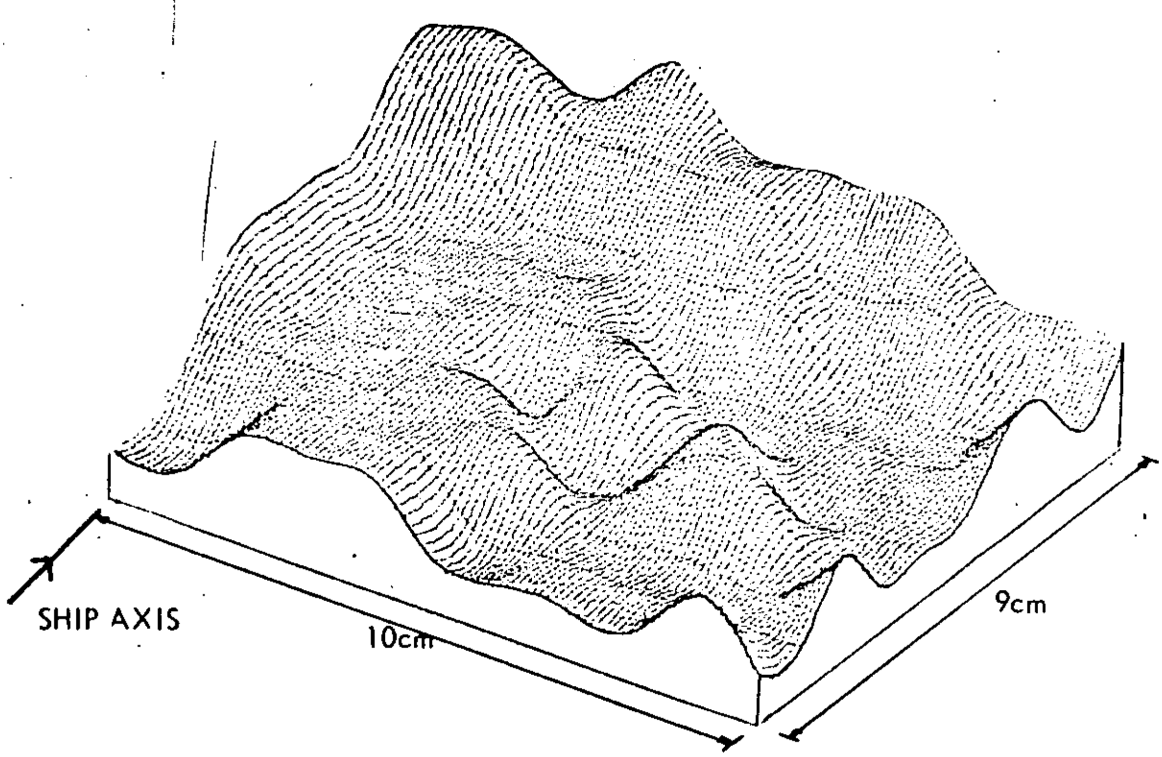
FIG. 10



HISTOGRAMS OF THE TAYLOR WAKE FRACTION

MAX VALUE=0.46

FIG. 11

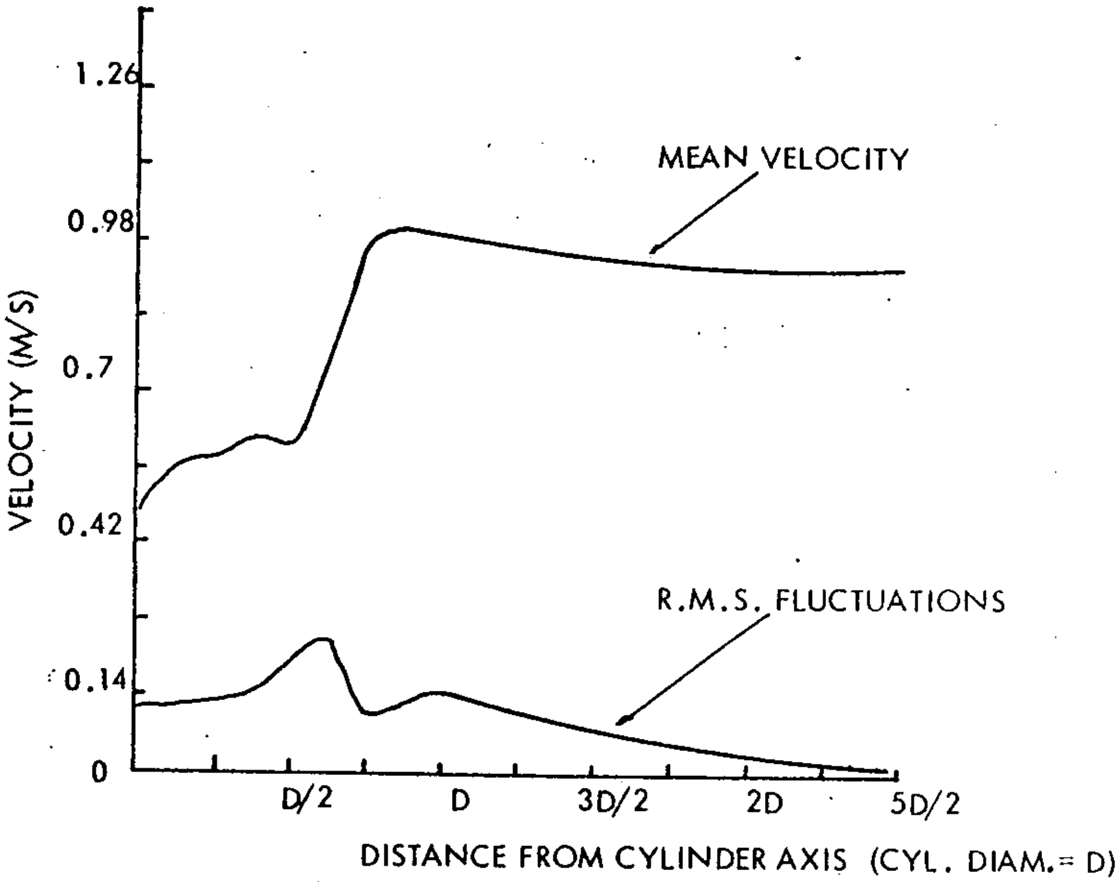


3-D PLOT OF THE RMS VELOCITY FLUCTUATIONS
IN THE SHIP WAKE

MAX VALUE= 0.04 M/S

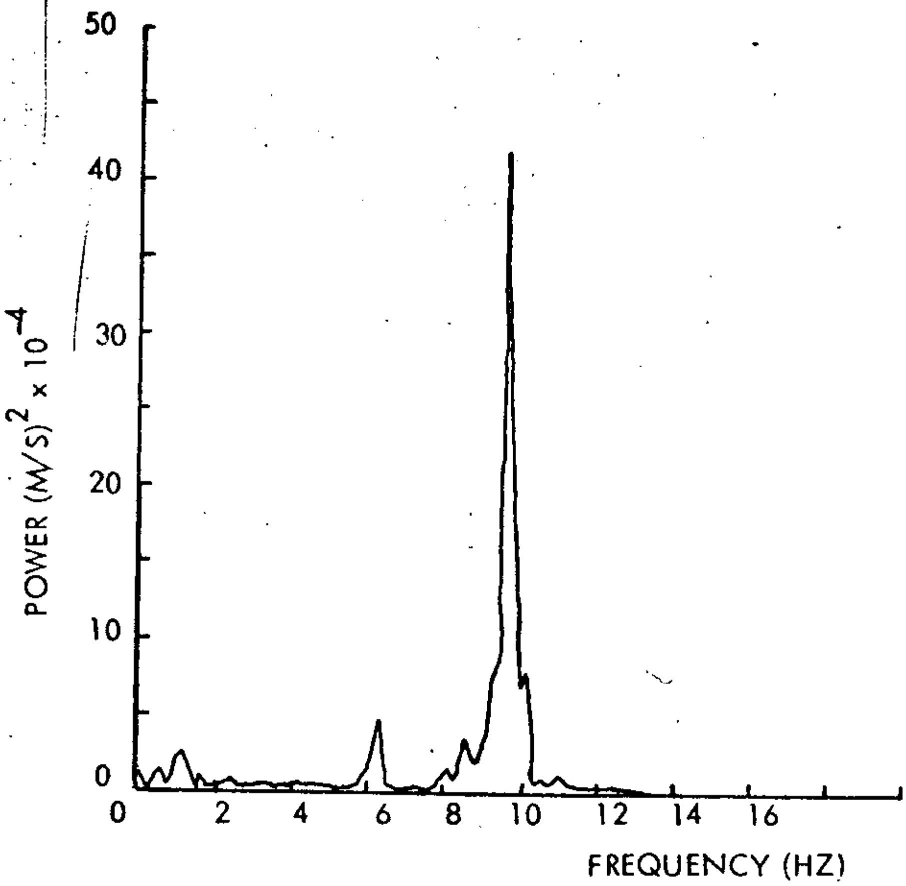
MIN VALUE= 0.01 M/S

FIG. 12



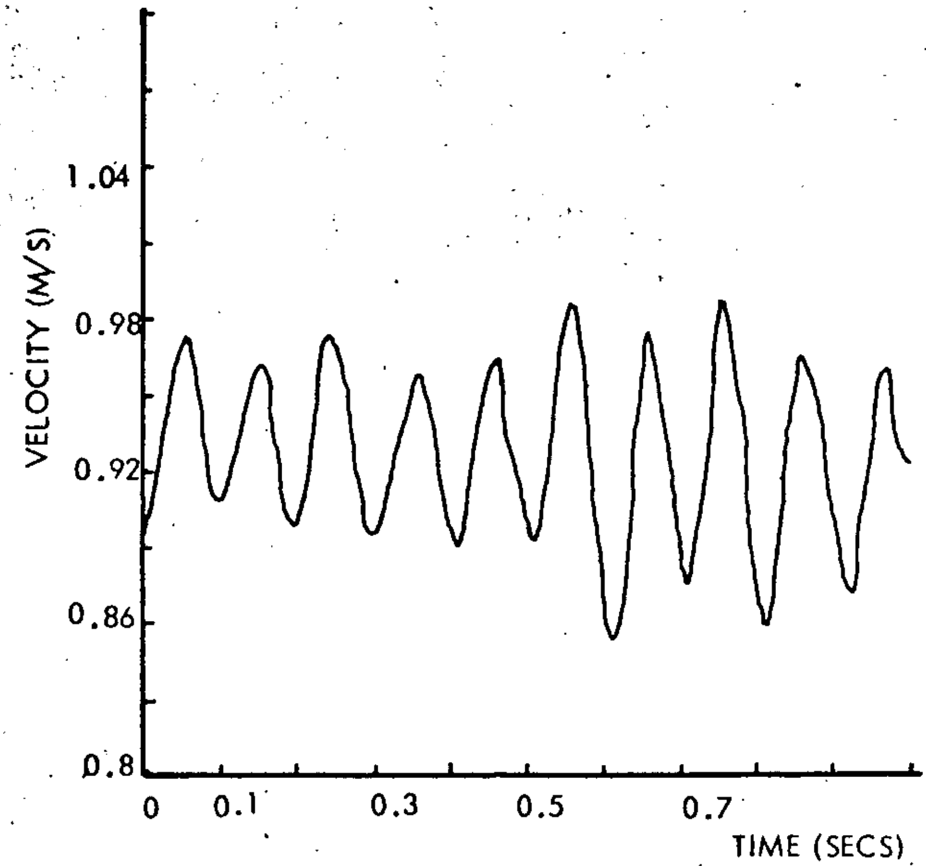
MEAN VELOCITIES AND R.M.S. FLUCTUATIONS
IN THE CYLINDER WAKE

FIG. 14



POWER SPECTRUM IN THE CYLINDER WAKE
NOTE ENERGY CONCENTRATION AT 10 HZ

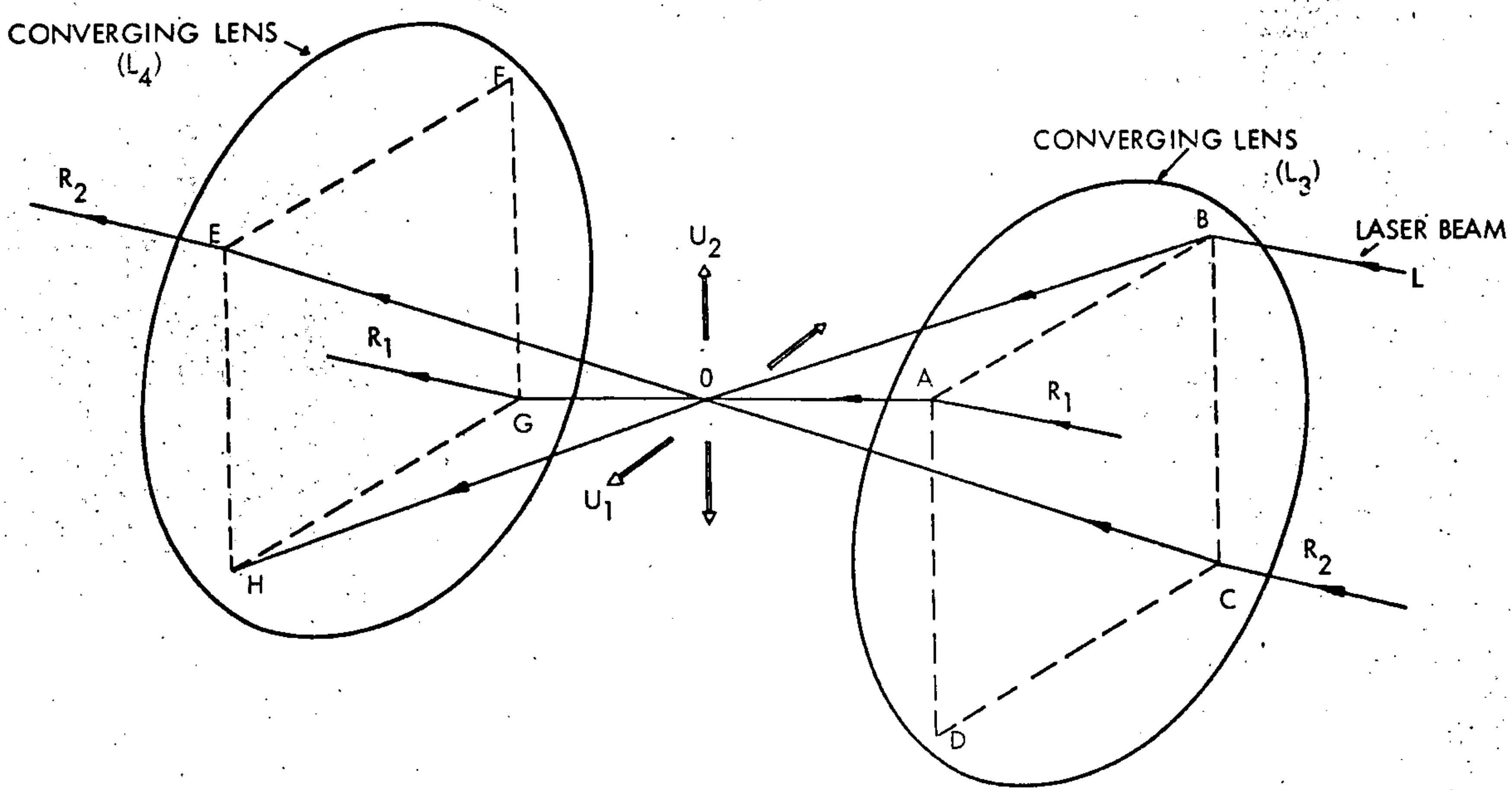
FIG. 15



TIME HISTORY OF A VELOCITY IN THE CYLINDER WAKE

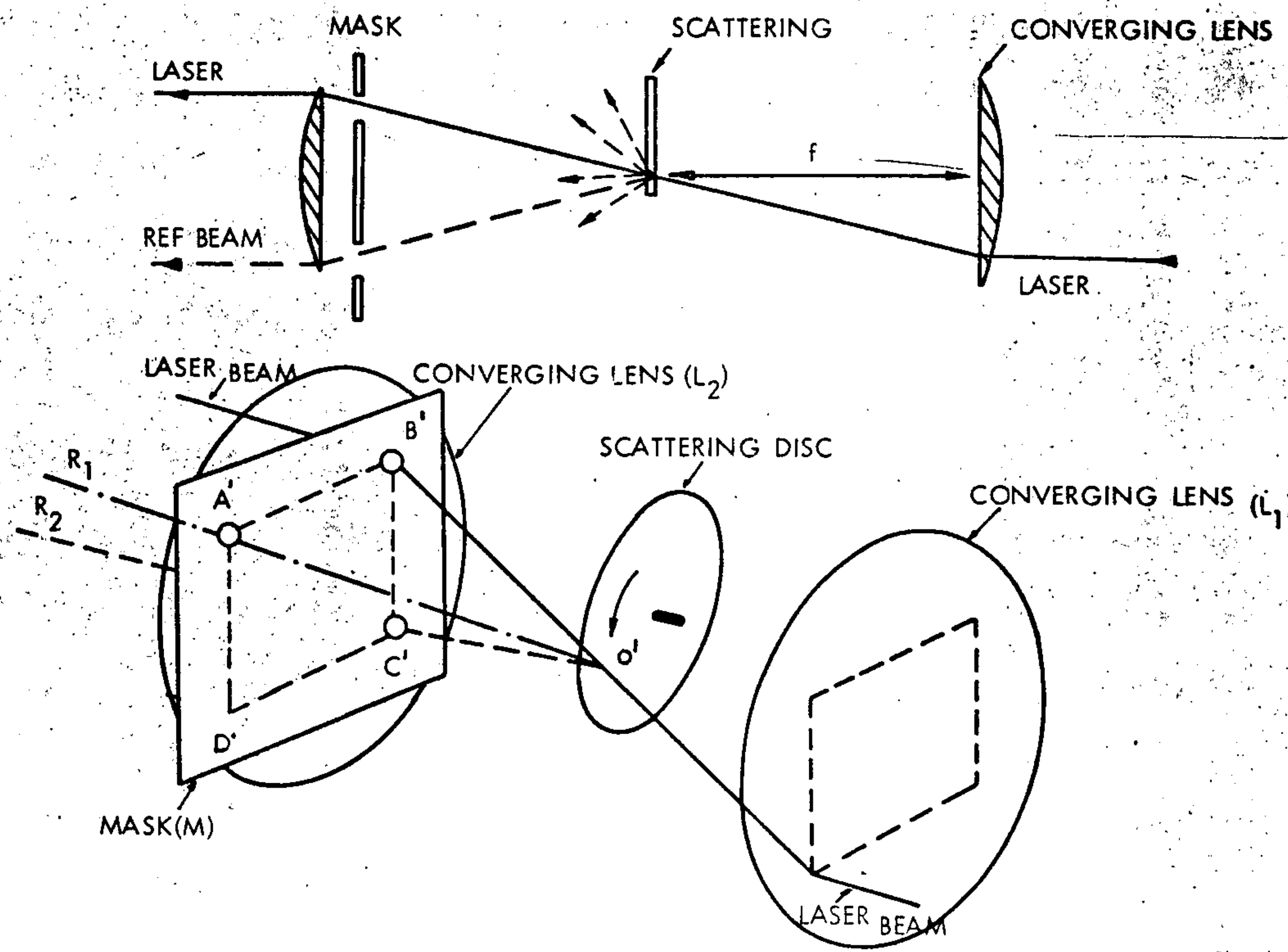
NOTE VORTEX SHEDDING AT 10 (HZ)

FIG. 16



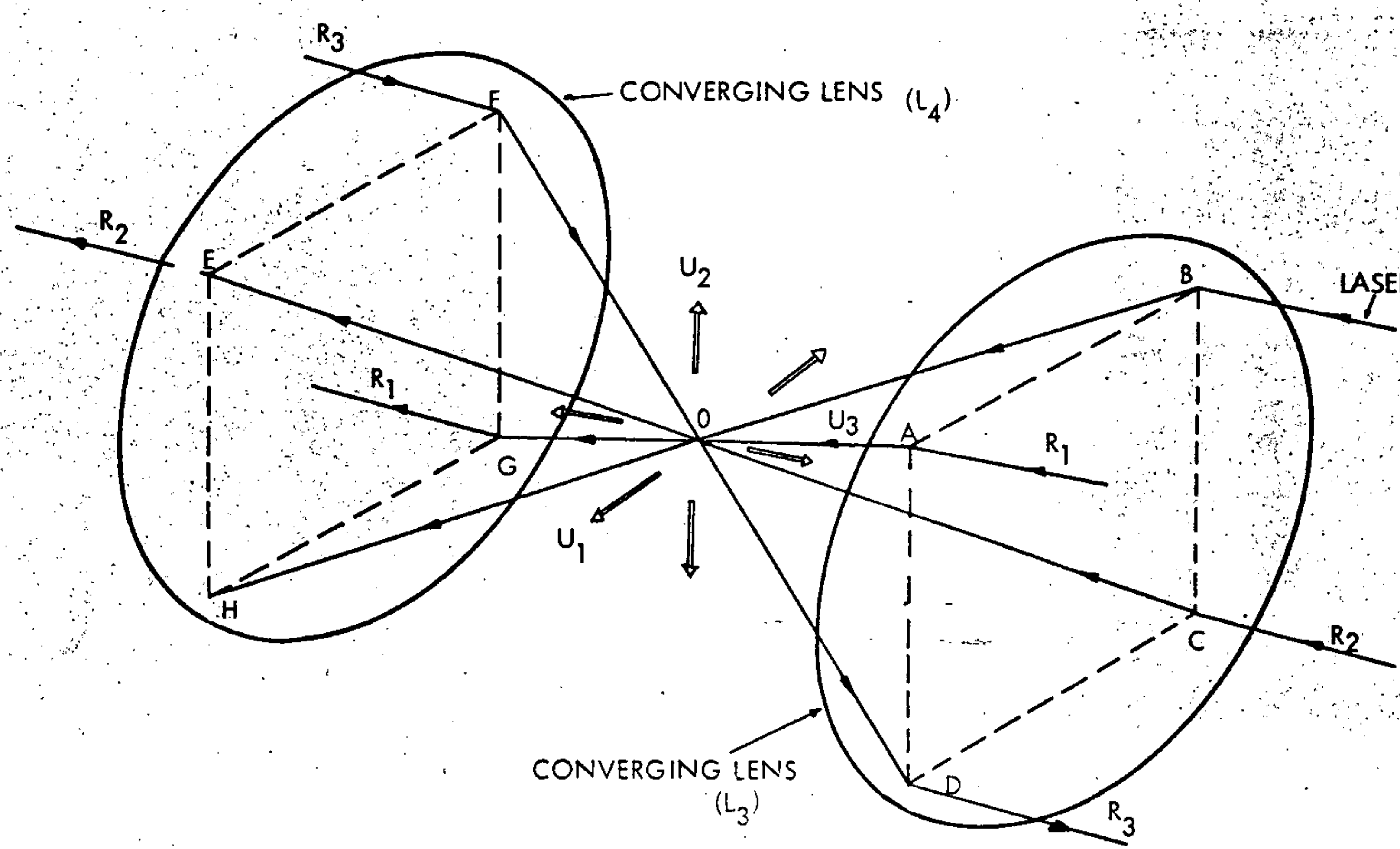
TWO-COMPONENT MEASUREMENT MODULE

FIG. 17



TWO-COMPONENT FREQUENCY SHIFTING MODULE

FIG. 18



3 COMPONENT MEASUREMENT MODULE.

FIG. 19