CHAPTER 20

A SYSTEM FOR MEASURING ORBITAL VELOCITIES IN WAVES

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Abstract

A single-ended, cylindrical hot-film sensor and a direction-vane transducer are studied as instruments for measuring flow fields in laboratory waves Errors in the hot-film measurements are discussed in terms of sensor voltage and water temperature drifts, and directional sensitivity The response of the direction-vane transducer is discussed in terms of the parameter b/r, which is the ratio of the vane chord length to the radius of curvature of the measured orbital flow

The instruments are tested in a laboratory wave system, using stationary and traversing measuring techniques The velocity measurements so obtained are compared to those obtained by a photographic technique, to determine instrument error The flow speed comparisons indicate that the maximum hot-film error in flow speed measurements is between ± 5 and ±1 0 inches/sec for the range 1 to 11 inches/sec tested The flow direction comparisons indicate that the direction vane response is subject to errors larger than 5° for b/r>0 1

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Introduction

This is a study of the utility of a hot-film sensor and a direction-vane transducer in the laboratory measurement of velocity fields in water waves It was motivated by a need for orbital data which is easier to obtain than by photographic techniques The photographic techniques, in which neutrally buoyant particles are suspended in the wave flow and photographed, have the advantage that they produce relatively accurate data, but the disadvantage that the reduction of such data to flow speed and direction is so time consuming and tedious that the quantity of such data reduced to date is rather limited

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As an alternative to this method of measurement, a study was made of the use of the hot-film and direction-vane, which have electrical outputs that can be digitized and subsequently processed by computer to reduce the task of data reduction

For flow speed measurements the 6 mil diameter, single ended, cylindrical hot-film sensor shown in Fig (1) was studied The sensor consists of an electrically heated metal film which conducts heat to the surrounding flow in proportion to the flow speed When positioned so that its cylindrical axis is perpendicular to the plane of flow in a two dimensional wave flow field, the sensor can measure flow speed regardless of flow direction

For measurements of flow direction, the direction-vane transducer shown in Fig (1) was studied It consists of a neutrally buoyant vane 1 25" long, 0 3" wide and 004" thick, attached to a rotateable shaft Fluid drag tends to align the vane with the direction of flow By monitoring the angular orientation of the shaft with a sensing device in the transducer housing, it is possible to obtain measurements of flow direction in a two dimensional wave flow field

The two instruments are mounted back to back on a strut and submerged to any location where simultaneous measurements of flow speed and direction are desired

The Hot-Film Sensor

Experience with the hot-film sensor in this study showed that

1) The water in which measurements are made must be filtered to prevent output signal drift due to accumulation of dirt particles around the sensor

2) The water must be deaerated to below about 16 ppm at 70°F dissolved gas content to prevent formation of gas bubbles on the sensor surface and the accompanying signal drift

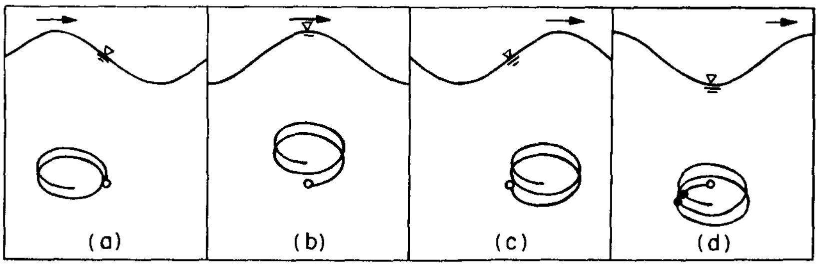
3) The overheat ratio, which is a measure of the degree to which the sensor is heated above the water temperature, must be less than about 1 15 to further prevent formation of gas bubbles on the sensor surface

4) The presence of the sensor in the orbital flow field of wave motion can result in velocity and thermal disturbances in the flow which tend to remain in the vicinity of the sensor and interfere with measurement These disturbances are illustrated schematically in Fig (2) where the wake emanating from the sensor is shown at four different times during the passage of a wave past a stationary sensor Since the motion is orbital, the wake is orbital And since the water in the wake is warmer than the surrounding water the wake tends to rise and have a spiral shape Whenever a wave trough is passing the sensor, the sensor is crossed by previously formed loops of its own wake Since the sensor is sensitive not only to flow speed but to water temperature, wake crossings therefore result in the aberrations of output signal schematized in Fig (2e) and (2f).

FIGURE (1) Hot-film Sensor and Direction-Vane Transducer mounted on Strut.

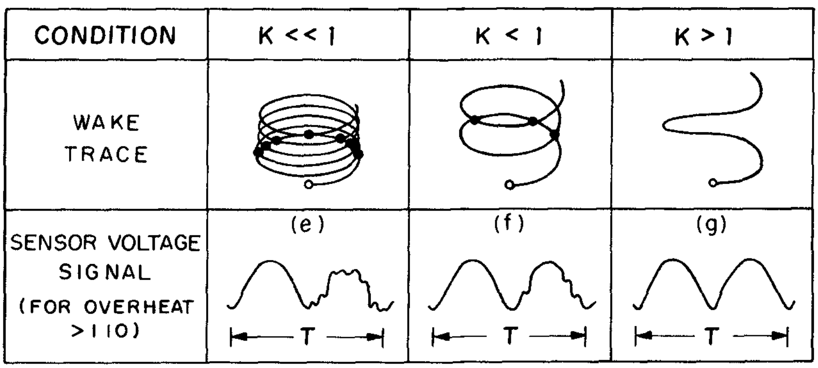
HEATED - WAKE EFFECTS

WAKE-TRACE CONFIGURATION UNDER PASSING WAVE



∘ STATIONARY SENSOR
• WAKE CROSSINGS

CONDITIONS FOR WAKE CROSSINGS



$$K = \frac{W_s}{(2A/T)}$$

W_s = VERTICAL VELOCITY OF BOUYANT WAKE

2A = MINOR AXIS OF PARTICLE ORBITS

T = WAVE PERIOD

FIGURE (2)

Through experiments it was found that signal disturbances due to heat wake crossings are reduced to tolerably low levels when the overheat ratio is kept between 1.02 and 1.12. At the lower figure, however, the hot-film becomes relatively more sensitive to long term variations in water temperature than to velocity so that it is desirable to operate at around 1.10.

We may obtain estimates of the sensitivities of the hot-film by use of Kings Law type empirical heat transfer equations. For example, at 1.10 overheat ratio a 1% drift in the sensor's output voltage corresponds to a 5% velocity error. Also, a 1°F change in water at 1.10 overheat ratio results in a 3% velocity error unless corrections for temperature are made.

5) The hot-film sensors tested in this study have an undesirable sensitivity to flow direction, in spite of efforts by the manufacturer to avoid it. A typical calibration for directional sensitivity is illustrated in Fig. (3) which shows the result that the normalized sensor output voltage varies with flow direction when the direction of a constant speed flow is varied but kept perpendicular to the sensor axis at all times. The points are representative of a range of constant flow speeds and overheat ratios and tend to fall on the same curve which is very nearly sinusoidal. Even though the maximum variation is only about ±3% in voltage, this however translates to a ±15% velocity error unless corrected for. Such corrections were possible in the present study since the calibration points collapsed to a single sinusoidal curve, but even so, flow direction had to be known before the corrections could be made. Hopefully such sensitivity can be reduced as the art of sensor fabrication improves.

The Direction-Vane Transducer

Experience with the direction vane in shallow water waves has shown that 1) The vane can properly respond to changes in flow direction, but only near the free surface where the orbits are more nearly circular than near the bottom boundary of the flow where they are highly eccentric ellipses. Near the bottom the vane tends to lag the flow direction. The problem of predicting the vane's response error due to considerations of inertia and friction of the moving parts is complicated by the difficulty of obtaining a solution of the vane's dynamic equation of motion, which is highly non-linear. Furthermore, the forcing function in the equation, fluid drag on the vane, is not known for the general unsteady case, including the effects of virtual mass and separation. Although some approximations might be made about the drag force and numerical methods might be employed to solve the equations, no solutions were obtained in this study. Rather, it was decided to carry out some quantitative experiments first to establish criteria for the vane's response.

2) Apart from the dynamics, the fact that the vane is rigid whereas the flow is curvilinear means that the vane will generally lag the flow by an amount which is a function of b/r, where b is the chord length of the vane and r is the radius of curvature of the flow past the vane. This is illustrated in Fig. (4) where, schematically, we have, initially, several particles on either side of the vane identified by

DIRECTIONAL SENSITIVITY OF HOT-FILM SENSOR

V' = DIRECTIONAL SENSITIVITY FACTOR = V_θ / V_A
V_θ = SENSOR VOLTAGE FOR FLOW DIRECTION θ
V_A = AVERAGE VOLTAGE OVER 360° RANGE

• EXPERIMENTAL POINTS FOR ALL COMBINATIONS OF
OVERHEAT = 1 10, 1 07, 1 05
VELOCITY = 3 5, 7 74, 12 12, 16 26 IN/SEC

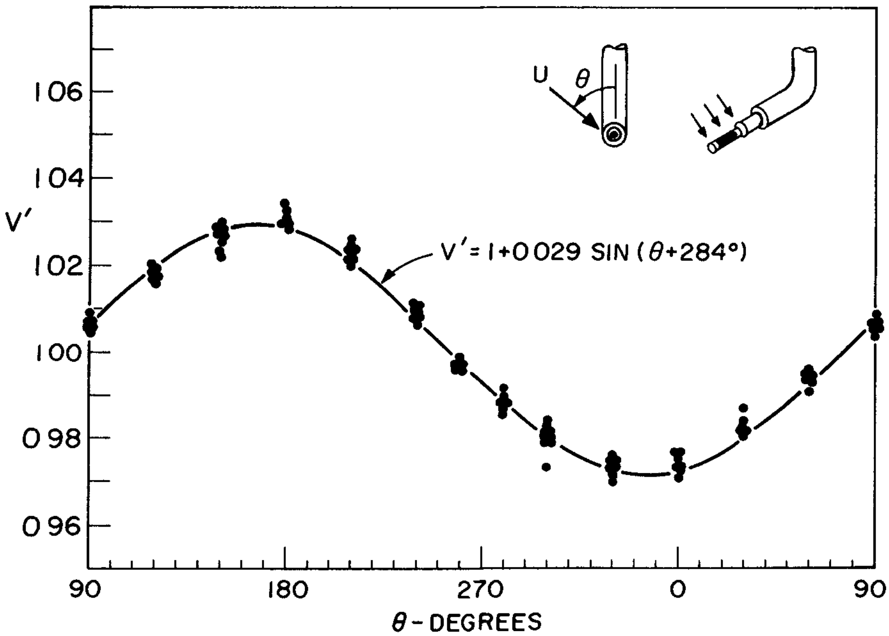


FIGURE (3)

KINEMATIC INCOMPATIBILITY

$r<b$

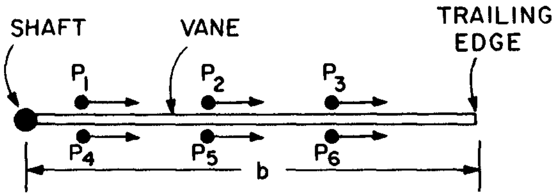


FIGURE (4a)

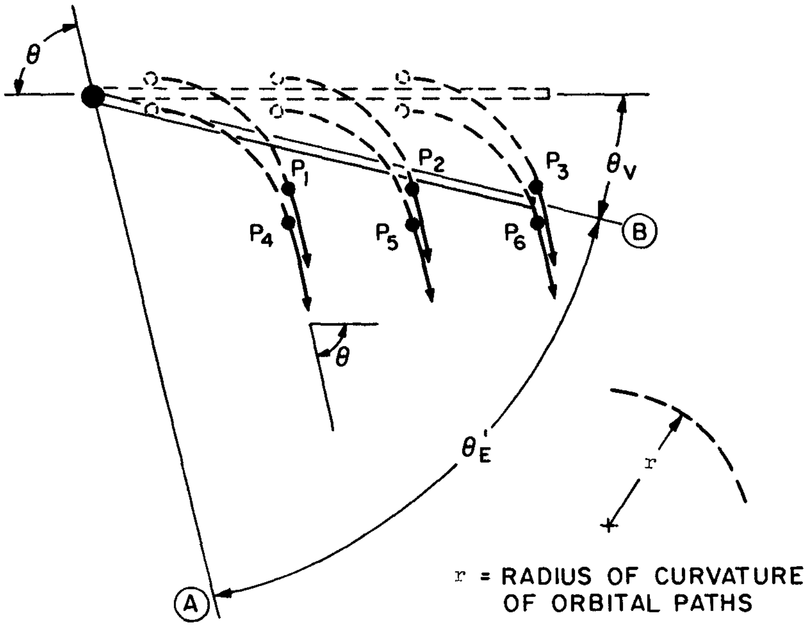


FIGURE (4b)

small circles, Fig (4a) For the sale of illustration, let the vane at this time be aligned with the direction of the flow It is seen that if the particles undergo portions of their undisturbed orbital motion, they move to the new locations shown in Fig (4b), but the rigid vane cannot possibly respond by pivoting about a fixed shaft and yet remain between the particles without deforming In fact, the vane will more likely point in the Θ_V direction rather than in the actual direction Θ of the flow This illustration is for the case of $b/r>1$, but it can be extended for the case $b/r<1$, and we realize that this purely kinematic consideration shows that the vane will in general lag the flow An approximate calculation of the resulting directional error, Θ_E, yields

$$\Theta_E = \sin^{-1}[b/2r] \tag{1}$$

which gives $\Theta_E \leq 5°$ for $b/r \leq 0\ 1$

To obtain experimental verification of this and some other quantitative aspects of the hot-film's response, measurements of the same flow field were made by the instruments and by a photographic technique and the results were compared to estimate instrument error

Measuring Techniques

The instruments were utilized in a number of ways

1) The "stationary" technique - here the instruments are submerged to a given depth and kept stationary for several wave periods' duration This is the simplest measuring technique, however, the response of the vane is rather limited by the small orbital radius of curvature near the wave tank bottom

2) The "transversing" techniques - these are represented in Fig (5) for the case of towing the instruments vertically upwards during measurement Refering to Fig (5a), as the instruments are towed upwards at uniform speed we obtain data along a straight line depth-time characteristic A-B If the flow is periodic, repeating itself exactly, every wave period, then portion C-B may be shifted by one wave period to D-E, so that the data can be viewed within the time domain of a single periodic wave Thus, by making several traverses, all at different beginning phase times, it is possible to fill the y-t plane with data Later, by subtracting the towing velocity rector from the relative flow vector measured, we obtain a mapping of the flow field along a vertical section through the flow The advantage of such a technique is that the radius of curvature and the flow speed of the relative flow past the vane are both larger than for the stationary technique and the vane response improves However, such improvements in response occur only during times when the vertical component of the flow is opposite to the direction of towing Thus to obtain data of superior relative accuracy a set of upward traverses is needed for $T/4 \leq t \leq 3T/4$ and a set of downward traverses for $0 \leq t \leq T/4$ and $3T/4 \leq t \leq T$, where T is the wave period and t is time

3) The "dual tow" technique - where it is possible to obtain measurements of flow direction using only the hot-film sensor and not the direction vane transducer The procedure is to first fill the

CHARACTERISTIC REPRESENTATIONS OF MEASURING TECHNIQUES

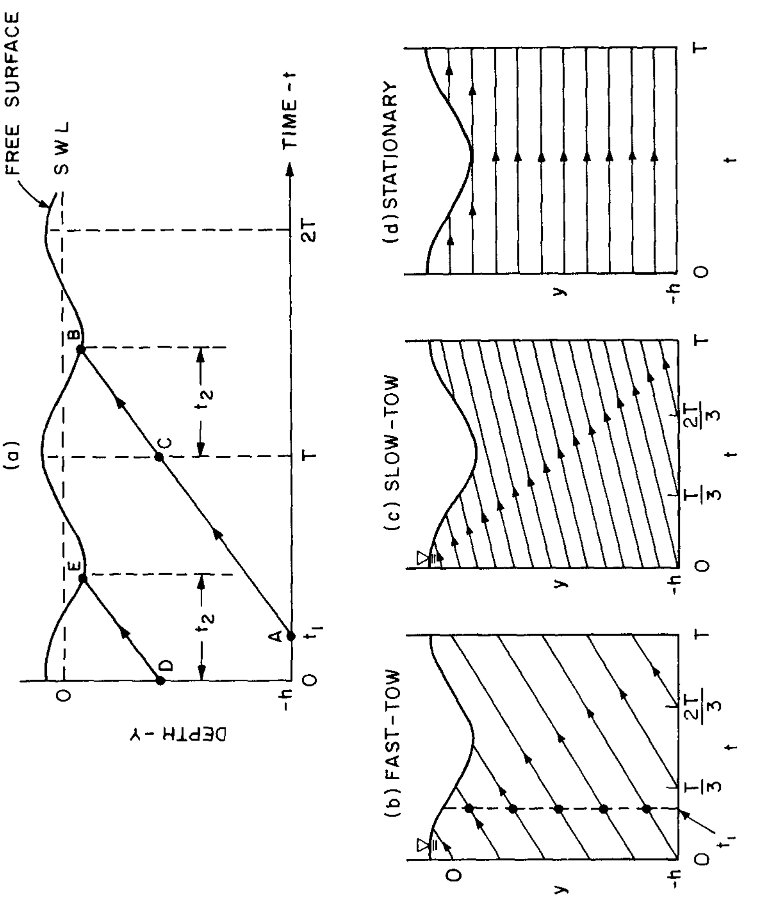


FIGURE (5)

depth-time plane with measured relative flow speed data, $R_1(y,t)$, having made traverses at towing speed S_1 Then the measurements are repeated but at a different towing speed, S_2, giving relative flow speed data, $R_2(y,t)$ The result is that at every point in the y-t plane, we now have the four knowns, R_1, S_1, R_2, S_2, from which it is possible to solve for the two unknowns, U, the local flow speed, and θ, the local flow direction With Fig (6) representing the vector diagram of the variables the Cosine Law for triangle ABC is,

$$R_1^2 = S_1^2 + U^2 - 2S_1 U \cos(\pi - \theta) \tag{2}$$

and for triangle ABD,

$$R_2^2 = S_2^2 + U^2 - 2S_2 U \cos(\pi - \theta) \tag{3}$$

Subtracting and rearranging, we obtain

$$U = \left[\frac{(S_2{}^2 - R_2{}^2)S_1 - (S_1{}^2 - R_1{}^2)S_2}{S_2 - S_1} \right]^{1/2} \tag{4}$$

from which U can be obtained since S_1, S_2, R_1 and R_2 are known Equation (3) may then be used to solve for

Since Equation (4) yields only the principal values of , additional information about whether the vertical component of U is up or down, is required to resolve the ambiguity In practice, the position of the free surface may be used as an indicator

Experimental Results

Typical experimental results for the stationary technique are shown in Fig (7), where the differences between hot-film measurements and photographic technique measurements are plotted against time for various depth locations, y/h, where y is the depth at measurement and h is the total depth The hot-film error for this typical case is seen to be generally less than 1 in/sec for the range of flow speeds, 1 to 11 in/sec tested These results are for plane progressive waves 4 3" high, 10 3 ft long and having a 1 474 sec period

Similar comparisons of flow direction data for the stationary technique are shown in Fig (8) It is seen that near the free surface, y/h = 0 138, the direction-vane error is generally less than 10° for this case, whereas near the bottom, serious errors occur

Fig (9) shows the decrease in direction errors achieved by utilizing the traversing technique

Fig (10) shows the directional errors for the case of the dual-tow technique Errors generally less than 10° were obtained even for locations well below the water surface

VECTOR DIAGRAM FOR THE DUAL-TOW TECHNIQUE

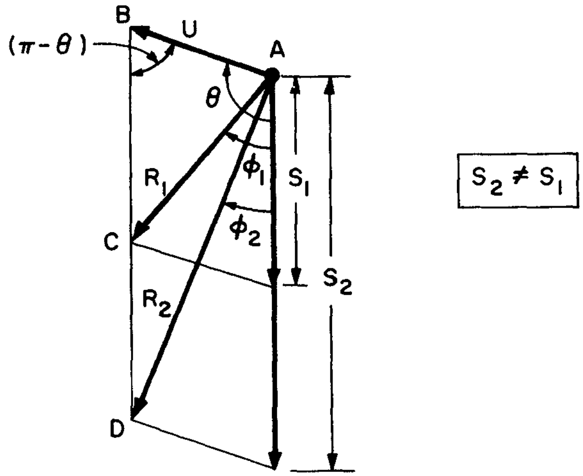


FIGURE (6)

VELOCITY ERROR
FOR
STATIONARY TECHNIQUE, STA - 15
$U_E = U_{HOT\text{-}FILM} - U_{PHOTOGRAPHIC}$

CURVE	①	②	③	④	⑤	⑥
-y / h	138	354	465	589	708	830

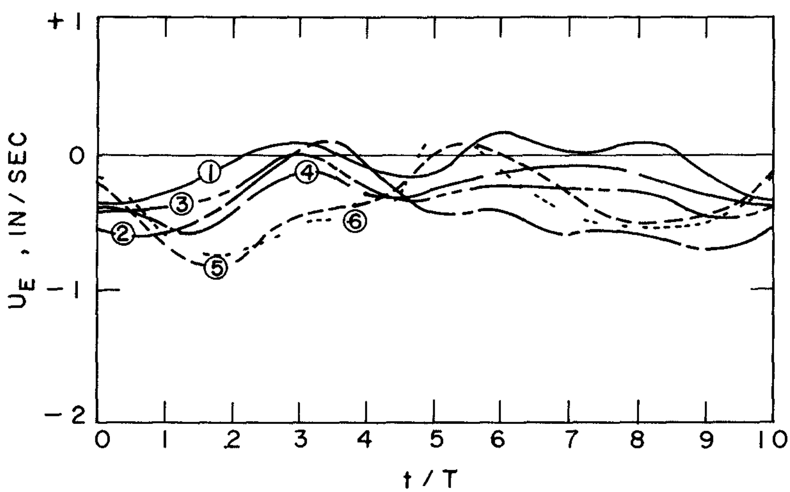


FIGURE (7)

DIRECTION - VANE ERROR
FOR
STATIONARY TECHNIQUE, STA +9

$$\theta_E = \theta_{\text{DIRECTION VANE}} - \theta_{\text{PHOTOGRAPHIC}}$$

CURVE	①	②	③	④	⑤
-y/h	217	395	545	704	882

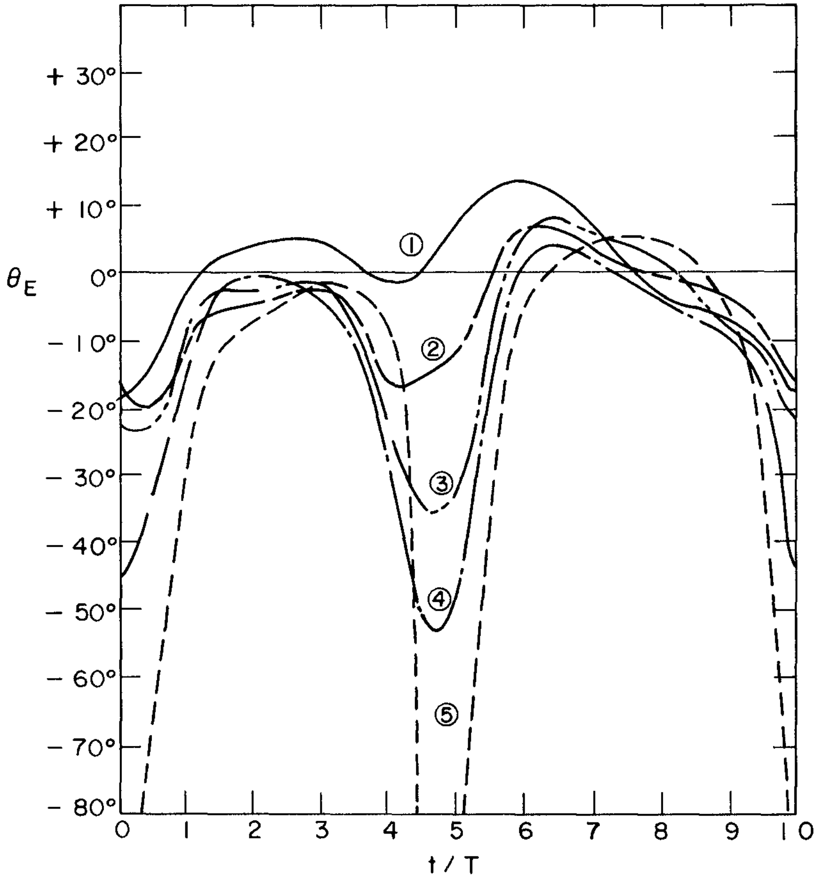


FIGURE (8)

DIRECTIONAL ERROR

FOR

FAST-TOWS UPWARDS, STA-15

TOWING SPEED = 10 2 IN/SEC

$\theta_E = \theta_{FAST\text{-}TOW} - \theta_{PHOTOGRAPHIC}$

CURVE	1	2	3	4	5
-y/h	138	354	465	589	708

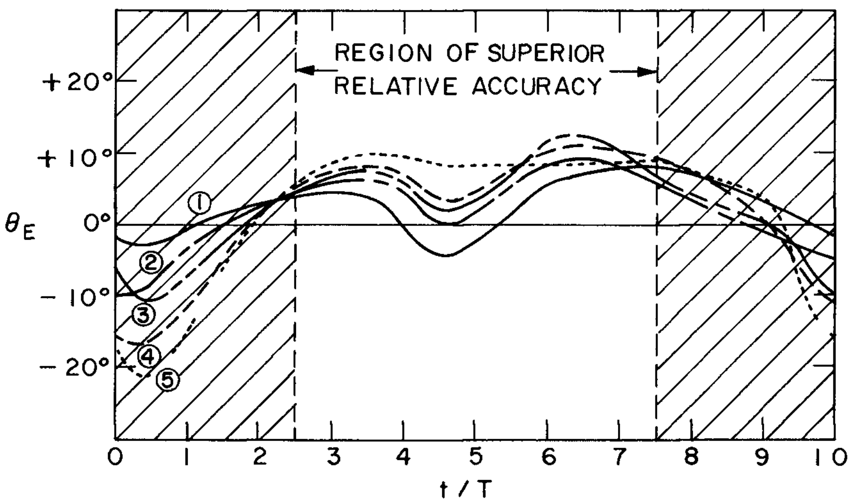


FIGURE (9)

DIRECTIONAL ERROR

FOR

DUAL-TOW, STA -15

TOWING SPEEDS = 0, 2 52 IN/SEC

$\theta_E = \theta_{DUAL\text{-}TOW} - \theta_{PHOTOGRAPHIC}$

CURVE	①	②	③	④	⑤
-y / h	138	354	465	589	708

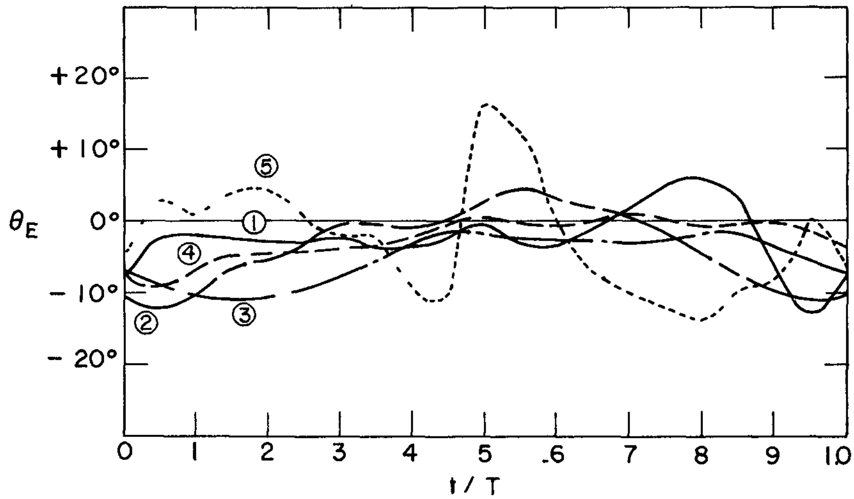


FIGURE (10)

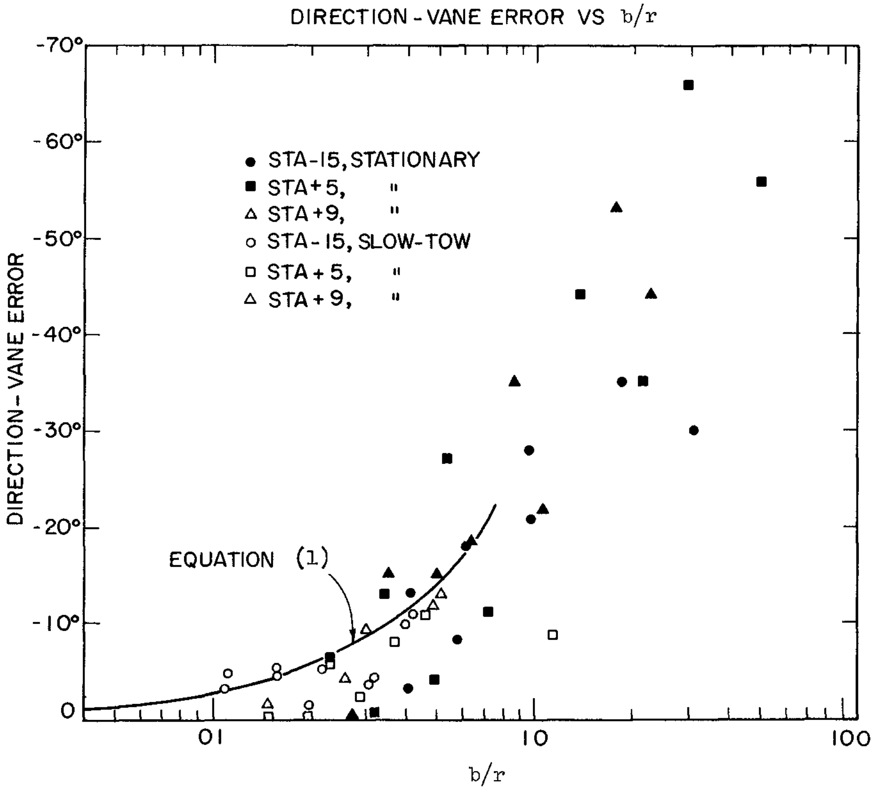

DIRECTION - VANE ERROR VS b/r
DIRECTION - VANE ERROR
-70°
-60°
-50°
-40°
-30°
-20°
-10°
0
STA-15, STATIONARY
STA+5, "
STA+9, "
STA-15, SLOW-TOW
STA+5, "
STA+9, "
EQUATION (1)
01
10
100
b/r

FIGURE (11)

Fig (11) shows experimental values for the vane plotted against the parameter b/r The approximate relation for error given by Equation (1) appears to define the upper envelope of the points corresponding to small b/r fairly well The data thus confirm that $\theta_E \leq 5°$ for $b/r \leq 0.1$

Conclusions

1) Since the problem of miniaturizing the physical dimensions of the vane sufficiently to make its chord length, b, an order of magnitude smaller than r, becomes prohibitive for the case of small laboratory waves, it appears that the direction-vane transducer is more suitable for larger scale wave flows, such as real ocean waves

2) The directional sensitivity of the hot-film sensor appears to limit its accuracy at present to ±15% of the velocity measured unless corrections are made Apart from this, the sensor can measure flow speed to within at least 10% of the velocity

3) The dual-tow technique allows measurement of flow direction without the need for a separate direction measuring instrument It is not scale dependent and thus makes possible measurements in small scale laboratory flow fields However, the flow field must be periodic for the technique to be valid