ON THE ANALYSIS OF SHIP TRIAL DATA

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The value of measured mile ship trials depends in the final analysis on the reliability of the results. Reliable results are again dependent on two factors; first, the sufficiency and accuracy of the data taken and, second, on the proper analysis of the test data.

In this paper we shall take the first for granted and describe a method of analyzing trial data by means of which a large amount of information is obtained, notably as to the effect of the wind, the weather and the tide, and by means of which these effects can be eliminated. It will be seen that this method has the further advantage that only two runs at any particular speed, one in each direction of the course, are necessary for the elimination of the tide effect, while ordinarily it is assumed that at least three such runs are required. This is of particular interest in merchant-ship trials where the available time is limited.

The following data are assumed to be given: The shaft horsepower (s.h.p.), the revolutions per minute of the propeller (N), the speed of the ship over the ground (V), the direction and the speed of the relative wind (u), and the characteristic curves of the propeller. It is further assumed that for each group of runs the revolutions of the propeller were held as nearly constant as possible.

It is well known that the amount of power absorbed by a propeller is given by the following equation:

Equation 1. $\quad \text{Power} = K(N^3)\, f(\frac{V}{N})$

where: K is a coefficient depending on the geometrical properties of the propeller.

$f(\frac{V}{N})$ is a function determined by experiment.

This relationship between power, revolutions and speed and the analogous relationship between thrust, revolutions and speed are generally presented in the form of the "characteristic coefficients" of the propeller:

Equation 2.
$$\left(\begin{array}{l} C_T = \dfrac{T}{n^2\ P^2\ D^2} \\[2ex] C_Q = \dfrac{Q}{n^2\ P^3\ D^2} \\[2ex] e = \dfrac{T\ v}{2\pi Q\ n} \end{array} \right.$$

plotted as ordinates on an abscissa of true slip ratio, defined by:

$$s = \frac{Pn - V_a}{Pn}$$

where: T = Thrust in lbs.

Q = Torque in lb - feet.

n = Revolutions per second.

V_a = Speed of Advance in feet/sec.

P = Propeller pitch in feet.

D = Propeller diameter in feet.

e = Propeller efficiency.

A set of these characteristic curves is shown in figure 1 for illustration.

The above coefficients, C_T and C_Q, not only are useful in presenting free water test data but are also well suited for the analysis of ship trial results. They are easily calculated from the measured values and when plotted on propeller revolutions per minute their graph shows as a level line for a considerable part of the range, thus making interpolation easy and accurate. But even more important is the fact, that the speed of the ship through the water, which is unknown due to the influence of the tide, does not enter into this presentation and in fact could be deduced from the C_T or C_Q curve of the model propeller, if the wake fraction of the ship were known. The latter is ordinarily not the case; however, we may safely assume that the wake fraction remains the same for two trial runs at constant r.p.m., one with the wind and one against the wind, so that a difference in speed of the ship through the water caused by the wind and the weather may be assumed to be equal to the corresponding difference in speed of advance of the propeller through the water. This fact enables us to separate the effect of the wind from the effect of the tide. In analyzing the trial data we proceed as follows: From the given data, shaft horsepower and revolutions per minute we calculate the C_Q coefficients for the runs with and against the wind. Let us denote by:

C_Q'', C_Q' = The C_Q coefficients for the runs with, respectively against the wind.

C_T'', C_T' = The C_T coefficients for the runs with, respectively against the wind.

u'', u' = The given relative wind speed.

C_{T_o}, C_{Q_o} = The coefficients for zero relative wind speed, i. e. for a vessel without superstructure, which is very closely the condition for the self-propelled model.

If the thrust of the propeller was measured during the trials we can calculate the C_T'' and C_T', as well as, the C_Q'' and C_Q' coefficients directly. If the thrust was not measured, we obtain the former by entering the characteristic C_Q curve (figure 1) with the values for C_Q'' and C_Q' and reading the corresponding values off the C_T curve. Then we insert these values in the equation:

Equation 3: $$C_{T_o} = \frac{C_T''\,(u')^2 \mp C_T'(u'')^2}{(u')^2 \mp (u'')^2}$$

In which, the plus sign applies when the direction of the relative wind is from ahead, the minus sign applies when the direction of the wind is from astern.

Again entering figure 1 we obtain the C_{Q_o} values corresponding to the calculated C_{T_o} values. It is best then to plot these corrected C_{T_o} and C_{Q_o} coefficients on r.p.m. as abscissa and to draw smooth curves through the spots as indicated in figure 2.

The difference in speed caused by the air and weather resistance may then be obtained by the following formulae, the derivation of which is given in Appendix I.

Equation 4:

$$\left\{\begin{array}{l} \Delta v' = \dfrac{PN}{101\ 1/3q}\,(C'_Q - C_{Q_o}) \\[2ex] \Delta v'' = \dfrac{PN}{101\ 1/3q}\,(C''_Q - C_{Q_o}) \\[2ex] v_o = v' + \Delta v' = v'' + \Delta v'' \end{array}\right.$$

In which equations, v denotes the ship speed in knots, q denotes the slope of the tangent drawn to the C_Q curve in figure 1 at the points C'_Q, C''_Q. The single prime superscripts denote again runs against the wind, double prime superscripts denote runs with the wind and the zero subscript denotes the condition of zero relative wind speed.

It will be noticed from equation 3 that the above method breaks down for the case of absolutely calm air and smooth sea. In this case we must estimate the air resistance by an empirical formula. It is usually assumed that the air resistance can be expressed by the following formula:

Equation 5: $R_a = k\,A\,u^2$

where: A is a characteristic area of the ship's above-water structure, u the relative wind speed in knots and k is a coefficient varying with the type of the ship, which is generally given between .003 and .0045.

In the case that the trials were conducted with a moderate wind blowing over the course, in which case the method outlined above is applicable, the coefficient "k" in equation 5 may be deduced from the trial results by the following formula:

$$\text{Equation 6:} \quad k = \frac{R_o}{A\,u^2}\left\{ \frac{C_T' - C_{T_o}}{C_{T_o}} + 2\frac{v' - v_o}{v_o} \right\}$$

where: R_o is the ship resistance for the speed v_o, taken from the model test, and the other quantities have the meaning given before.

It remains to consider the effect of the tide. Barring cross currents and other irregularities, the tidal current may be assumed to be a sine function of the elapsed time. That is, in general, we may write:

$$\text{Equation 7:} \quad V_{Tide} = K \sin \frac{\pi h}{H}$$

where: H is the time interval between high and low water taken from the tide tables nearest to the time and date of the trials; h is the time interval before or after the time at which the tidal current reversed its direction. As will be shown, the time of reversal of the current can be determined directly from the trial data. In order to show graphically the effect of the tidal current it is desirable to use a function of the ship speed which will remain nearly level when plotted on ship speed. The "apparent slip" defined by the equation:

Equation 8: $$s_a = \frac{PN - v_o}{PN}$$

is found to possess this characteristic, provided, the propeller is not cavitating. If then, we calculate the apparent slip from the trial data and plot the spots on time of the day, we obtain a very clear presentation of the tide effect. This is illustrated in figure 3. The nodal point in this figure fixes the exact time of the reversal of the tidal current, quite independently of tide or current tables. Knowing this point, the value of h, defined above, is given for each trial run. The mean apparent slip ratio, corrected for tide, may then be calculated by the following equation, the derivation of which is given in Appendix III:

Equation 9: $$s_{a_o} = \frac{\sin\theta''(s_a' N') + \sin\theta'(s_a'' N'')}{N''\sin\theta' + N'\sin\theta''}$$

or, if several runs were made in a given direction over the trial course, the equation becomes:

Equation 10: $$s_{a_o} = \frac{\Sigma\sin\theta''\,\Sigma s_a' N' + \Sigma\sin\theta'\,\Sigma s_a'' N''}{\Sigma N''\,\Sigma\sin\theta' + \Sigma N'\,\Sigma\sin\theta''}$$

In these equations:

Values with a single prime superscript refer to runs against the tide.

Values with a double prime superscript refer to runs with the tide.

Values with a zero subscript are the corrected values.

s_a = The apparent slip ratio.

N = The propeller revolutions per minute.

θ = $\frac{\pi h}{H}$, where h and H have the meaning given above.

These equations are much simplified if the revolutions were held absolutely constant for each group of runs. In this case $N' = N''$ and cancels out from the numerator and denominator, so that we have:

Equation 9a: $$s_{a_o} = \frac{\sin\theta'' s'_a + \sin\theta' s''_a}{\sin\theta'' + \sin\theta'}$$ and:

Equation 10a: $$s_{a_o} = \frac{\Sigma \sin\theta'' \Sigma s'_a + \Sigma \sin\theta' \Sigma s''_a}{\Sigma \sin\theta'' + \Sigma \sin\theta'}$$

For purposes of interpolation, and also to find the variation of the apparent slip with the r.p.m., we proceed to plot the values of s_{a_o} found by the above method on revolutions per minute, and draw a fair curve through the spots, as is illustrated in figure 4.

This completes the correction of the trial data. Corrected values for the shaft horsepower, the revolutions and the speed can be recalculated from the C_{Q_o} and s_{a_o} curves.

It should be emphasized that these curves were corrected down to the model condition, i. e. to the complete absence of air resistance. Hence, to find the ship power for any given strength of wind, the power to overcome the wind resistance must be calculated separately, for example by formulae 5 and 6 and the propulsive coefficient, and added. The corresponding increase in revolutions may be found by the following formula:

Equation 11: $$\frac{\Delta\, SHP}{SHP} = \left\{ 2 + \frac{C_Q - \overline{C}_Q(1-s)}{C_Q\ s} \right\} \frac{\Delta N}{N}$$

where: s = The true slip ratio.

$\overline{C}_a$ = The intercept on zero slip of the tangent drawn to the C_Q curve at the point C_Q,s.

One further question frequently arises when making a comparison between the self-propelled model tests and the ship trials, viz, concerning the effect of a difference between the wake of the ship and the wake of the model. This question will be investigated below.

The wake of a ship consists of two major components, the frictional wake and the streamline wake. It can be shown that the width of the boundary layer surrounding the hull of the ship is approximately proportional to the 4/5 power of the length. Hence, it appears that the width of the frictional belt is relatively wider at the stern of the model than at the stern of the ship, assuming that the above relation is not disturbed by greater roughness of the ship's hull. The propeller of a single screw ship which is located directly in the frictional wake may thus be assumed to work in a smaller wake than the model propeller. This in turn would cause the ship's propeller to turn at higher r.p.m. than the corresponding model propeller. The amount of this difference in r.p.m. and the corresponding difference in power is what concerns us most in this discussion.

It has frequently been assumed that the difference in revolutions was proportional to the difference in the speed of inflow into the propeller. This assumption is incorrect. Instead, we must find the effect of a variation of the speed of inflow on the revolutions and the power of the propeller at constant propeller thrust. This problem can be readily solved by means of the characteristic curves of the propeller. The solution is given in the form of two equations one of which connects the percentage difference in r.p.m. with the percentage difference in the speed of inflow into the propeller, while the other connects the percentage difference in power with the percentage difference in r.p.m. The derivation of these equations is given in Appendix IV. Let us assume that the C_T and C_Q coefficients can be represented "locally" by straight line equations, and let us denote by:

s = The true slip ratio.

m = The slope of the C_T curve.

q = The slope of the C_Q curve.

$\bar{C}_T \; \bar{C}_Q$ = The intercepts on zero slip ratio.

w_m = The wake fraction of the model.

$\frac{\Delta w}{1-w_m}$ = The fractional difference in the speed of advance of the propeller.

$\frac{\Delta N}{N}$ = The fractional difference in the r.p.m.

$\frac{\Delta S}{S}$ = The fractional difference in the shaft horsepower.

Then we have:

Equation 12: $$\frac{\Delta N}{N} = \frac{\Delta w}{1-w} \quad \frac{(1-s)}{2\,\bar{C}_T/_m + (1+s)} = \frac{\Delta w}{1-w} \times \frac{(1-s)}{a + (1+s)}$$

Equation 13: $$\frac{\Delta S}{S} = \frac{\Delta N}{N} \; \frac{(3\,\bar{C}_Q/_q - 2\,\bar{C}_T/_m) + s}{\bar{C}_Q/_q + s} = \frac{\Delta N}{N} \; \frac{(3b - a) + s}{b + s}$$

Equation 12 shows that the fraction connecting $\frac{\Delta N}{N}$ and $\frac{\Delta w}{1-w}$ is always less than one and that it is a maximum at zero effective slip and becomes zero at 100% slip; for the ordinary type of ship and propeller it is approximately .40. The fraction in equation 13 connecting $\frac{\Delta SHP}{SHP}$ and $\frac{\Delta N}{N}$ has a value of about 1.6 for the ordinary type of ship and propeller; this shows that the effect of a wake difference on the power is approximately $1\frac{1}{2}$ times the effect on the revolutions.

The fraction $\frac{\Delta w}{1-w}$ may be estimated by theoretical reasoning. (For example, see W.R.u.H. 1925, pp.115-6) Its magnitude is approximately from .005 to .05, the smaller figure applying to high speed vessels of the destroyer type and the larger figure applying to low-speed vessels of the cargo carrier type. If we use these approximate figures in equations 12 and 13 we find that for single screw ships the difference in the wake between the model and the ship may well cause a discrepancy of 2% in the r.p.m. and 3% in the shaft horsepower between the model results and the ship trial results. This fact should not be overlooked when making a comparison between the model and the ship.

APPENDIX I

Let us assume that the wind resistance varies as the square of the relative wind speed and use the following notation:

A single prime superscript for runs against the wind.

A double prime superscript for runs with the wind.

A small zero subscript for complete absence of air.

v = The ship speed.

u = $v \pm w$ = The relative wind speed.

w = The absolute wind speed.

R = The resistance of the ship.

k = A coefficient.

N = The propeller revolutions.

C_T = The thrust coefficient.

Then:

Equation a: $R' = R_o + k(v' + w)^2 = R_o + ku'^2$

Equation b: $R'' = R_o \pm k(v'' - w)^2 = R_o \pm Ku''^2 \begin{Bmatrix} + \text{ when } v > w \\ - \text{ when } v < w \end{Bmatrix}$

Subtracting equation b from equation a, we get:

Equation c: $R' - R'' = k \left(u'^2 \mp u''^2\right)$

Dividing equation a by equation b we get:

Equation d: $\dfrac{R'}{R''} = \dfrac{R_o + ku'^2}{R_o \pm ku''^2}$

Combining equations c and d and solving for R_o we obtain:

Equation e: $$R_o = \frac{R''(u')^2 \mp R'(u'')^2}{(u')^2 \mp (u'')^2}$$

For R we may substitute T, the propeller thrust, inasmuch as, the thrust deduction coefficient remains practically constant for moderate differences in thrust.

Hence, equation e becomes:

Equation f: $$T_o = \frac{T''(u')^2 \mp T'(u'')^2}{(u')^2 \mp (u'')^2}$$

Since we have made the assumption that the runs with and against the wind were made at constant propeller revolutions, both sides of equation f may be divided by N^2 and we finally get the equation of the text:

Equation g: $$C_{T_o} = \frac{C_T'' \ (u')^2 \mp C_T' \ (u'')^2}{(u')^2 \mp (u'')^2}$$

APPENDIX II

Assume that the C_T and C_Q curves in figure 1 may be represented "locally" by the straight line equations:

$$\text{Equation a:} \begin{cases} C_T = \overline{C}_T + m\ s \\ C_Q = \overline{C}_Q + q\ s \end{cases}$$

where: s = The true slip ratio.

m,q = The slopes of the curves.

Let: V = The speed of advance of the propeller in knots.

P = The pitch of the propeller in feet.

N = The revolutions per minute.

Then: $101\ 1/3 V = (1-s)PN$

From which we get, if N is constant:

Equation b: $\Delta v = -\Delta s \dfrac{PN}{101\ 1/3}$

From equation a we obtain:

Equation c: $\Delta C_Q = q \Delta s$

Combining equations b and c we get:

Equation d: $\Delta v = -\dfrac{PN}{101\ 1/3\ q} \Delta C_Q$

Assuming now that the difference in the speed of the ship, caused by the wind and the weather, is equal to the corresponding difference in the speed of advance of the propeller, equation d may be written:

Equation e: $\Delta v' = \dfrac{PN}{101\ 1/3q} (C'_Q - C_{Q_o})$

$$\Delta v'' = \dfrac{PN}{101\ 1/3q} (C''_Q - C_{Q_o})$$

APPENDIX III

Denote by:

v = The ship speed over the ground in ft/min.

v_t = The speed of the tidal current in ft/min.

H = The time interval between high and low water taken from the tide tables.

h = The time interval between the time at the middle of the trial run and the time of reversal of the tidal current.

N = The propeller revolutions.

s = The apparent slip of the propeller.

K = A coefficient.

Single prime superscripts are for runs against the tide.
Double prime superscripts are for runs with the tide.
No superscript denotes the corrected values.

Assume that:

Equation a: $v_t = K \sin\left(\frac{\pi h}{H}\right)$

We have further:

Equation b: $v' + v_t = (1-s_a)\ PN'$

Equation c: $v' = (1-s'_a)\ PN'$

hence by subtracting equation c from b we get:

$v'_t = -s_a PN' + s' PN'$

or:

Equation d: $K \sin\left(\frac{\pi h'}{H}\right) = K \sin \theta' = P(s_a' N' - s_a N')$

Similarly we get for runs with the tide:

Equation e: $K \sin \frac{\pi h''}{H} = K \sin \theta'' = P(s_a N'' - s_a'' N'')$

Dividing equation d by equation e, we get:

Equation f: $\frac{\text{Sin } \theta'}{\sin \theta''} = \frac{s_a' N' - s_a N'}{s_a N'' - s_a'' N''}$

From which we get, by solving for s_a:

Equation g: $s_a = \frac{\sin \theta''(s_a' N') + \sin \theta'(s_a'' N'')}{N'' \sin \theta' + N' \sin \theta''}$

If $N' = N''$ this reduces to:

Equation h: $s_a = \frac{\sin \theta'' \, s_a' + \sin \theta' \, s_a''}{\sin \theta' + \sin \theta''}$

If several runs were made in the same direction over the course equation g and h become respectively:

Equation i: $s_a = \frac{\Sigma \sin \theta'' \, \Sigma \, s_a' N' + \Sigma \sin \theta' \, \Sigma \, s_a'' N''}{\Sigma N'' \Sigma \sin \theta' + \Sigma N' \Sigma \sin \theta''}$

Equation k: $s_a = \frac{\Sigma \sin \theta'' \, \Sigma \, s_a' + \Sigma \sin \theta' \, \Sigma \, s_a''}{\Sigma \sin \theta' + \Sigma \sin \theta''}$

APPENDIX IV

Denote by:

T = The propeller thrust in lbs.

Q = The propeller torque in lb-feet.

N = The propeller revolutions per minute.

S = The propeller horsepower.

v_a = The speed of advance.

s = The true slip ratio.

C_T = The thrust coefficient.

C_Q = The torque coefficient.

m q = Slopes of the C_T and C_Q curves.

$\overline{C}_T$ $\overline{C}_Q$ = Intercepts on zero slip ratio of the C_T and C_Q curves.

k K = Constants.

Assume:

EQUATION a
$$\left(\begin{array}{lcl} T & = & \text{constant} \\ C_T & = & \overline{C}_T + m\,s \\ C_Q & = & \overline{C}_Q + q\,s \end{array}\right)$$

Now: $T = k\ C_T\ N^2$ hence:

$$\frac{\Delta T}{T} = \frac{\Delta C_T}{C_T} + 2\,\frac{\Delta N}{N} = 0 \quad \text{from which,}$$

Equation b: $$\frac{\Delta C_T}{C_T} = -2\,\frac{\Delta N}{N}$$

Also: $v_a = (1-s)PN$ hence:

Equation c: $$\frac{\Delta v_a}{v_a} = -\,\frac{\Delta s}{(1-s)} + \frac{\Delta N}{N}$$

From equation a, we get:

$$\frac{\Delta C_T}{C_T} = \frac{m \Delta s}{C_T} = \frac{\Delta s}{1-s} \quad \frac{m(1-s)}{C_T} \qquad \text{or:}$$

Equation d: $$\frac{\Delta s}{1-s} = \frac{\Delta C_T}{C_T} \quad \frac{C_T}{m(1-s)}$$

Combining equations b and d, we obtain:

Equation e: $$-\frac{\Delta s}{1-s} = \frac{2 \Delta N}{N} \quad \frac{C_T}{m(1-s)}$$

Combining equations c and e we find:

$$\frac{\Delta v_a}{v_a} = \frac{2 \Delta N}{N} \quad \frac{C_T}{m(1-s)} + \frac{\Delta N}{N} = \frac{\Delta N}{N} \left(\frac{2 \; C_T}{m(1-s)} + 1 \right)$$

or:

$$\frac{\Delta N}{N} = \frac{\Delta v_a}{v_a} \quad \frac{1}{1 + \frac{2 \; C_T}{m(1-s)}}$$

This can be transformed and becomes:

Equation f: $$\frac{\Delta N}{N} = \frac{\Delta v_a}{v_a} \quad \frac{(1-s)}{2 \frac{C_T}{m} + (1+s)} = \frac{\Delta v_a}{v_a} \quad \frac{1-s}{a + (1+s)}$$

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Again we have: $$S = K \; C_Q \; N^3$$

From which:

Equation g: $$\frac{\Delta S}{S} = \frac{\Delta C_Q}{C_Q} + 3 \frac{\Delta N}{N}$$

Also from equation a: $$\frac{\Delta C_Q}{C_Q} = q \quad \frac{\Delta s}{C_Q}$$

Introducing this in equation g, we obtain:

Equation h: $$\frac{\Delta S}{S} = \frac{q\,\Delta s}{C_Q} + \frac{3\,\Delta N}{N} = \frac{\Delta s}{(1-s)}\;\frac{q(1-s)}{C_Q} + 3\,\frac{\Delta N}{N}$$

Combining equations e and h we get:

$$\frac{\Delta S}{S} = -\frac{2\,\Delta N}{N}\;\frac{q}{m}\;\frac{C_T}{C_Q} + 3\,\frac{\Delta N}{N}$$

or:

Equation i: $$\frac{\Delta S}{S} = \frac{\Delta N}{N}\left(3 - \frac{q}{m}\,2\,\frac{C_T}{C_Q}\right) = \frac{\Delta N}{N}\;\frac{3\frac{\overline{C}_Q}{q} - 2\,\frac{\overline{C}_T}{m} + s}{\frac{\overline{C}_Q}{q} + s}$$

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Now, if w_s = The wake fraction of the ship.

and, if w_m = The wake fraction of the model.

then: $$v_a = (1-w_s)\,v$$

$$v_a' = (1-w_m)\,v$$

Hence: $$v_a - v_a' = (w_m - w_s)\,v$$

$$\frac{v_a - v_a'}{v_a'} = \frac{(w_m - w_s)}{(1-w_m)}$$

or: $$\frac{\Delta v_a}{v_a'} = \frac{\Delta w}{1-w_m}$$

Introducing this expressinn in equation f we finally obtain:

Equation k: $$\frac{\Delta N}{N} = \frac{\Delta w}{1-w}\;\frac{m(1-s)}{2\overline{C}_T + m(1+s)} = \frac{\Delta w}{1-w}\;\frac{1-s}{\frac{2\overline{C}_T}{m} + (1+s)}$$

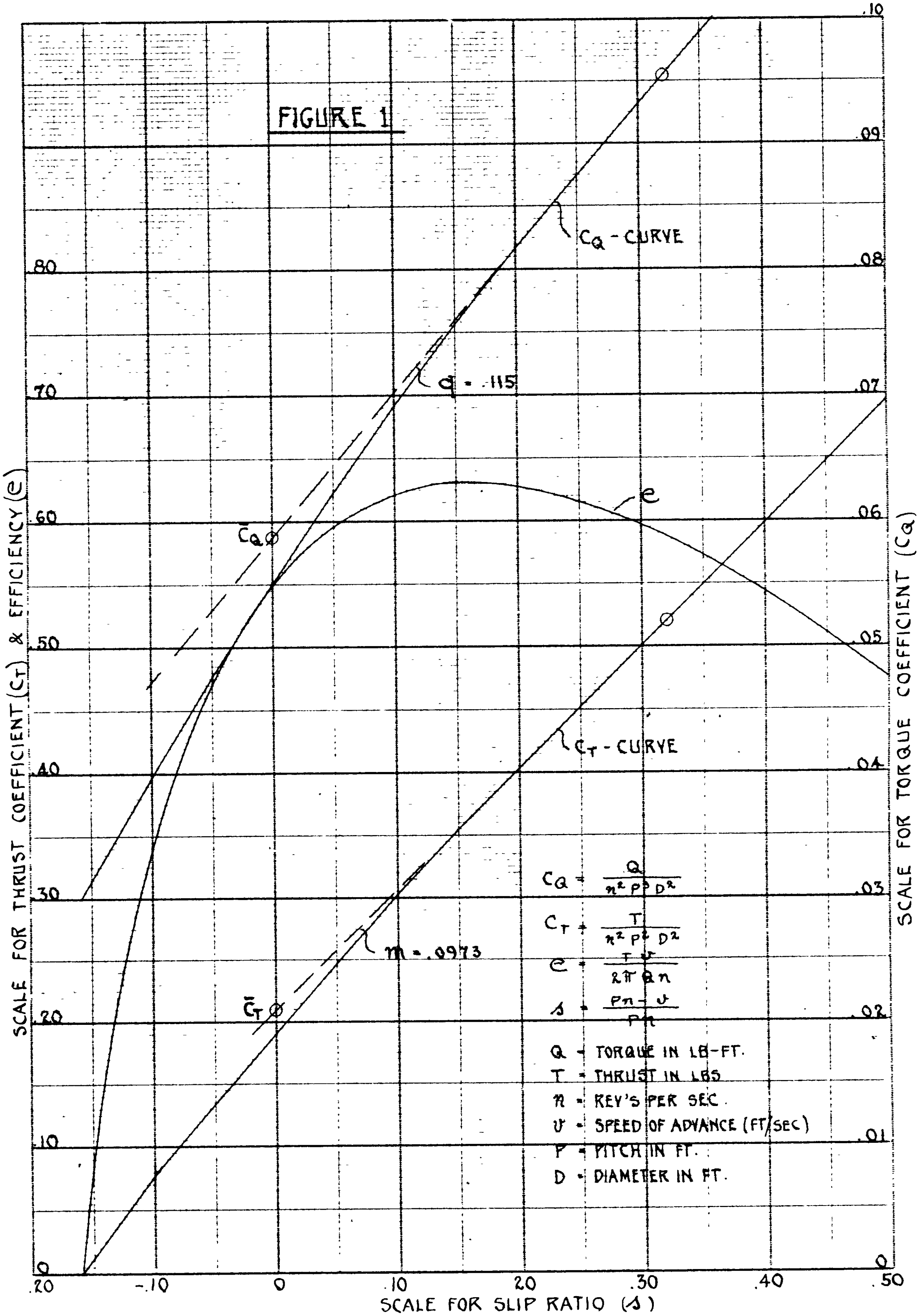

FIGURE 1
C_Q - CURVE
q = .115
e
C_Q
C_T - CURVE
m = .0973
$\bar{C}_T$
$C_Q = \frac{Q}{n^2 P^3 D^2}$
$C_T = \frac{T}{n^2 P^2 D^2}$
$e = \frac{T v}{2\pi Q n}$
$s = \frac{Pn - v}{Pn}$
Q = TORQUE IN LB-FT.
T = THRUST IN LBS
n = REV'S PER SEC
v = SPEED OF ADVANCE (FT/SEC)
P = PITCH IN FT.
D = DIAMETER IN FT.
SCALE FOR THRUST COEFFICIENT (C_T) & EFFICIENCY (e)
SCALE FOR TORQUE COEFFICIENT (C_Q)
SCALE FOR SLIP RATIO (s)
.20 -.10 0 .10 .20 .30 .40 .50
0 .10 .20 .30 .40 .50 .60 .70 .80
0 .01 .02 .03 .04 .05 .06 .07 .08 .09 .10

FIGURE 2

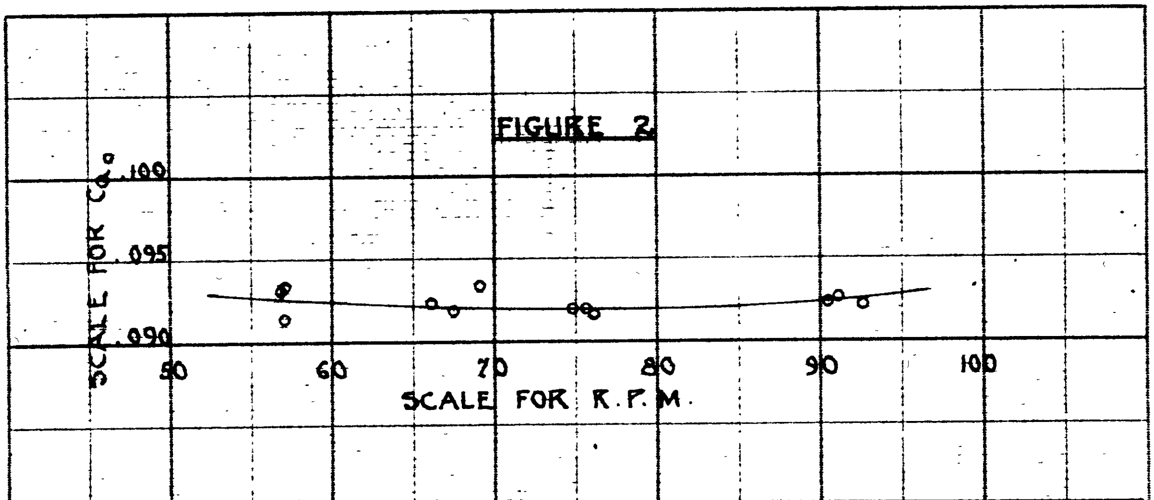

FIGURE 3

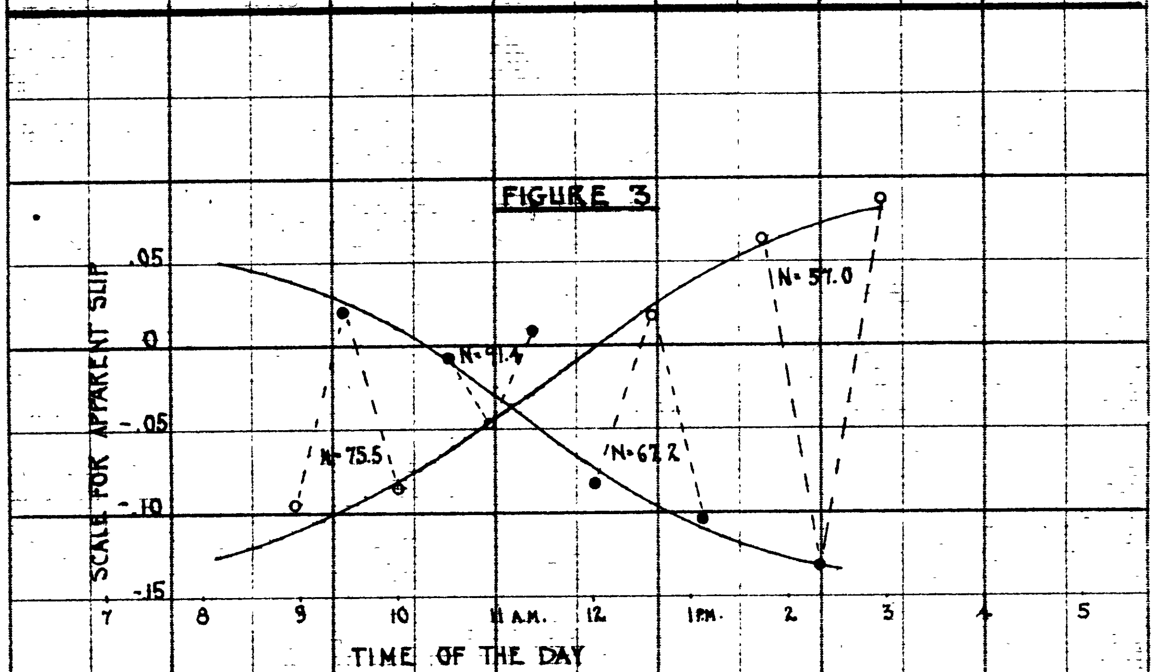

FIGURE 4