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THE MEASUREMENT OF THRUST FLUCTUATION AND FREE SPACE OSCILLATING PRESSURES FOR A PROPELLER

by

A. J. Tachmindji and M. C. Dickerson

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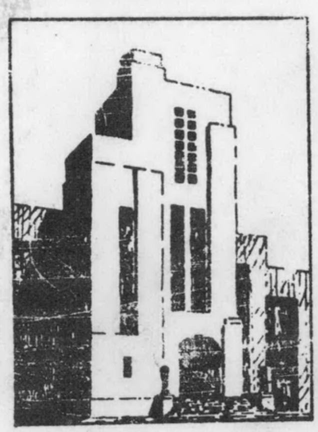

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Research and Development Report

JANUARY 1957 Report No. 1107

THE MEASUREMENT OF THRUST FLUCTUATION AND FREE SPACE OSCILLATING PRESSURE FOR A PROPELLER

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TABLE OF SYMBOLS

$b_{0.7}$	=	Section length at 0.7 radius
d	=	Propeller diameter
e	=	Propeller efficiency
J	=	$\frac{V}{nd}$ = Speed coefficient
K_T	=	$\frac{T}{\rho n^2 d^4}$ = Thrust coefficient
K_p	=	$\frac{p}{\rho n^2 d^2}$ = Pressure coefficient
K_Q	=	$\frac{Q}{\rho n^2 d^5}$ = Torque coefficient
n	=	Revolutions per unit time
p	=	Oscillating pressure at blade frequency for a point in space (single amplitude)
Q	=	Mean propeller torque
R_e	=	$b_{0.7} \frac{\sqrt{V^2 + (0.7\pi nd)^2}}{\nu}$
T	=	Mean Propeller Thrust
T_F	=	Thrust fluctuation at blade frequency (single amplitude)
V	=	Mean velocity
x,y,z	=	Coordinate axes
Z	=	Number of blades
α_β	=	Blade angle for maximum thrust or pressure (measured from z-axis in the direction of rotation)
β^*	=	Advance angle

β_i = Hydrodynamic pitch angle

β = Angle of wake producer (positive clockwise looking down)

γ = Angle of flow to the propeller (positive clockwise looking down)

ν = Kinematic viscosity

ρ = Density

ABSTRACT

The present report gives the instrumentation and technique of measurement of the thrust fluctuation produced by a propeller when operating in a variable inflow field. It also describes the method of measurement of the oscillating pressure at a point in space in the vicinity of the screw. Representative results are given for a propeller operating in a series of similar wake distributions of varying magnitudes.

INTRODUCTION

In view of increasing powers and speeds which are being placed in many new vessels the problem of propeller excited forces is increasing in importance. These forces can generally be considered to be transmitted to the hull surface through the water or directly through the shaft bearings and they are known as "surface" and "bearing" forces respectively. Each of these forces can be regarded as composed of six components; three couples and three forces.

This report will give the results of developing and using a dynamometer designed to measure one of the bearing forces, namely, the thrust fluctuation. For a propeller operating in a variable velocity field and subjected to the proximity of the hull surface, a periodic or fluctuating thrust will be superimposed upon the mean propeller thrust. This fluctuating thrust occurs primarily at blade frequency (revolutions per minute times the number of blades). Although the magnitude of this fluctuation may be a relatively small percentage of the mean thrust, its absolute value may be of considerable magnitude and may result in design difficulties at the thrust bearing and engine foundations.

In addition to the thrust fluctuation there is also a hydrodynamic couple transmitted to the shaft bearing which results from the eccentricity in the point of applications of the thrust. This effect is particularly noticeable for a propeller operating behind a single screw vessel. The measurement of this couple presents, however, large experimental difficulties and no attempts have yet been made to measure the couple directly. Furthermore, a fluctuating torque will also be superimposed upon the mean propeller torque, which will tend to excite torsional vibration in the shafting. Instrumentation ~~is~~ not as yet available for the measurement of the oscillating torque at DTMB.

Measurement of the surface forces has previously been made by the "double - model" technique[1]. An attempt has been made here to measure the local pressure fluctuations by means of a pressure gauge located in the

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References are listed on page 9

vicinity of the propeller. The measurements obtained are the equivalent to the free space oscillating pressures. Such pressure measurements can be conducted on a ship model and theoretically can be integrated over the surface in order to yield the total surface force. Although this procedure is rather laborious and time consuming, measurement at selected points would give indications of the effect of certain design features, such as tip and axial clearances and number of blades.

This report will describe only the instrumentation and give some results of oscillating pressure measurements for various operating conditions. The effects of clearances and number of blades will be described in a later report.

INSTRUMENTATION

The tests were conducted in the 12" Variable Pressure Water Tunnel at DTMB using a dynamometer specially designed for measuring the thrust fluctuation. The propeller used during the tests was an 8 inch, four bladed propeller (No. 2406) whose geometrical and performance characteristics are shown in Figures 1 and 2. The propeller was mounted directly on the shaft of the transient thrust dynamometer which, in turn, was connected to the tunnel drive shaft.

The wake variation was produced by a symmetrical airfoil strut located ahead of the propeller plane. The configuration of the propeller and strut are shown in Figure 3, which also indicates the axes of reference and angles of rotation. The characteristics of the strut and its location are indicated in Table 1.

Table I

Characteristics and Location of Wake Producer

Section		=	Symmetrical EPH
Chord		=	1.45 inches
Thickness ratio		=	0.163
Location	x/d	=	0.61 to maximum thickness
	y/d	=	0
z/d (lower tip)		=	0.26
Aspect Ratio		=	2.76

The thrust fluctuations produced by the wake variation were measured on the TMB Transient Thrust Dynamometer[2], Type 235-1A, shown in Figures 4 and 5 and having overall dimensions of 1.12 inches in diameter by 4.5 inches long. It is an electro-mechanical device operating on the principle of a differential transformer. The mechanical element consists of an annular section of shaft in which a series of slots are cut perpendicular to the centerline of the shaft, thus forming a compression flexure. The electrical component consists of a differential transformer which is held stationary. When thrust is applied, the flexure is put in compression, thus varying the air gap and producing a corresponding change in electrical output. This output is proportional to the applied thrust for either positive or negative loadings.

In order to obtain a response frequency as high as possible, the flexure is very stiff. The natural frequency of the unit was obtained by exciting it with an electromagnetic vibration generator. The response curve, which has been corrected for an attached mass of four pounds, is shown in Figure 6. It can be seen that the predominant natural frequency is about 245 cps. The magnification factor is small from 60 to 120 and a corrected static calibration can be used in that range. Figure 7 shows the linearity response of the instrument for various loads, as obtained from a static calibration.

The thrust dynamometer was supplied with a 5000 cps carrier signal by a TMB 5K strain indicator[3] which was also used for balancing out the mean propeller thrust. The resulting fluctuating signal was then fed into a vibration analyzer, Figure 8, in order to determine the amplitude of component of the signal at blade frequency and the phase relationship of this component with respect to a reference signal. The reference signal is produced by a sine wave generator mechanically geared to the propeller shaft and rotating at blade frequency. The vibration analyzer then reads the amplitude of vibration in phase with the reference signal and at the frequency of that signal. By supplying two reference signals in quadrature from the sine-wave generator the amplitude and phase relationship of the vibration signal can be determined.

The vibration analyzer consists of an amplification stage with an overall gain of approximately 25, a discriminating network for demodulation[4], an integrating circuit and an output circuit with an indicating meter.

Measurement of harmonic components at frequencies different than blade frequency was accomplished by using a General Radio Wave Analyzer Type 736-A.

Measurement of oscillating pressures were performed by using a Hathaway gauge Type PS-16. This gauge is a small (0.468" diameter and 0.320" long) pressure sensitive unit having a natural frequency of 500 cps and a full scale range of 0.5 psi. The pressure sensitive element is a beryllium copper diaphragm on the back of which is attached a small armature. When the diaphragm is deflected, the armature is moved along the axis of a differential transformer, thus changing the voltage induced in the secondary coils. The gauge was installed in the centerline plane of the tunnel upstream of the propeller and its coordinates with respect to the propeller center were

$$\frac{x}{d} = 0.145, \; \frac{y}{d} = 0, \; \frac{z}{d} = 0.598.$$

The pressure gauge was also supplied, Figure 8, with a 5000 cps carrier from a 5A strain indicator and the same circuit was used for determining the amplitude and phase relationship of the pressure signal as that used for the thrust measurements.

The wake produced by the strut was measured in the absence of the propeller with a cylindrical three-hole pitot tube installed in tunnel in such a way that it could traverse the plane of the propeller disc. The tube is 0.375" in diameter with orifices spaced 33° apart and located at 0.7 of the propeller radius.

RESULTS

Thrust Fluctuation

Measurements of the thrust fluctuation were obtained for various angles (β) of the wake producer and over a range of speed coefficients. The velocity inflow to the propeller is shown on Figure 9 for wake producer angles of 5°, 25° and 35° as obtained by a horizontal traverse at the 0.7 radius. Figure 10 shows for the same wake producer positions, the angle of flow (γ) measured from the centerline of the tunnel.

The tests were conducted with the propeller operating at constant revolutions (1080 rpm) for all wake producer angles of plus and minus 5°, 15°, 25° and 35° and over a range of speed coefficients from 0.3 to 0.8. Figure 11 shows the resulting thrust fluctuation (single amplitude) occurring at blade frequency, and Figure 12 gives the blade position (α_B) when the thrust is maximum. It is noted that for large wake concentrations the thrust fluctuation tends to increase with decreasing thrust, while the opposite occurs for small wake fractions. Figure 13 shows a plot of the ratio of the thrust fluctuation to the mean propeller thrust for the same conditions.

It should be noted that the results presented above are only valid for the reduced frequency for which they were obtained. The effect of changing the reduced frequency will be discussed later.

Measurements were also obtained for the magnitude of the harmonic components which are multiples of blade frequency. The amplitude of these components is expressed as a percentage of the amplitude at blade frequency and is shown in Figures 14 and 15 for various speed coefficients. It is noted that the magnitude of the components decreases considerably for the higher harmonics. It should be emphasized, however, that these results are applicable only to this wake distribution and this propeller. The higher harmonics are primarily functions of the number of blades and decreases rapidly with increasing number of blades.

Pressure Measurements

The time dependent pressure was measured at a point in space having the coordinates $\frac{x}{d} = +0.145$, $\frac{y}{d} = 0$, and $\frac{z}{d} = +0.598$. The pressure fluctuation at blade frequency is expressed in non-dimensional form as

$$K_p = \frac{p}{\rho n^2 d^2} \qquad (1)$$

where p = pressure oscillation (single amplitude) at blade frequency

Figure 16 shows the variation of K_p with wake distribution and speed coefficient, and Figure 17 gives the blade angle for maximum pressure for these conditions. Additional tests were also conducted for a wake producer angle of -15° and the pressures measured at $\frac{x}{d} = +0.114$, $\frac{y}{d} = 0$, $\frac{z}{d} = +0.598$ and $\frac{z}{d} = -0.598$. Measurements were also conducted at $\frac{x}{d} = +0.114$, $\frac{y}{d} = -0.598$ and $\frac{z}{d} = 0$. The relative magnitude of these measurements is shown in Figure 18, indicating that pressure fluctuation inside the wake region is higher than that measured at the same relative point outside the low velocity region.

Effect of Reduced Frequency

It is known[5] that for a two dimensional airfoil subjected to a periodic non-uniform motion, a significant parameter in the magnitude of the lift is the frequency of encounter or in non-dimensional form the reduced frequency. For the two dimensional case the reduced frequency is given by

$$f = \frac{\omega c}{2U} \qquad (2)$$

where ω = frequency of encounter

c = chord length

U = mean velocity of approach

For a propeller we can define a similar parameter for the section at 0.7 radius (assuming a lightly loaded propeller)

$$f_{0.7} = \frac{Z\, n \quad b_{0.7}}{2 \frac{V}{\sin \beta^*} \cos (\beta_i - \beta^*)} \qquad (3)$$

where $b_{0.7}$ = chord length at 0.7 radius

Z = number of blades

n = revolutions per unit time

β^* = advance angle at 0.7 radius

β_i = hydrodynamic pitch angle at 0.7 radius

When the induced velocities are neglected, Equation (3) becomes

$$f_{0.7} \simeq \frac{Z \quad b_{0.7}}{2d \left[J^2 + (0.7\pi)^2 \right]^{1/2}} \qquad (4)$$

Similarly a reduced frequency for the entire propeller can be based on the forward speed only, giving

$$f_V = \frac{Z}{2} \frac{n d}{V}$$

$$= \frac{Z}{2J} \qquad (5)$$

It is noticed from equations (4) and (5) that the reduced frequency is inversely proportional to the speed coefficient. Therefore, for a model operating at the same J as the full scale, the reduced frequency similarity is automatically satisfied.

DISCUSSION

The values which have been measured and presented above give an indication of the magnitude of the thrust fluctuation for a propeller operating in a velocity field similar to the one used in these experiments. These values are, however, only a part of the total fluctuation which is produced by the propeller in a similar velocity field behind a vessel. In general, the time dependent quantities can be regarded as composed of two effects. A variation in thrust will be experienced when a propeller is operating in an infinite fluid (sufficiently removed from external surfaces) and the velocity distribution to the propeller is non-uniform. A similar variation in thrust, however, will also occur for a propeller operating in completely uniform flow, but subjected to the interference effects of external surfaces. The second case can be easily imagined for ideal flow when the propeller is operating in the vicinity of a thin surface placed in the direction of the flow. The thrust fluctuation due to the interference effects will then be dependent on the clearances from the propeller to the surface. Both these effects are a function of reduced frequency.

In actual case the two effects are interdependent. Decreasing the clearances, will, in general increase the local wake fraction and result in an increase in thrust fluctuation from both causes. However, due to the large axial clearance between the wake producer and the propeller plane, the present tests give primarily the thrust fluctuation resulting from the non-uniformity in velocity inflow. This is also verified by the negligible fluctuation measured when the wake producer is in line with the flow ($\beta = 0$). However, for small axial clearances between the wake producer and the propeller a fluctuation will occur even for the case of $\beta = 0$.

CONCLUSIONS

The present report describes the instrumentation and the results of an investigation conducted for the measurement of the thrust fluctuation of a propeller. The fluctuation which was measured was that resulting from a non-uniformity in velocity inflow and was not due to the interference effects between the propeller and adjacent surfaces.

The instrumentation which was developed, showed that the thrust fluctuation can be measured with good accuracy (down to 0.05 lb. amplitude) when the blade frequency is in the range of 60 to 120 cps. The measurements also indicated that the higher harmonics of blade frequency are lower than the fundamental for the wake distribution which was tested.

The results given in this report are applicable only for the tested propeller operating in the measured wake fields and are not necessarily applicable to other wake distributions.

Time dependent pressure measurements were also obtained in the vicinity of the propeller at one point in space. Additional results of pressure fluctuations will be reported in a later report.

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1. Lewis, F. M. and Tachmindji, A. J., "Propeller Forces Exciting Hull Vibrations", Transactions SNAME, 1954

2. Norman, G. J., Wilson, M. W. and Bryant, F. B., "Propeller Dynamometer Instrumentation at the DTMB", DTMB Report 1068, July 1956

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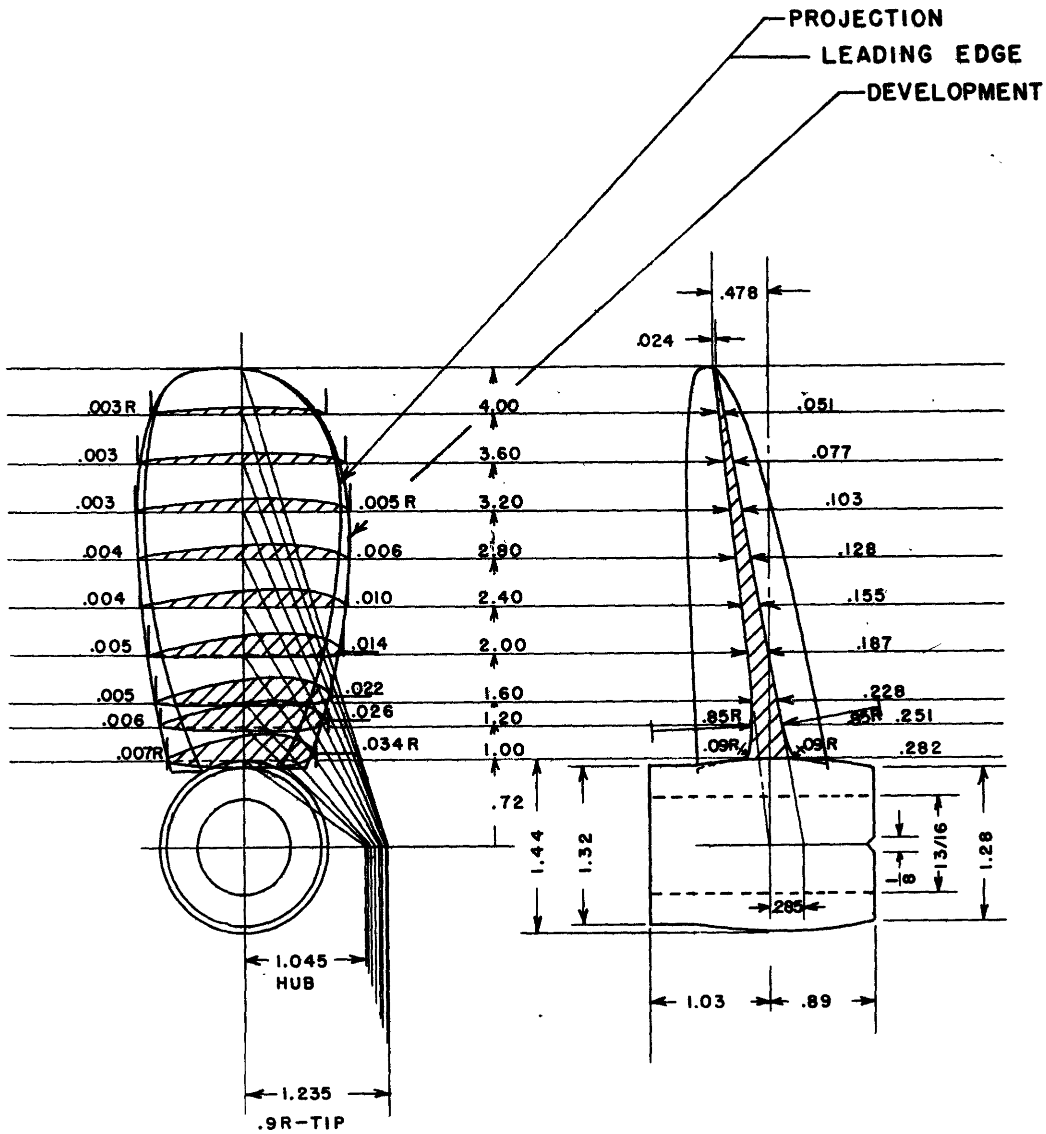
4. Cook, G. W., "A Resonant Bridge Carrier System for Measuring Minute Changes in Capacitance", DTMB Report 626, February 1951

5. Karman, T. H. and Sears, W. R., "Airfoil Theory for Non-uniform Motion", Journal Aeronautical Sciences, Vol. 5, No. 10, p 379-390, 1938



NUMBER OF BLADES	4	HUB DIAMETER RATIO	0.180
EXPANDED AREA RATIO	0.420	p ÷ d (at .68 r)	0.957
M W R	0.201	DIAMETER	8.000 Ins.
B T F	0.036	PITCH (at .68 r)	7.655 Ins.
		ROTATION	R. H.

Figure 1 - Geometric Characteristics of TMB Propeller, Model 2406

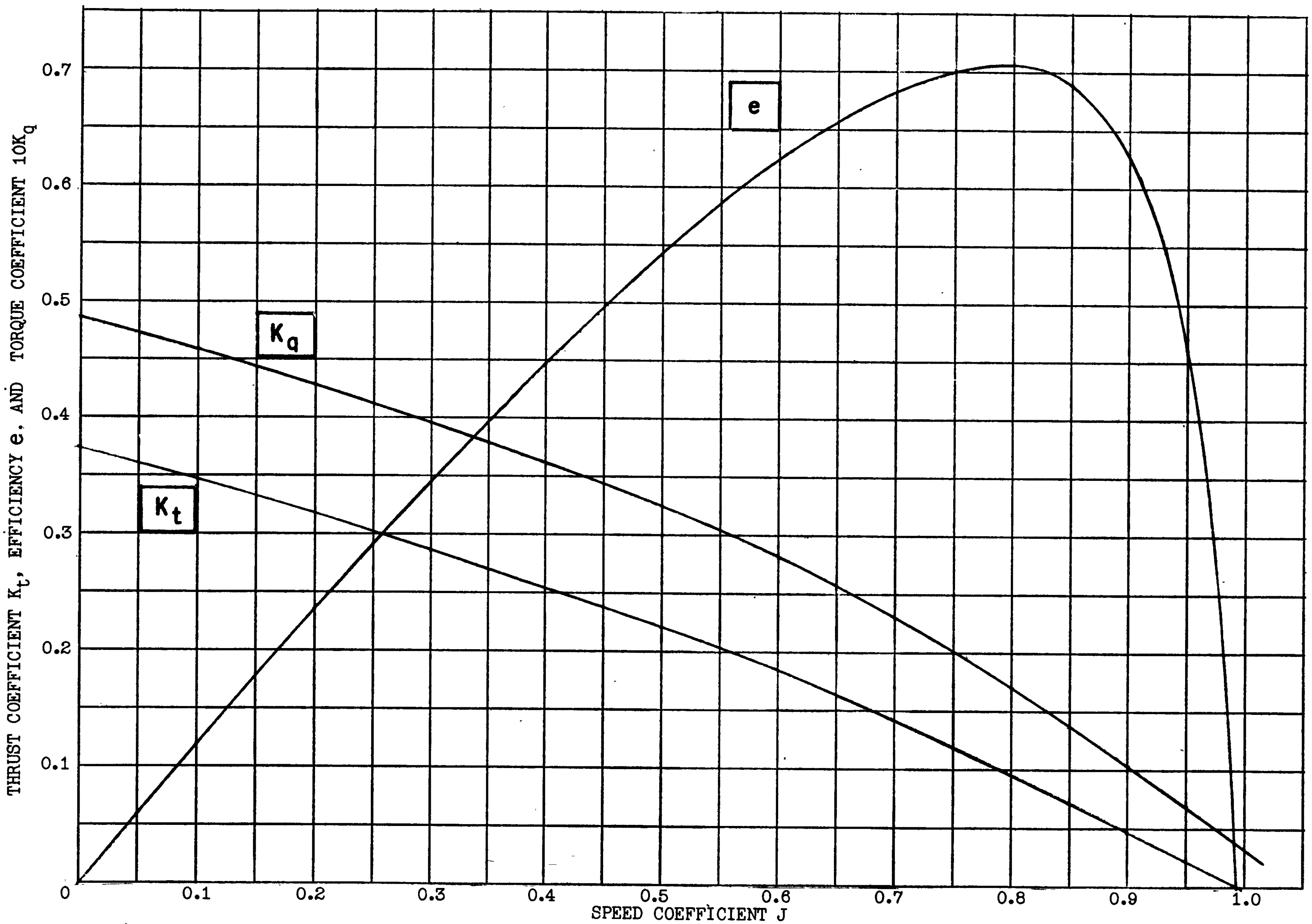


Figure 2 - Performance Characteristic Curves of Propeller 2406

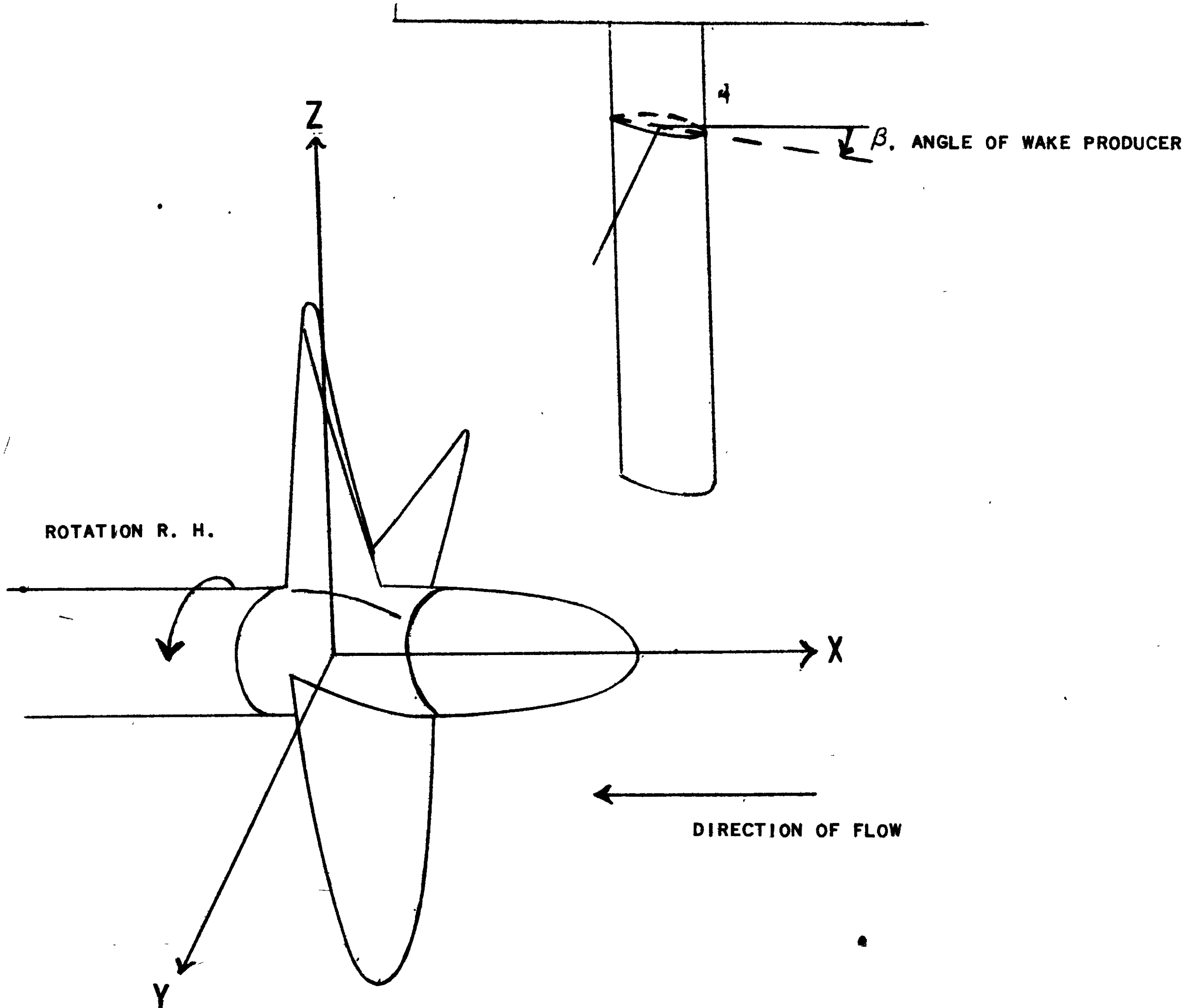


Figure 3 - Co-ordinate Systems

Rectangular System of Propeller and Polar system of Wake Producer

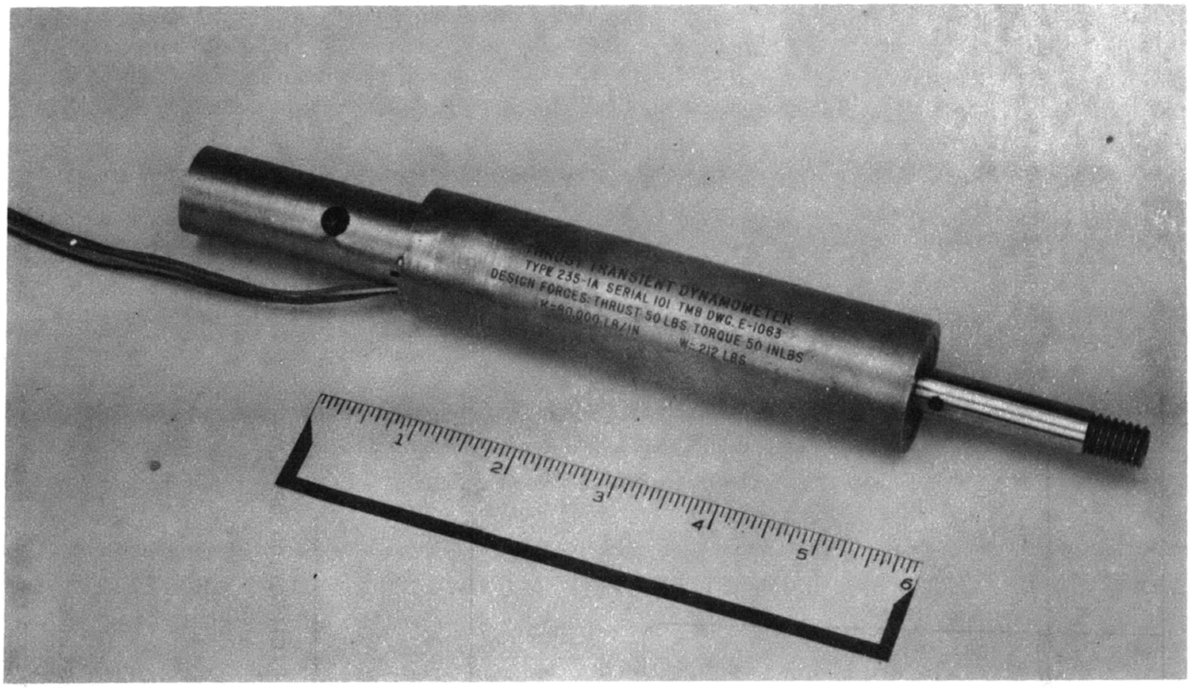


Figure 4- Photograph of Transient Thrust Dynamometer

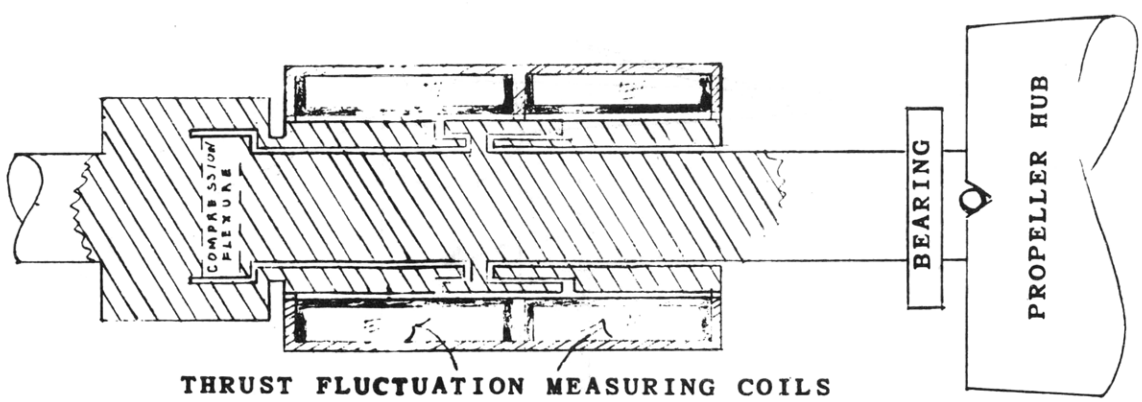


Figure 5 - Cross Section of Transient Thrust Dynamometer

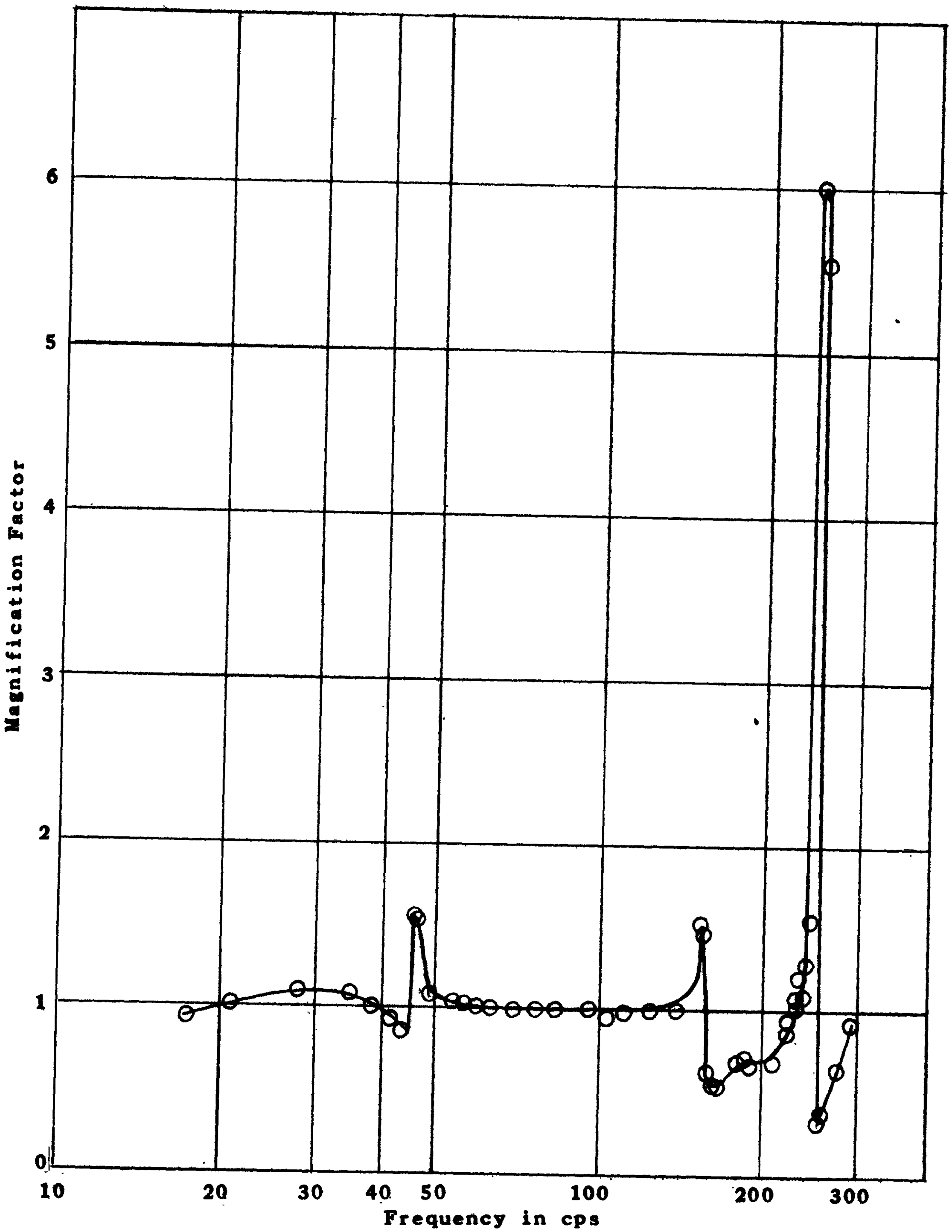


Figure 6 - Response Curve for Transient Thrust Dynamometer

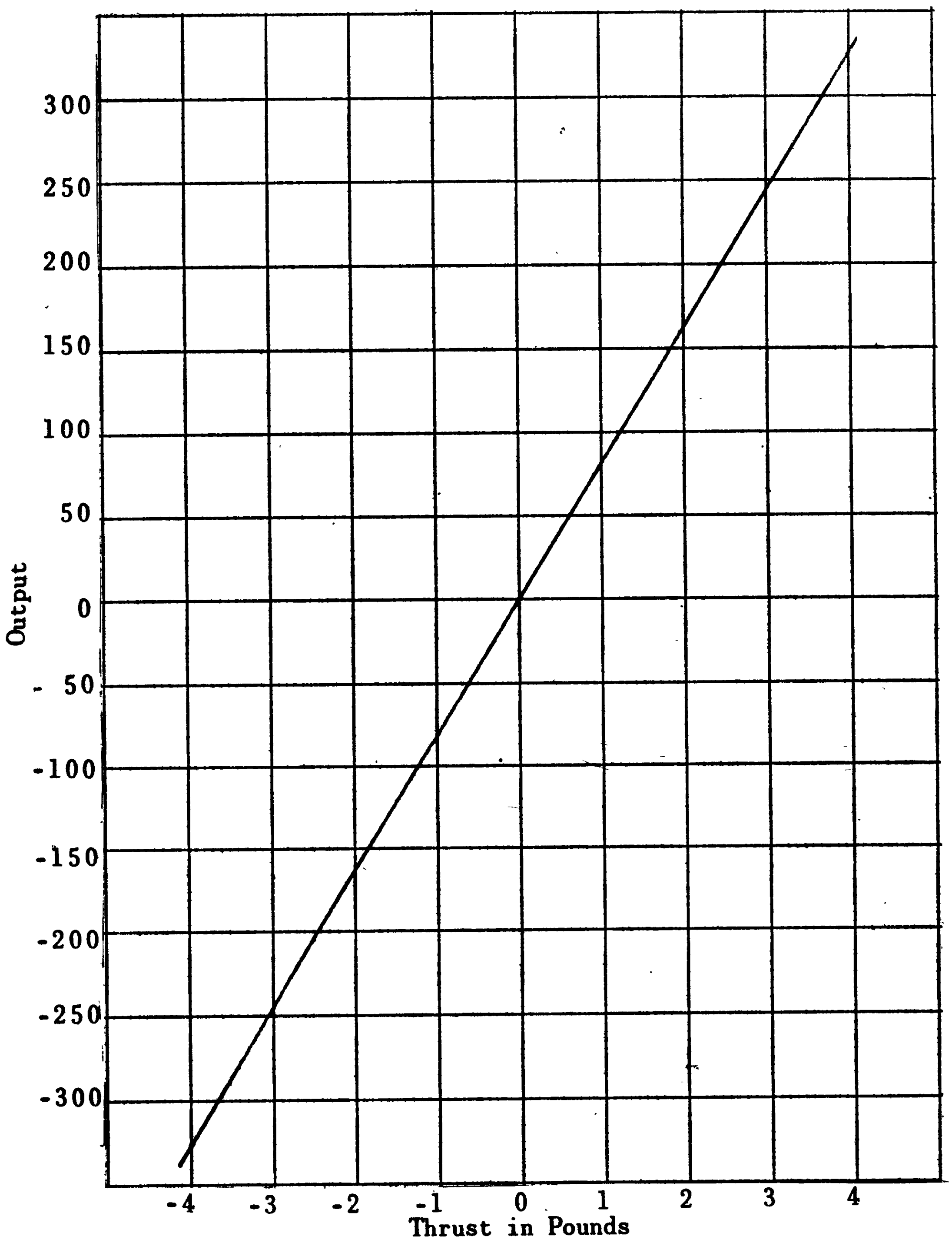


Figure 7 - Transient Thrust Dynamometer Calibration
(Output is in volts multiplied by attenuation of 5-K strain indicator)

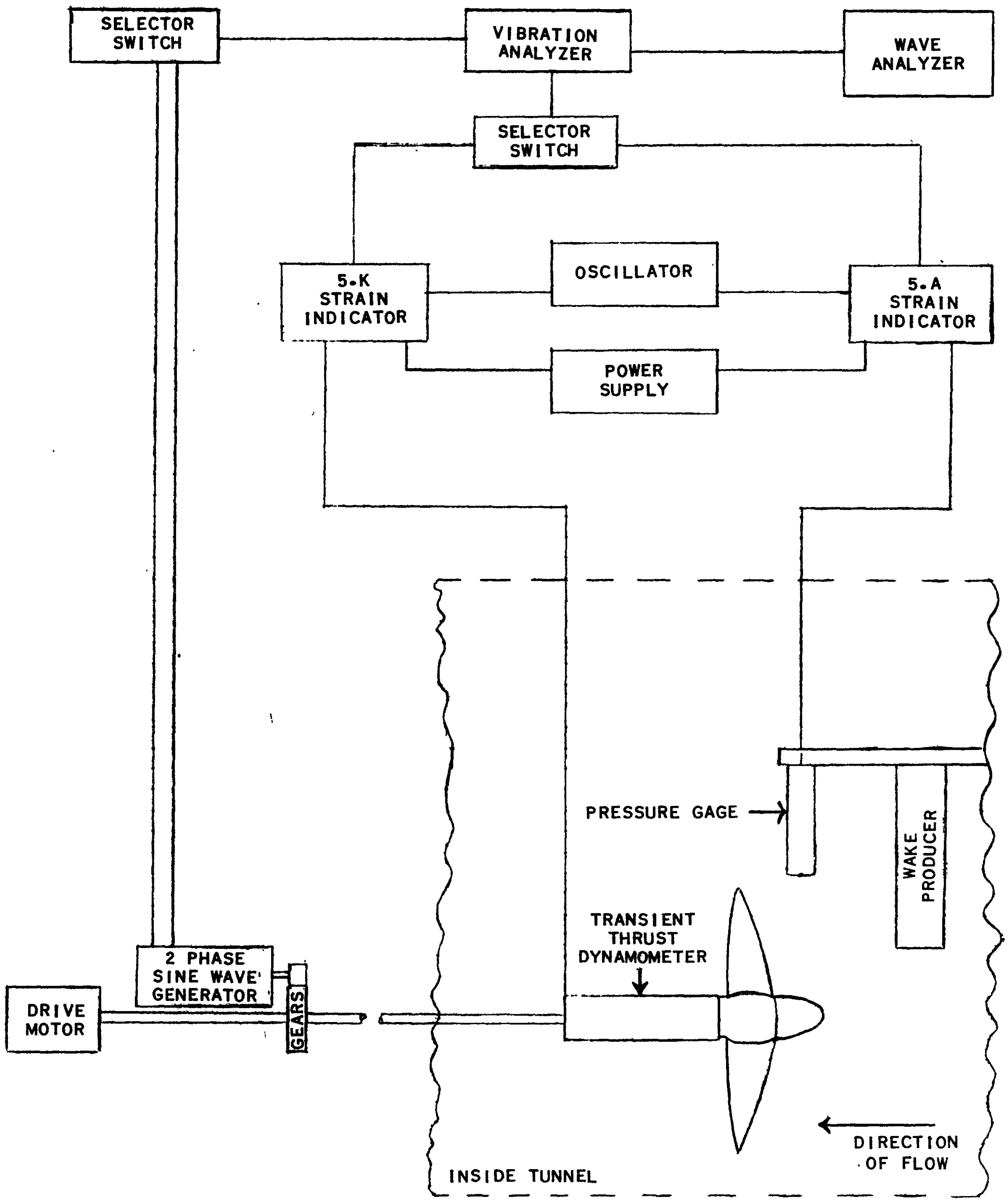


Figure 8 - Instrumentation Layout

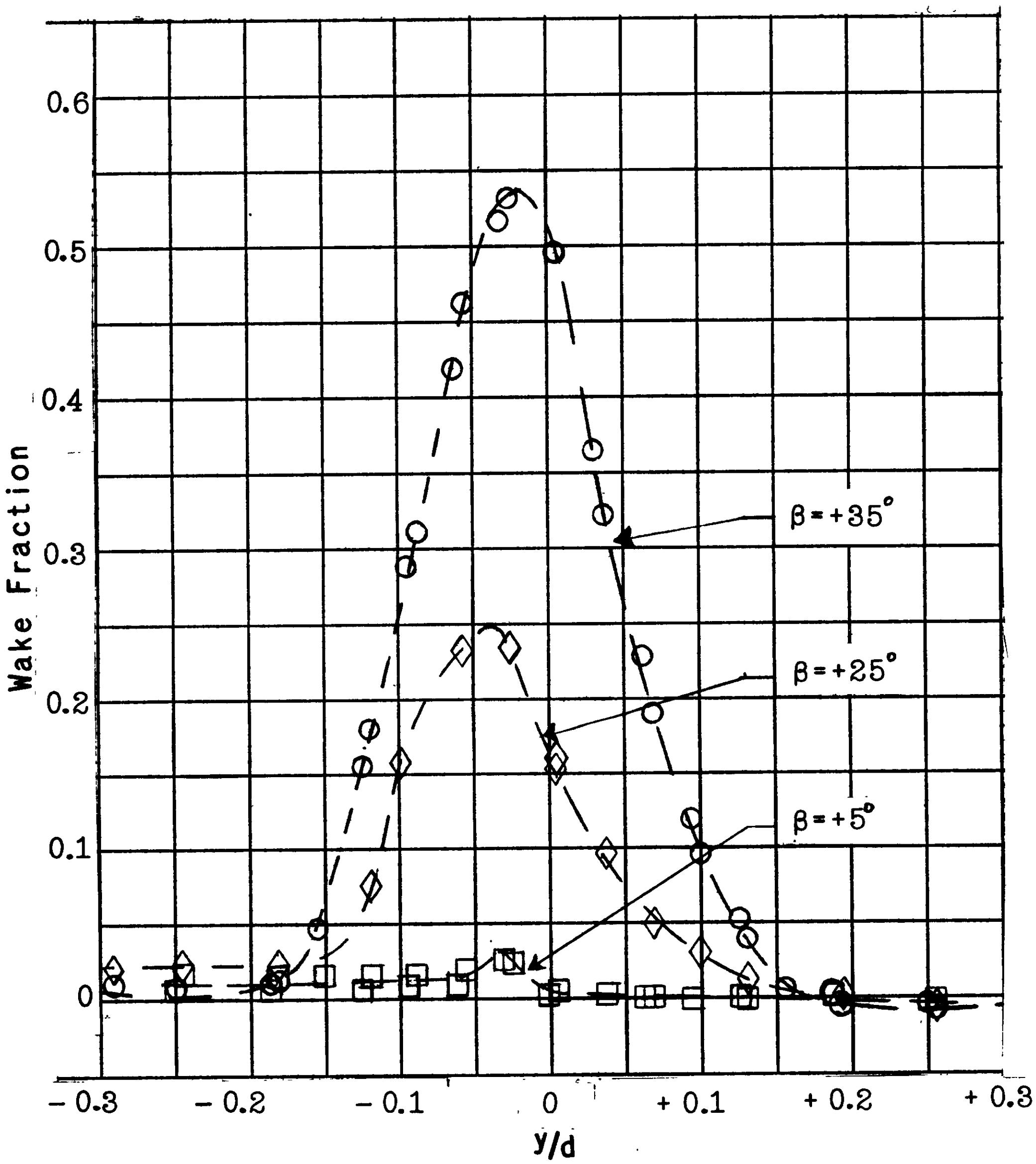


Figure 9 - Wake Fraction at $z/d = 0.35$

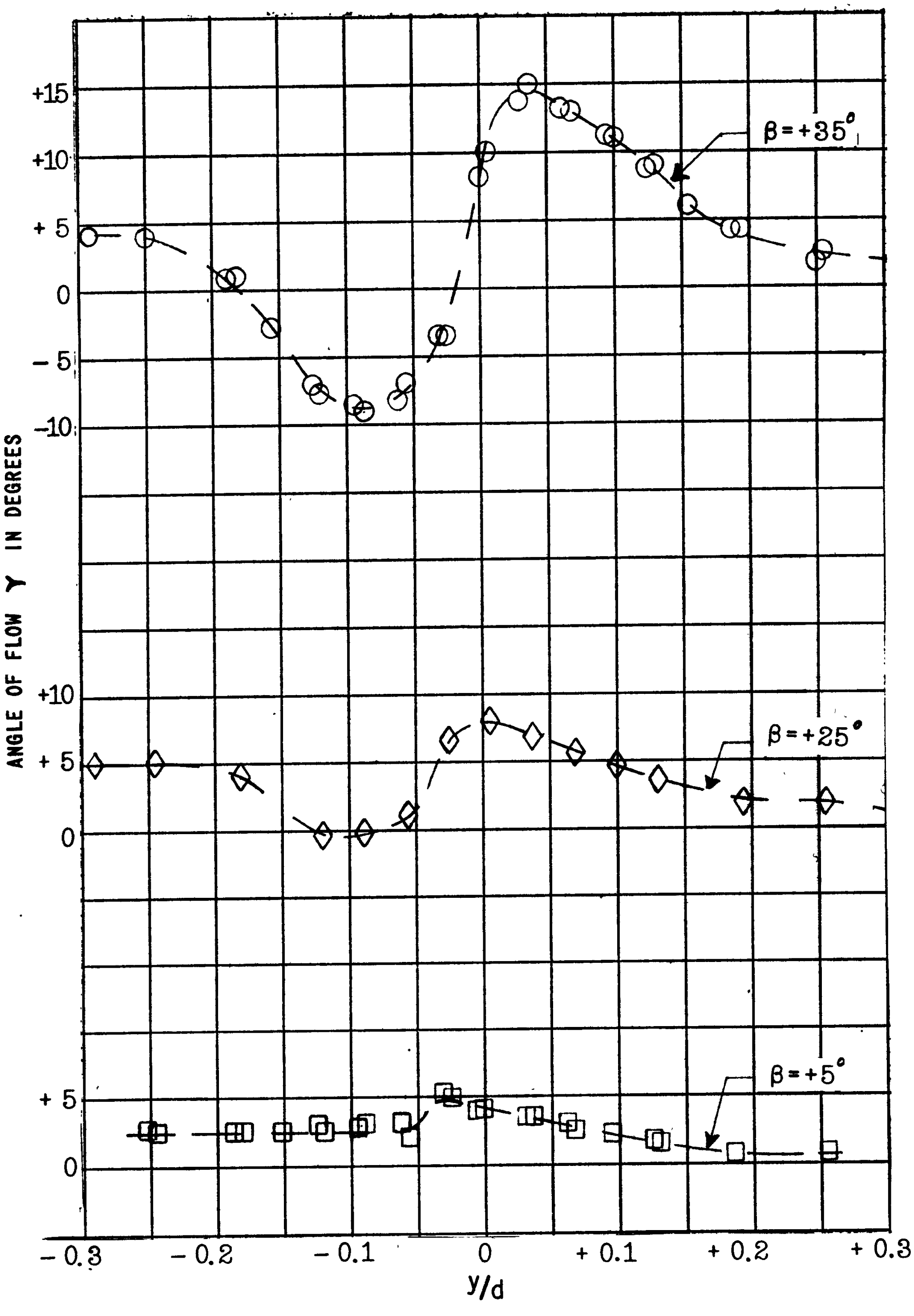


Figure 10 - Angle of Flow at $^{z}/_{d}$ = 0.35

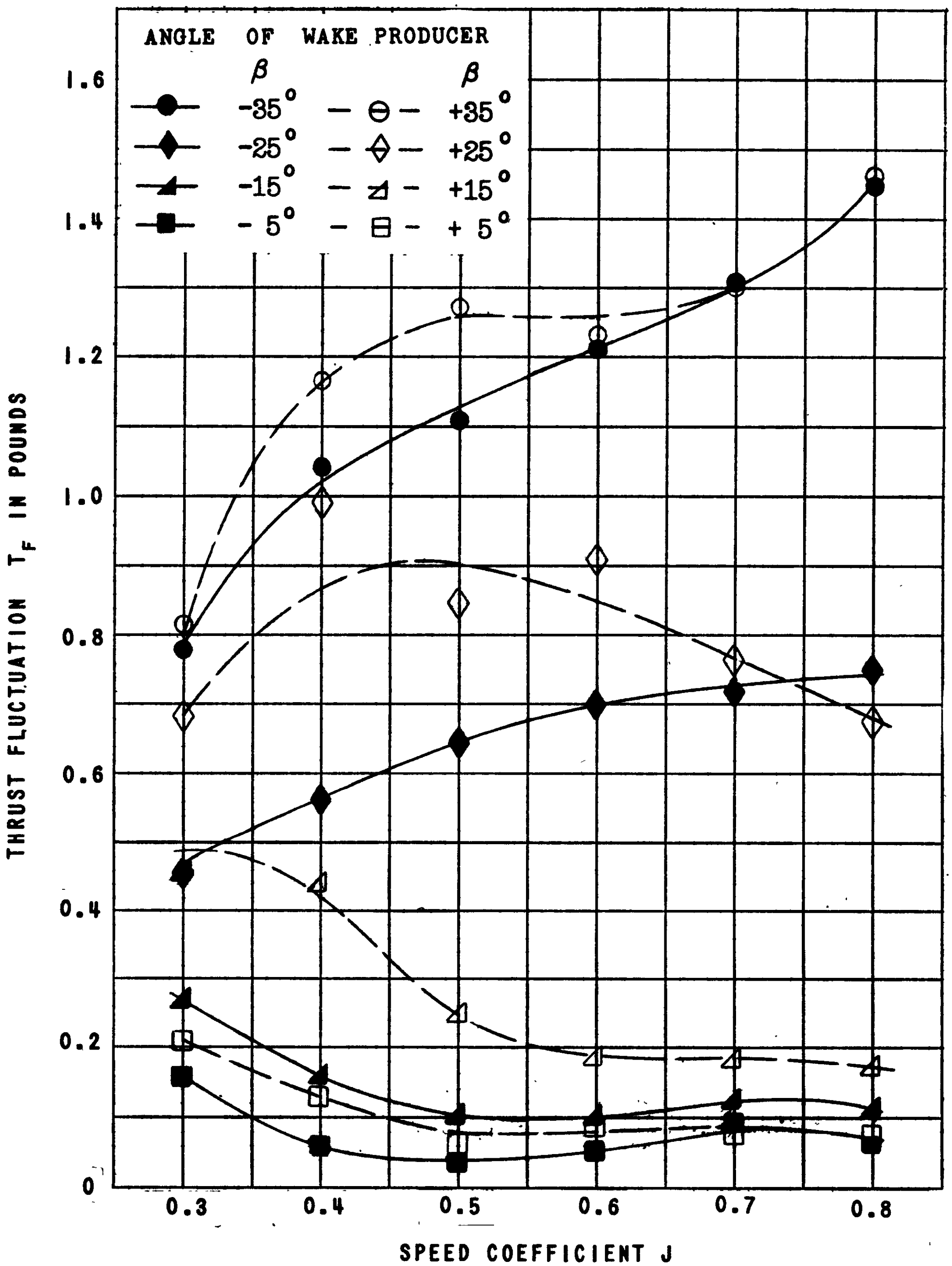


Figure 11 - Magnitude of Thrust Fluctuation

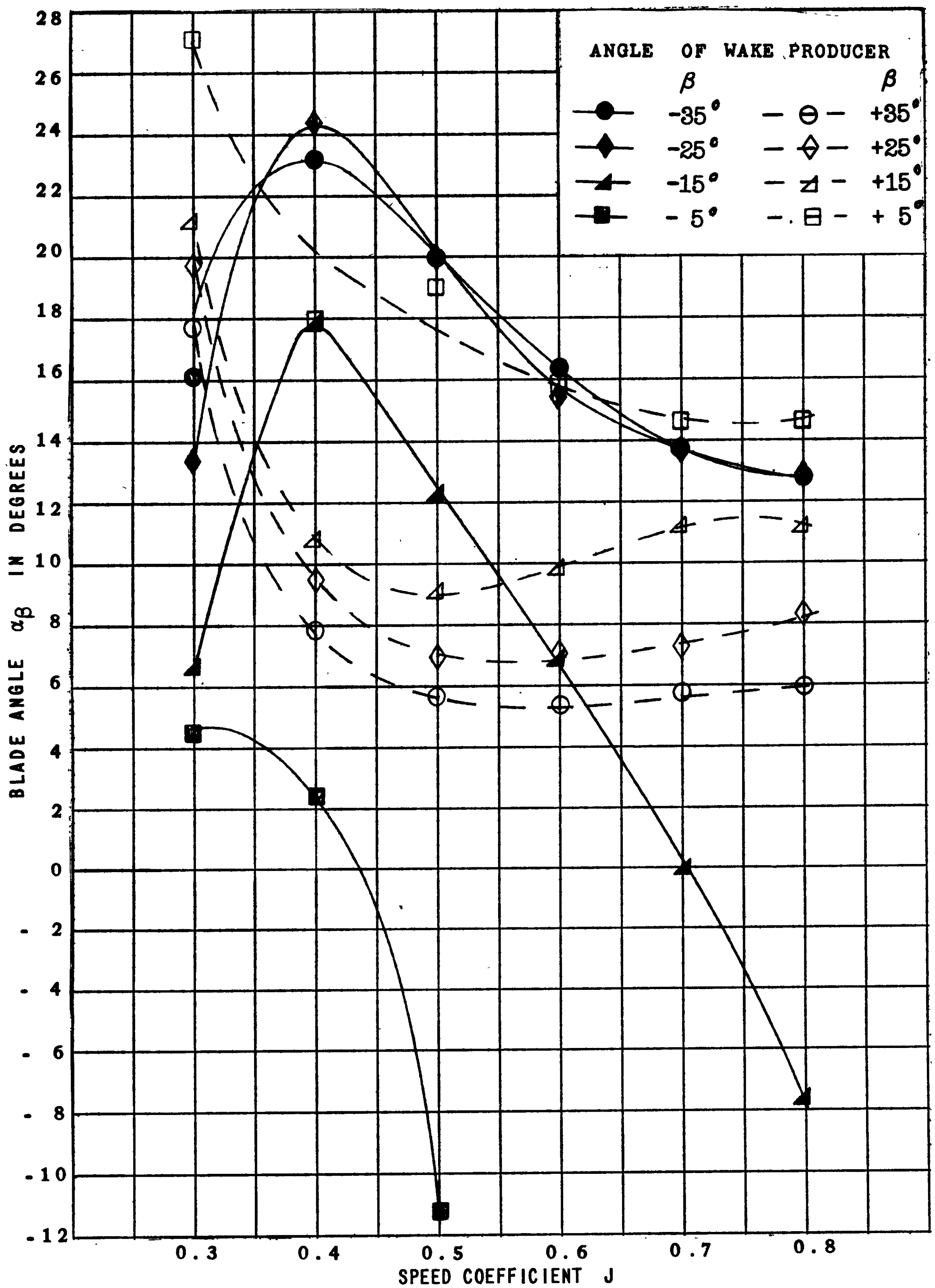


Figure 12 - Blade Angle for Maximum Thrust

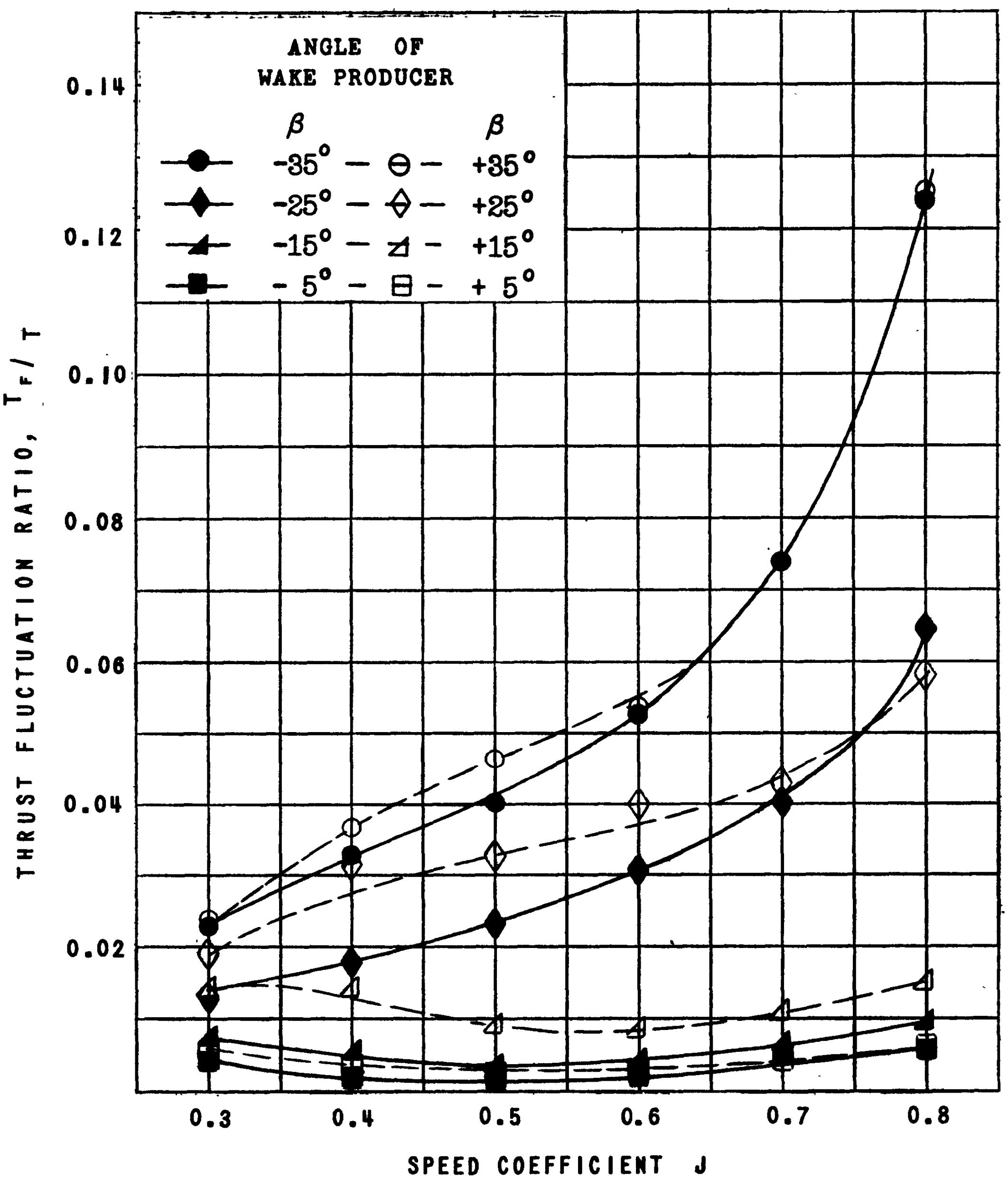


Figure 13 - Thrust Fluctuation as Percentage Mean Thrust

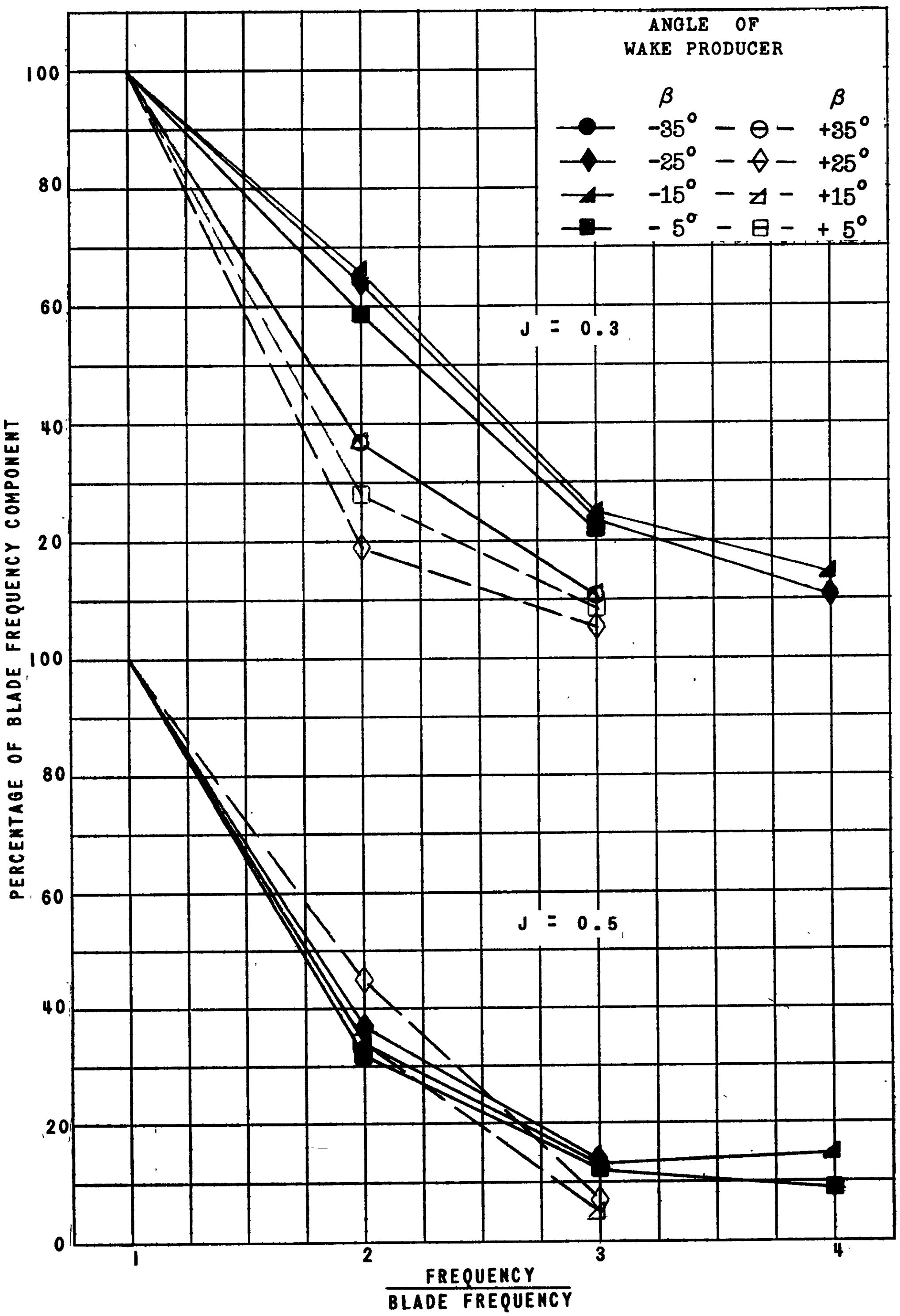


Figure 14 - Thrust Fluctuation at Higher Harmonics

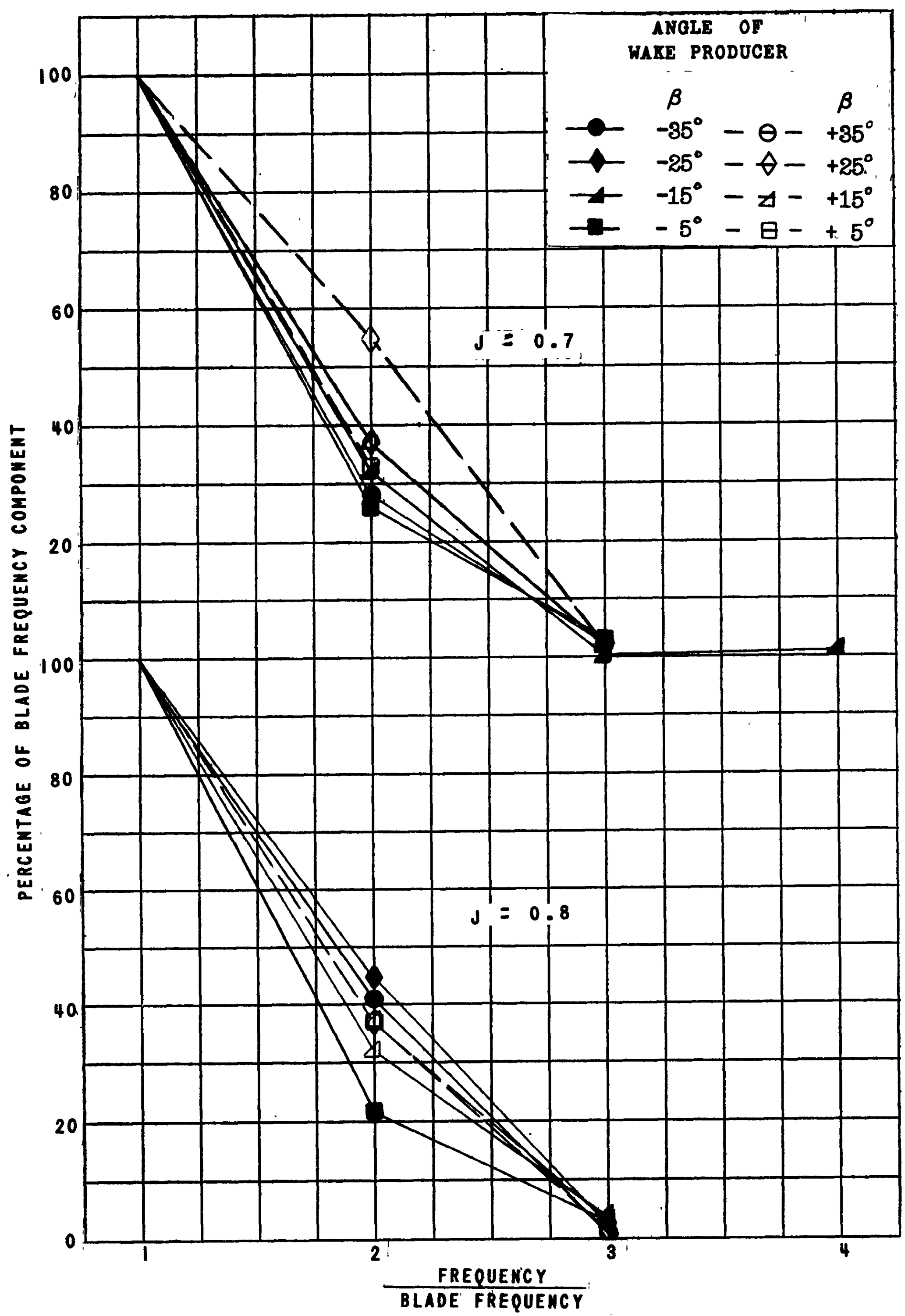


Figure 15 - Thrust Fluctuation at Higher Harmonics

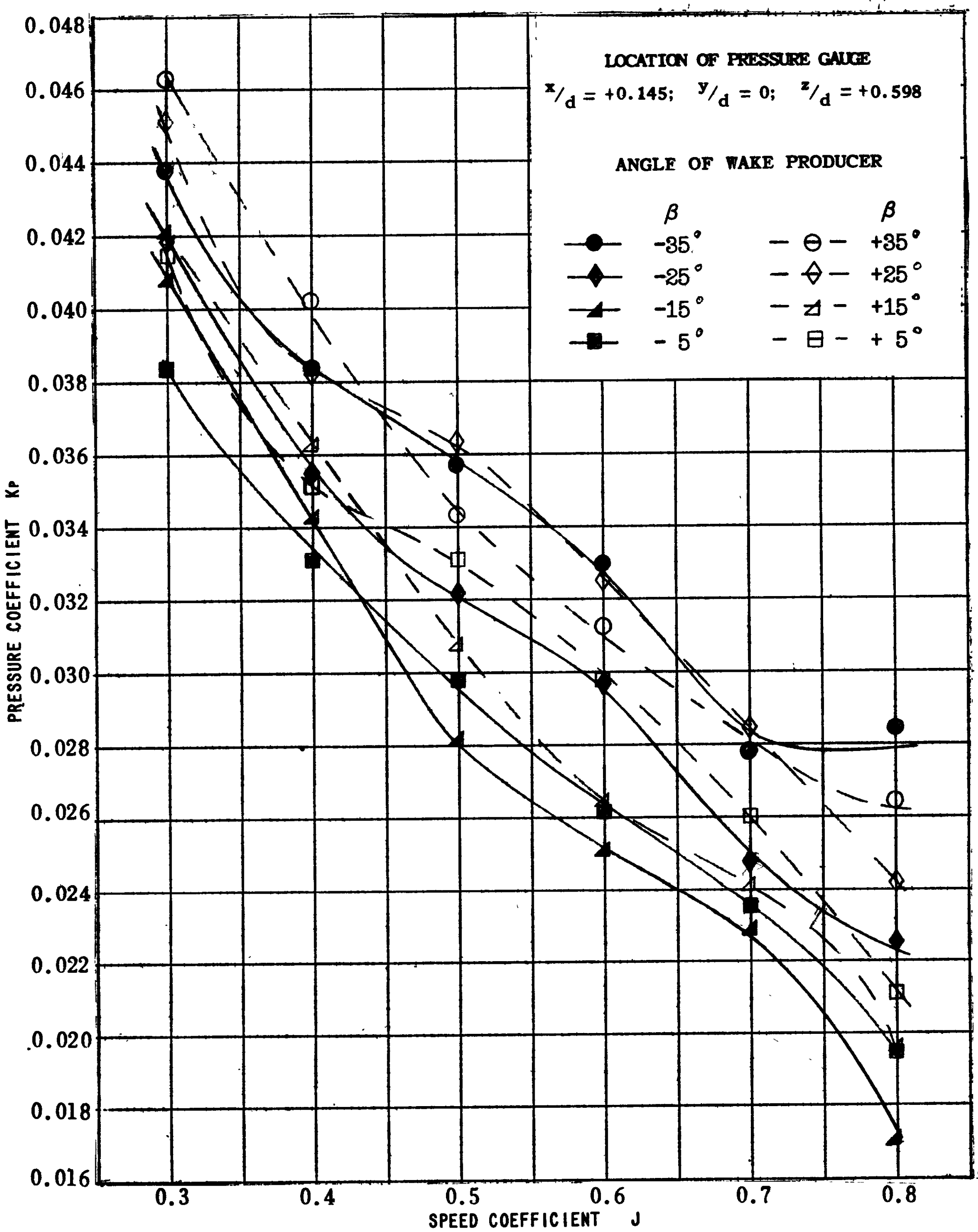


Figure 16 - Magnitude of Oscillating Pressure

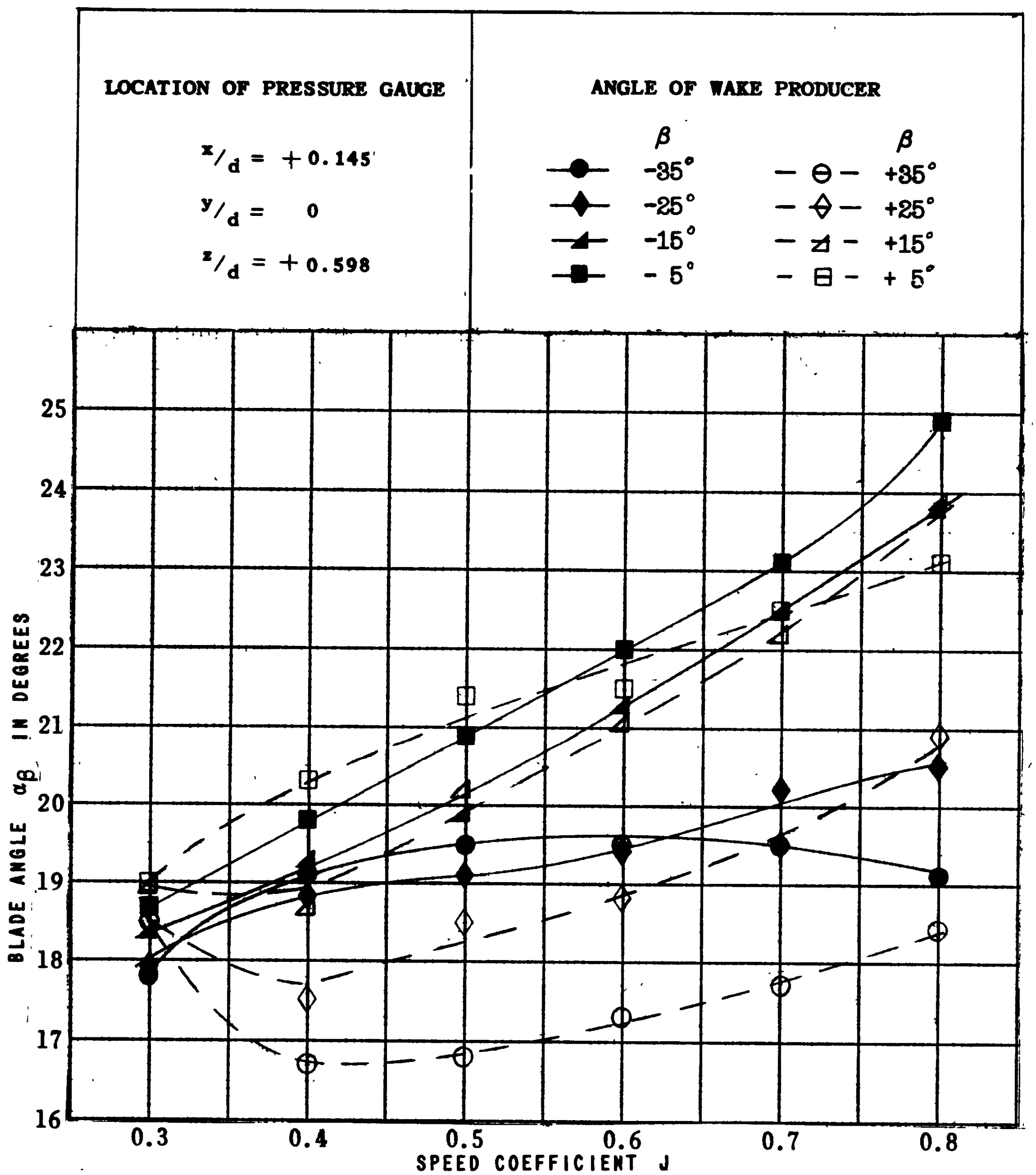


Figure 17 - Blade Angle for Maximum Pressure

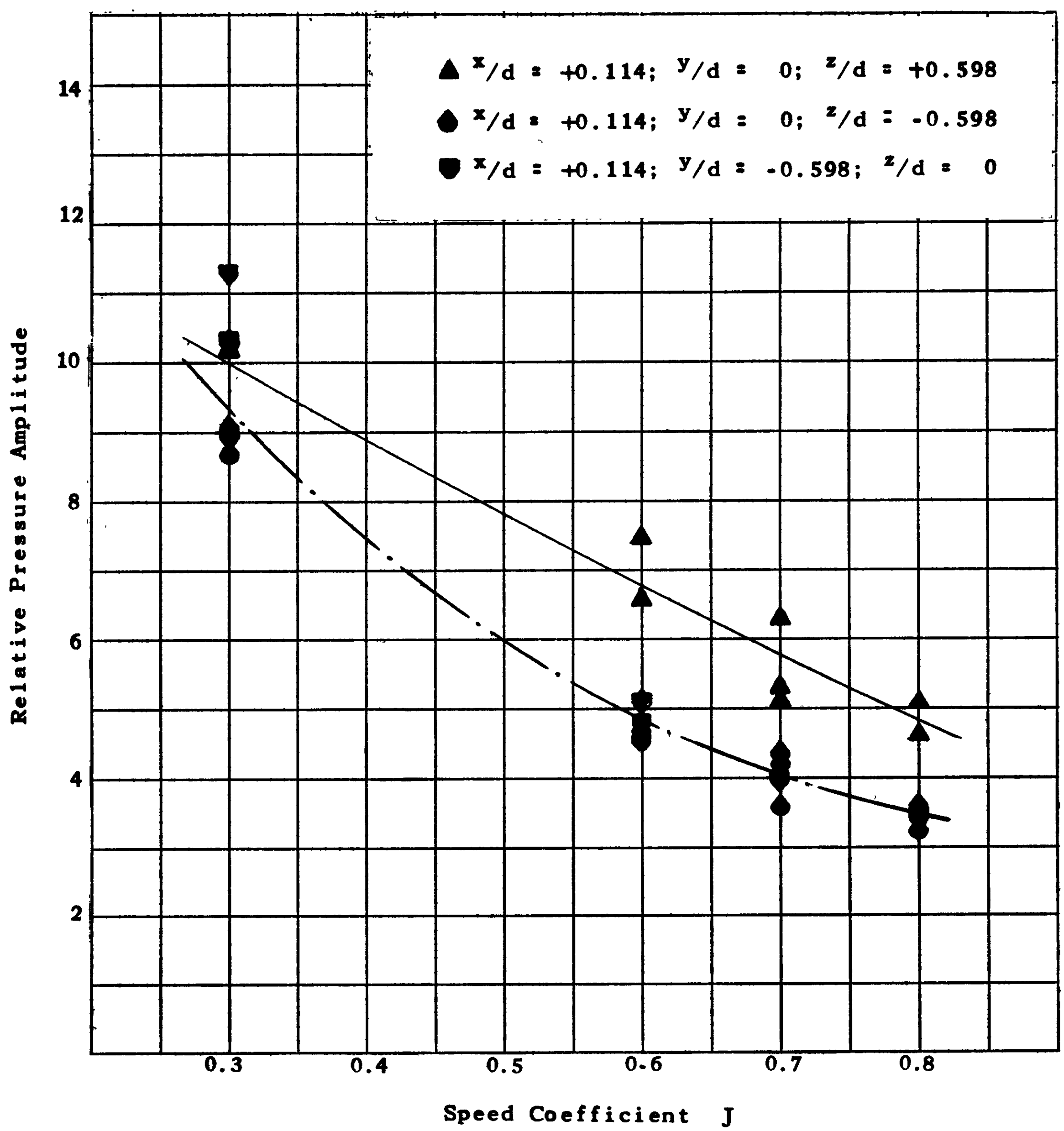


Figure 18 - Pressure Measurements Inside and Outside the Wake Region

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