A Steady State Control Program to Minimise Fuel Consumption for a Vessel Using a Controllable Pitch Propeller

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NOTE ON REPORT

This study was undertaken by G.A. Webb B.Sc. as part of his M.Sc degree course in Marine Engineering at the University of Newcastle upon Tyne.

The Sea Fish Industry Authority commissioned Mr. Webb to undertake this study as part of its Research and Development programme contracted by the Ministry of Agriculture Fisheries and Food.

This report forms part of the Ministry contract to study the possible use of microprocessor control of propeller pitch and engine speed in order to reduce fuel consumption.

A STEADY STATE CONTROL PROGRAM TO MINIMISE FUEL CONSUMPTION FOR A VESSEL USING A CONTROLLABLE PITCH PROPELLER

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This thesis is submitted as a constituent part towards an M.Sc. in Marine Engineering at the University of Newcastle Upon Tyne.

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ABSTRACT

Besides the traditional advantages (such as better manoeuvrability), the controllable pitch propeller (CPP) offers the capability of improving fuel economy. This study shows how correct settings of propeller pitch and engine speed may obtain the maximum propulsive efficiency. This results in the minimum fuel flow, and the optimum settings are dependent on ship speed and required propeller thrust.

This study investigates the fuel savings possible, using an optimising steady state control system, based on a fishing vessel, the Glenugie IV.

A digital ship simulation was set up, but significant errors were produced by linear interpolation. However, a method was proposed for overcoming the lack of data provided from model CPP tests, to rectify simulation errors. The variation in fuel flow, for constant ship speed and required propeller thrust, under trawling conditions was thereby found to be about 25%.

A control program was developed and observed to satisfy various requirements, locating the optimum within 0.5%.

A control system package was thereby proposed which could have an application for a large range of ship types.

CONTENTS

NOMENCLATURE

B	breadth
BAR	blade area ratio
C_B	block coefficient
C_F	frictional resistance coefficient
C_p	prismatic coefficient
CPP	controllable pitch propeller
C_r	residual resistance coefficient
C_T	total resistance coefficient
D	depth
D_p	propeller diameter
FF	mass fuel flow
FF1	mass fuel flow at Ne1
FF2	mass fuel flow at Ne2
FF3	mass fuel flow at Ne3
FPP	fixed pitch propeller
FRP	fuel rack position fraction
IS	iteration step
J	propeller advance coefficient
J_t	propeller advance coefficient trawling
K_Q	propeller torque coefficient
K_S	average hull roughness
K_T	propeller thrust coefficient
LBP	length between perpendiculars
LOA	length overall
LWL	length of waterline
n	propeller speed rps
N_e	engine speed RPM
N_{ef}	maximum engine speed
N_e1	lower case engine search speed
N_e2	middle case or reference engine search speed
N_e3	upper case engine search speed
P	propeller pitch
P_B	brake engine power
P_C	total fuel pump capacity
P/D	pitch-diameter ratio
Q_e	engine torque

Q_{em}	maximum allowable engine torque
Q_p	propeller hydrodynamic torque
R_g	shaft speed gear reduction ratio
R_{gp}	fuel pump drive shaft gear reduction ratio
R_s	total ship resistance
R_T	required propeller thrust
S	wetted surface area
T	draught
T_a	additional resistance
t_d	thrust deduction factor
V_a	propeller speed of advance
V_s	ship speed
W_t	Taylor wake fraction
X	engine speed reduction step
Δ	displacement
ΔC_F	roughness coefficient increment
ΔR_T	propeller thrust/ship resistance difference
∇	underwater volume
η	propeller efficiency
ηh	hull efficiency
ηop	overall propulsion efficiency
ηp	quasi-propulsive efficiency
ηr	relative rotative factor
ηth	thermal efficiency
ηtr	transmission efficiency
ρ	density of sea water
ρf	density of diesel oil
ϕ	pitch angle

1. INTRODUCTION

The controllable pitch propeller, (hereon referred to as CPP) is as the name suggests, capable of altering the angle of attack, or pitch angle of the blades. This gives a tremendous flexibility to the operation of the propulsion plant, and its relative merits compared to a fixed pitch propeller (FPP) are discussed on page 4.

The CPP was first developed for sailing rigs during the mid nineteenth century, in which case it was used for auxiliary power. By the use of a blade feathering mechanism in the hub when the shaft had stopped, propeller drag was reduced when under sail.

The later development of hyraulic actuation enabled changes of propeller pitch with the shaft rotating by a servo-mechanism usually in the hub. Refinement of the servo-mechanism in terms of size, reliability and pitch setting accuracy continues, with its potential for propulsive efficiency and flexibility now having been realised [18].

Figure 1 shows the basis layout of a typical CPP system but there are many variations of the actuating mechanism. One example is where the servo-piston is mounted onboard and the pitch blades are turned by a push/pull rod inside the shaft, moving a crosshead blade turning mechanism in the hub. This system is used for the lower power installations and is commonly employed in fishing vessels. The basis principle of operation however, can be summarised as follows:-

For a new pitch demand signal from a lever on the bridge, a spool valve system is moved away from its equilibrium position by the error generated by a connected mechanical feedback on the cylinder yoke. This causes oil to flow from the oil distribution box to and from the two sides of the servo-piston. The relative exchange of oil will, of course, depend on the direction of pitch change. The piston then moves and turns the blades usually by means of a sliding pin arrangement until the mechanical feedback brings the spool valve back to equilibrium.

The control of a CPP propulsion system is basically in two forms, either a single lever or so called combinator system, or a dual lever control.

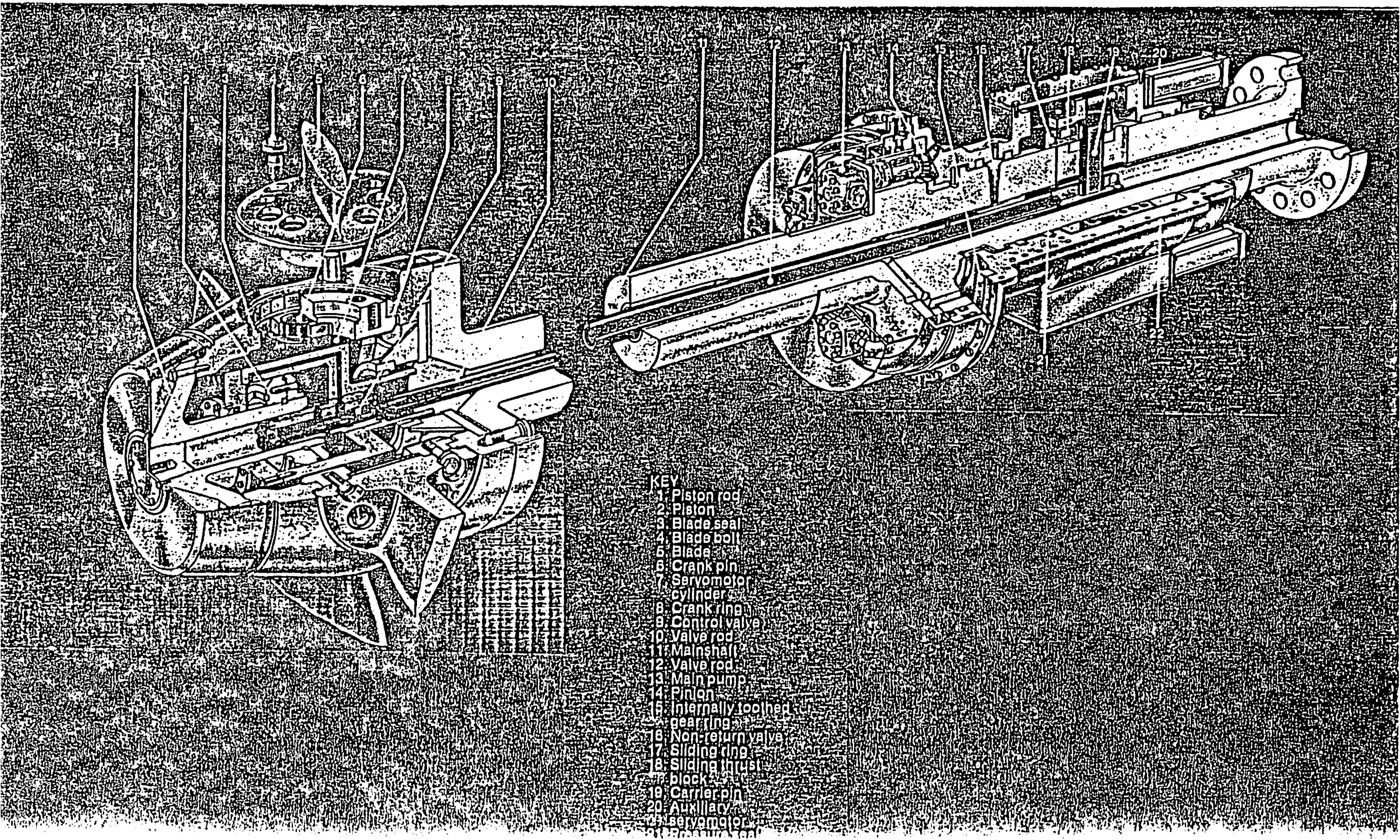


Figure 1 - A typical CPP layout

The combinator system is only applicable to ship types whose resistance characteristics do not vary excessively. These include naval craft such as frigates and destroyers, and certain merchant machinery installations. The system can work on a correlation of lever position to engine speed (N_e) and propeller pitch (P/D), or to N_e and engine torque (Q_e) [1], or to ship speed (V_s). The latter is more applicable to naval vessels where a linear relationship is obtained between V_s and lever position, and also includes control of the starting and stopping of various prime movers. Merchant vessels requiring a wide range of ship speeds usually use a N_e-P/D correlation, but sometimes a combination may be employed using a P/D-Q_e relationship at higher powers. It is also common to keep N_e constant where electrical shaft generation is additionally required, in which case only P/D may be altered.

For vessels having extreme variations in resistance, ie. due to towing such as tugs or trawlers, then a single lever system is not appropriate. This study mainly deals with the problem of employing a dual lever system for a trawler including the application of automatic controls to this. Combinator systems are also considered with the objective of improving propulsion plant efficiency. Before doing this the case for and against using a CPP as a propulsor relative to a FPP must be clarified.

1.1 ADVANTAGES OF A CPP

1. The ability to utilise the full range of engine power at any ship speed eg. high thrust and low speed of advance is required for towing vessels as well as a high free-running speed. Also, merchant ships requiring the use of very low speeds, such as for canal passages, would be restricted when using a FPP in conjunction with gas turbines or medium and high speed diesels. This is due to their relatively small engine speed operating range.

2. Increased maneouvring ability.

3. The elimination of reverse gears or the need for a reversing prime mover.

4. Rapid reversing capability of pitch gives a vessel better crash stop ability [1].

5. Free-running ship speed can be maintained with increased hull fouling [17].

6. The CPP facilitates the running of electrical service requirements of the main engine improving the specific fuel consumption for electrical generation.

7. Reduction of engine speed for adverse weather conditions may, with a FPP, result in running near or at a torsional vibration resonance point. This would require a further reduction in engine speed, thus ship speed.

8. It is possible to use a multi-engined machinery plant which may be run as a single prime mover at full ship speed, or one engine run at low ship speeds for improving specific fuel consumption. This sort of system would not be possible with a FPP. Good examples are the Type 21 and 22 frigates using a COGOG (combined gas or gas turbine) system with a CPP.

9. The overall propulsive efficiency (ηop) of the plant can be maximised under any ship speed or thrust condition [1]. Although this is true in theory, consistent realisation in practice is a fallacy as no guidance is given for a dual lever system, and a combinator system will usually have design priorities either for maximum engine efficiency or a linear lever position-ship speed correlation.

10. It is amenable to integration into unmanned machinery spaces.

11. Blades can usually be easily removed for reconditioning without having to spit the hub, ie. the blades are bolted to their trunnions.

Less cylinder liner wear is sometimes quoted as an advantage [1], due to avoidance of the thermal effects caused by cold air restarting for reversing using a FPP. However, Bille [19] found no evidence of this.

1.2 DISADVANTAGES OF A CPP

There are two main disadvantages that bias ship owners against fitting a CPP:-

1. The higher initial cost of the installation as compared to a FPP [1].

2. The complicated mechanism has in the past been prone to reliability problems but are such today as to approach the FPP in maintenance costs. Even in 1970 Bille [19] estimates reliability at 85% for five years with nearly half of these 'failures' being due to normal blade damage.

3. Operation at high constant engine speed for electrical generation purposes can lead to severe cavitation damage and high fuel consumption [15].

4. Some types of CPP require splitting of the hub for blade removal.

5. Some types of CPP, eg. Newage are not fully reversing thus increasing the system cost with the inclusion of a reversing gearbox [9].

6. Regarding performance at design conditions, the CPP is about 2% less efficient due to a larger boss diameter and blade thickness. When designing for a large power unit, the CPP can be designed to initially obtain maximum propeller and engine efficiency for the new ship condition. However, the FPP design point is normally increased by 3 to 6 per cent from maximum engine efficiency to allow for over torque sea conditions. This results in the η_{op} for both types of propeller being about the same; thus writing off the CP propeller's reduced efficiency [17].

7. Blade spindle torque and pitch setting accuracy problems have occured, but have now generally been rectified [1].

The advantages listed 1 to 7 are what can be termed the 'traditional' arguments for adopting a CPP, 8 and 10 are highlighted as the more 'recent' developments to which a CPP has shown its worth. The ability to achieve maximum overall propulsive efficiency (ηop) has been, and still is a confused area of understanding.

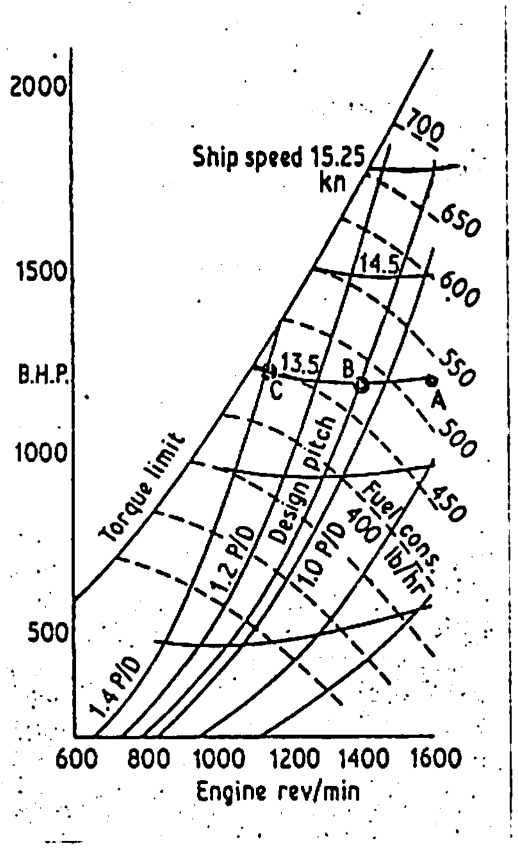
The confusion stems from the naval architect's view of ηop being maximum propeller efficiency (ηp) and the marine engineer's being maximum engine thermal efficiency (ηth).. An example is the designing of combinator systems to work through a line of maximum ηth. The optimum settings for ηop is where the product of ηth and ηp is a maximum and fuel flow a minimum. This will be unique being dependent on ship speed (V_S) and required propeller thrust (R_T).

As a ship ages then the engine and propeller performance will degrade and the ship hull will roughen, thereby increasing resistance and wake. For a given ship V_S the optimum settings will therefore change with time. For merchant vessels the nearest combinator program to achieve ηop from theory is a Q_e-N_e correlation given by Schanz [1], but is inaccurate, deviating from the optimums and not applicable for variations in R_T with time.

From this it can be seen that a more complex interactive control system is required for optimising fuel flow.

Figure 2 [7] shows an example of the fuel savings possible at 13.5 knots being 15% from best to worst settings (point C and A respectively) and 6.5% from design P/D to optimum (point C to B respectively).

Figure 2 - Performance Curves Showing the Variation of Fuel Flow for Constant Ship Speed [7].



From this, some idea of the penalties in fuel consumption from running at constant maximum N_e may be obtained. There is also a greater chance of severe cavitation damage, although Ono and Yashida [16] carried out model propeller tests aimed at reducing this problem. However, their paper failed to mention how propeller efficiency would be reduced by allowing greater margins for cavitation. Neither did it state how savings in fuel consumption by using off-main engine electric generation, compare to an increased fuel flow operating at maximum N_e.

Now that fuel costs have risen to typically 50% of the operating costs of a ship, marine engineers and naval architects are continually researching means of reducing costs. This study encompasses both disciplines and shows how the CPP may be used to improve fuel consumption from present practises.

The study uses a fishing vessel, the Glenugie IV, to exemplify how an optimising steady-state control program may achieve minimum fuel consumption for a particular operation. The project was carried out on a Columbia Data Products, dual disc drive personal computer programming in Microsoft Basic, and programs are provided in Appendix 4. A ship simulation was produced but found to give poor results due to a lack of complete data, but suggestions for correcting this are produced in the discussion. However, the control program was found to perform well and a control system package is suggested. The system is so designed as to find the optimum operating settings for any condition of ship or propulsion plant, and it is considered to have a wide application in the shipping world.

2. THE FISHING VESSEL SIMULATION MODEL

A steady-state computer ship model was required for the following reasons:-

1. To determine the variation in fuel flow for constant V_s and R_T by changing N_e and P/D.
2. To give an overall view of the interactive performance of ship, engine and propeller.
3. To determine optimum settings of N_e and P/D, for a V_s and R_T.
4. To form an integral part of the control program (see section 3).
5. To test the control program's search capability within the constraints of the propulsion plant.

A study fishing vessel was chosen, the Glenugie IV, and the simulation was based as far as possible on its specification.

The ship speed-resistance characteristic was derived using model data [10] and was simulated by a subroutine in the main program. Engine performance was simulated using provided data from the manufacturer (Figure 33, Appendix 1). Propeller performance simulation used open water model data in the form of K_T-J and K_Q-J diagrams (Figures 31 & 32, Appendix 1). These were adapted for the behind ship condition by simulating wake and thrust deduction fractions with ship speed.

The philisophy of the simulation was that for a particular V_s, ship resistance could be augumented to model the effects of trawling, weather etc. and are inputed at the start of the program. In order to determine the full working range, N_e was initially set at maximum and then stepwise reduced by an inputed amount. Comprehensive propulsion plant performance data is then displayed for overy iteration step. Once a constraint of maximum P/D, maximum Q_e or minimum N_e is met, then the program is stopped and ready for a new set of operating conditions.

2.1 STUDY VESSEL SPECIFICATION

This project was based on the M.F.V. Glenugie IV, a 24 m L.B.P. Seiner/Trawler built by Mctay Marine Limited, working from Peterhead, Scotland. Built in 1980 she is a good example of the modern, legislation constrained design (after the Fishing Vessels (Safety Provision) Rules, 1975) of a dual fishing role vessel.
Glenugie IV was used in this study due to the possession of the following properties:-

1. A modern efficient propulsion system incorporating a medium speed turbocharged main engine driving a CPP.

2. Her trawling mode requiring high propeller thrust at low speeds of advance.

3. The availability of comprehensive engine performance data.

Vessel Dimensions [8]

Length overall : 26.09 m
Registered length : 24.00 m
Beam : 7.66 m
Depth : 4.30 m

As a more detailed specification was not made available the following dimensions have been approximated.

Draft amidships = 0.75 x D = 3.23 m
Length of waterline = 1.05 x LPP = 25.2 m
Block coefficient = 0.55 (assumed)
Prismatic coefficient = 0.60 (assumed)
Full displacement = $C_B \times LPP \times B \times T \times \rho$
$= 0.55 \times 24 \times 7.66 \times 3.23 \times 1.025$
$= 335$ tonnes

where $\rho =$ density of sea water $kg/m^3 \times 10^{-3}$

2.1.1 Ship Performance Simulation

This was possible using model data [2] for determination of residual resistance coefficient (C_r) (Appendix 3, Table 3.1). Frictional resistance coefficient (C_F) was determined by using the I.T.T.C. 1957 formula plus a roughness allowance (ΔC_F) [10]. Additional resistances; mainly here due to trawling but could include added weather resistance, hull fouling, increased displacement etc; are inputed by the user at the start of the simulation and added to the normal ship resistance at that speed.

2.1.1.1 Calculation of total ship resistance (R_s)

1. Residual resistance coefficient (C_r)

The modern fishing vessel has developed into a length constrained design, with a trend towards higher engine powers for towing larger nets and thus facilitating a larger catch, which in turn, results in a requirement for a larger fish hold space. This has evolved the fishing vessel into a very large displacement-length ratio design and in order to use the model data [2], data values had to be extrapolated above the maximum given in the paper.

Table 3.1 gives the values of C_r against V_s, these are stored in a data file and C_r found for a particular V_s using a two-dimensional linear interpolation subroutine.

2. Frictional resistance coefficient (C_F)

The I.T.T.C (1957) frictional resistance correlation line is given by the formula:-

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2}$$

where R_n = Reynolds number

$$= \frac{\rho \times V_s \times LPP}{\nu}$$

ν = viscosity of sea water at 10°C

$\nu = 1.354 \times 10^{-6}\ m^2\ s^{-1}$

Allowance for hull roughness (ΔC_F) is by the modified I.T.T.C. formula:-

$$\Delta C_F = \frac{2}{3}\left[105\left(\frac{K_s}{LWL}\right)^{1/3} - 0.64\right] \times 10^{-3} \qquad [10]$$

K_s = average hull roughness

$\approx 200\mu m$ for an in-service ship

LWL = length of waterline

$\approx 1.05 \times LPP = 25.2$ m

thus $\Delta C_F = 1.33 \times 10^{-4}$

Total frictional resistance ie. $C_F + \Delta C_F$ was increased by 5% to allow for the hull damage inherent on fishing vessels due to the fishing operations.

3. <u>Total ship resistance</u>

Now $C_T = C_F + \Delta C_F + C_r$

and $C_T = \dfrac{R_s}{1/_2\rho.S.V_s^2}$

thus $R_s = 1/_2.C_T.\rho.\ S.\ V_s^2\ (+ T_a)$

where

C_T = total resistance coefficient

S = wetted surface area (m^2)

T_a = additional resistance (kN) eg. trawl load

S = LWL (C_B. B + 1.7 T) (Denny's formula)

thus $S = 25.2\ (0.55 \times 7.66 + 1.7 \times 3.23)$

$S = 244.5\ m^2$

The calculated ship resistance must now be increased by 10% for appendage resistance. Using these calculated resistance figures in adapting a new propeller (see 2.3) it was found that the resistance was too low and increased again by 10% to give a more realistic free-running speed (11.5 knots) so for V_s in knots.

$$R_s = {V_s}^2 \times C_T \times 34.86897 \times 1.2 + T_a$$

where T_a is inputed at the start of the program. Figure 3 shows the produced variation of R_s with V_s.

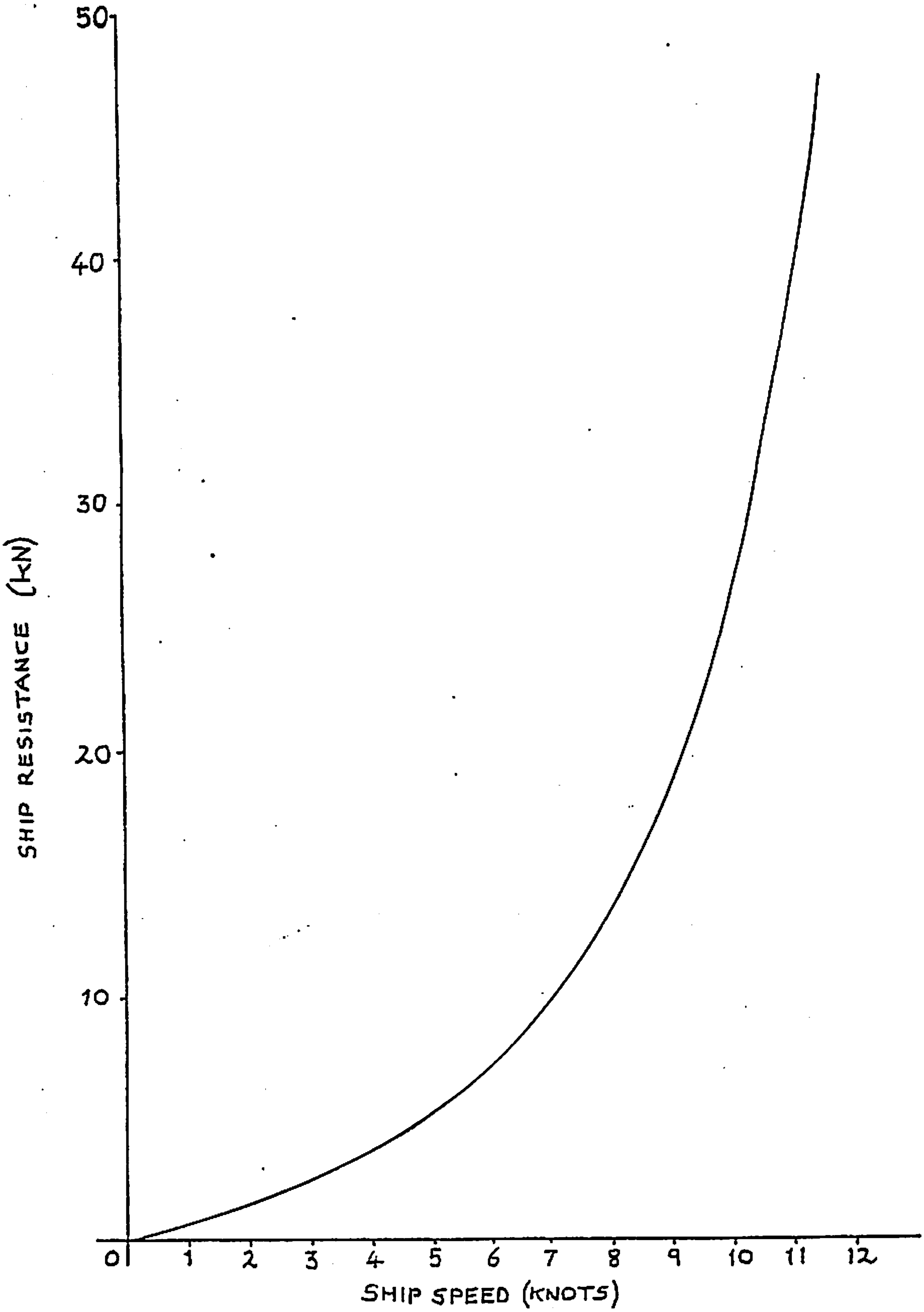
2.2 MAIN ENGINE SPECIFICATION

The main engine installed on the Glenugie IV is a Mirrlees Blackstone ESL6M Mark II air starting, turbocharged diesel. This is a four-stroke, medium speed, six cylinder in-line arrangement derated from 1000 BHP to 720 BHP at 790 RPM.

2.2.1 Main Engine Performance Simulation

This was possible using the engine operating data of fuel consumption for various engine powers and RPM, as supplied by the manufacturer

FIGURE 3 - SHIP SPEED VERSUS SHIP RESISTANCE



(Figure 33, Appendix 1). The viable operating 'envelope' of the engine was given by the supplied Lloyd's rules:-

Continuous ratings of diesel engines for marine propulsion use up to Lloyds unrestricted service conditions

No intermittent overload ratings are permitted. All engines are suitable for variable speed operation down to a minimum speed of 250 RPM. Maximum torque available is constant down to 60% of the full rated speed. At lower speeds maximum torque is decreased accordingly to a propeller type law.

ie. if continuous rating BHP = p

Full speed RPM = N_{ef}

RPM being considered = N_e

Maximum allowable torque = Q_{em}

Maximum allowable BHP = P

Between $0.6\ N_f$ and N_{ef}, $$Q_{em} = \frac{726.2.P}{N_{ef}} \text{ kgm} \qquad \text{—— (1)}$$

Between 250 RPM and $0.6\ N_{ef}$, $$Q_{em} = \frac{2017.P.N_e^2}{N_{ef}^3} \text{ kgm}$$

Between $0.6\ N_{ef}$ and N_{ef}, $$p = \frac{N_e.P}{N_{ef}}$$

Between 250 RPM and $0.6\ N_{ef}$, $$p = 2.778.P\left(\frac{N_e}{N_{ef}}\right)^3$$

The lower RPM limit for AC generation from the main engine is usually $0.6\ N_f$ [6] and is assumed the lower RPM limit. This results in a range of 475 to 790 RPM with a constant maximum torque of:-

$$Q_{em} = \frac{726.2 \times 720}{790} \qquad \text{(using equation (1))}$$

$$= 661.85 \text{ kgm}$$

$$= 661.85 \times 9.81 \times 10^{-3}$$

$$= 6.493 \text{ kNm}$$

Disallowed regions of RPM due to torsional vibration, and the consequent effects of constant and/or intermittent auxiliary power take-offs have not been considered in this study (see 5.2.1 for discussion).

Engine brake thermal efficiency (ηth) was calculated by use of the following equation:-

$$\eta th = \frac{P_B \times 3600}{LCV \times FF}$$

where P_B = brake engine power (kW)

LCV = lower calorific value (kJ/kg)

= 43250 kJ/kg for normal diesel oil

FF = mass fuel flow (kg/hr).

2.3 CPP SPECIFICATION

The Glenugie IV uses a Liaaen CPP driven through a 2.5:1 reduction gearbox. The following data was supplied by the manufacturer:-

3 blades
Diameter : 2 m
BAR : 0.425
Design P/D : 0.75
Full propeller RPM : 316
Average Taylor wake fraction : 0.23
Free-running speed : 10.5 knots

No compatible CPP performance data was available and it was felt that adapting FP propeller data would not give a representative model, for the purposes of this project. This is due to the 'unique' performance characteristics of CP propellers due to their changing radial pitch distributions with blade angle, resulting in lower efficiencies at off design pitch relative to FP propellers.

It was therefore decided to use model CPP data of a similar blade area ratio (BAR) and design P/D (the different blade number is not significant), made available by the University of Newcastle Upon Tyne Cavitation Tunnel [11]. The model design was for a fishing vessel designed by Stone Manganese Marine Limited, and is as follows:-

4 blades
BAR : 0.472
Design P/D : 0.80

In order to use this propeller design for the prime mover and transmission considered in this study an iteration had to be implemented. For the considered power unit and the associated propeller design it can be said:-

$$P + D_p = k$$

where

P = propeller pitch

D_p = propeller diameter

So since the model CPP uses a higher P/D then the full scale diameter must be reduced. In order to find the consequential diameter to absorb full engine power at full shaft RPM, ship speed was iterated for a particuar diameter to absorb full engine power power at P/D = 0.80. If the full RPM is not met or exceeded, diameter must be altered and speed iterated again.

The following specification was realised for the project CPP:-

4 blades
Diameter : 1.875 m
BAR : 0.472 m
Design P/D : 0.80
Full propeller RPM : 316
Average Taylor wake fraction
(see 2.3.1.1) : 0.22
Free-running speed : 11.458 knots

2.3.1 Propeller Performance Simulation

2.3.1.1 Open water model propeller performance data

The cavitation tunnel performance charts used [11] were in the form of K_T-J and K_Q-J for selected pitch angles (Figures 13 & 14, Appendix 1) where

$$\text{Thrust coefficient } K_T = \frac{R_T}{\rho n^2 D_p^4}$$

$$\text{Torque coefficient } K_Q = \frac{Q}{\rho n^2 D_p^5}$$

$$\text{Advance coefficient } J = \frac{V_a}{nD_p}$$

n = propeller rps

R_T = required propeller thrust (N)

Q_p = hydrodynamic torque (Nm)

V_a = propeller speed of advance (ms^{-1})

= $V_s(1-W_t)$

W_t = Taylor wake fraction (= 0 for open water)

Pitch angles were converted to pitch-diameter ratios for scaling and convenience.

where

$P = 2\pi r \tan\phi$

P = propeller pitch

r = radius of pitch action ($0.7D_p/2$)

ϕ = pitch angle

thus $P/D = \pi \times 0.7 \times \tan\phi$

at design pitch, $\phi = 20^\circ$

therefore $P/D = \pi \times 0.7 \times \tan 20^\circ$

$P/D = 0.800$

The lowest value of J used in the charts was 0.3, but for low speeds of advance ie, trawling, values will be below this (from about 0.075 to 0.3). It was therefore necessary to extrapolate the pitch curves back to the lowest J value. Also as only four ahead pitches were given (plus a past design pitch), it was found that linear interpolation between these gave distorted results. This was because of the non-linearity of the intermediate pitch variations with K_T and J, and K_Q and J. Therefore, due to the lack of data, P/D was plotted against K_T and K_Q, for values of constant J (Figures 34 & 35, Appendix 2). For selected intermediate pitches, J and K_T (see Tables 3.3 & 3.4) data were rationally extracted and formed into two main three-dimensional matrixes of P/D for various J and K_T, and K_Q for various J and P/D respectively.

2.3.1.2 Correcting data for the 'in-service' condition

There are four main correction factors

1. Taylor wake fraction (W_t)
2. Thrust deduction factor (t_d)
3. Transmission efficiency (ηtr)
4. Relative rotative factor (ηr)

The (Taylor) wake fraction is due to the induced velocity of water flowing into the propeller by the hull. This can be said to be generally dependent on Froude number, hull form factors and propeller aperture. Usually in propeller design a fixed value is applicable but for this study a velocity dependent value (ie. Froude number) was desirable. Lackenby and Parker [4] produced a regression analysis equation for wake fraction from standard series data:-

$$W_t = -0.8715 + 2.490 \times C_B - 1.475 \times C_B{}^2 - 0.3722 \times \frac{V_s.C_B}{\sqrt{L}}$$

$$+ 0.2525 \left(\frac{V_s.C_B}{\sqrt{L}} \right)^2 + 0.2260 \times C_B \times D_w$$

V_s = ship speed (knots)

L = LBP (feet)

C_B = block coefficient

$$D_w = \frac{B}{\nabla^{1/3}} \sqrt{\frac{\nabla^{1/3}}{D_p}}$$

where

B = breadth

∇ = underwater volume

$\nabla = \text{LBP.B.T.}C_B = 326.6\text{m}^3$

D_p = propeller diameter

so $D_w = 2.10$

and $$W_t = 0.30837 - 0.023073 \times V_s + 9.7029 \times 10^{-4} \times V_s^2 \quad (V_s \text{ in knots}) - (2)$$

This gives an average wake fraction of 0.22 which also agrees with the thrust deduction fraction recommended by O'Brien [5]. So it was decided to take a constant hull efficiency of one

ie. $$\eta h = \frac{1 - t_d}{1 - W_t} \qquad \text{where} \qquad W_t = t_d$$

The transmission efficiency (ηtr) is taken constant at 98%.

The relative rotative factor (ηr) is considered as being constant at unity.

The behind propeller efficiency or quasi-propulsive coefficient ηp is defined as

$$\eta p = \frac{R_T . V_a}{P_B} \times \eta r \times \eta h$$

where

R_T = propeller thrust

since

$$\eta r = \eta h = 1$$

here $\eta p = \frac{R_T . V_a}{P_B}$

2.3.1.3 The method of employent of equation in the propeller simulation

For a considered N_e, V_s, and T_a the propeller is simulated as follows:-

$$V_a = V_s (1-W_t)$$

$$n = \frac{N_e}{R_g . 60} \qquad (R_g = \text{gearbox reduction})$$

$$R_T = \frac{R_s + T_a}{(1-t_d)}$$

thus $J = \frac{V_a}{n.D_p}$ and $K_T = \frac{R_T}{\rho.n^2.D_p^4}$, and from these

P/D is interpolated, from J and P/D, K_Q is found and referred up to the shaft to the engine:-

$$Q_e = K_Q . \rho . n^2 . D_p^5 . 1.02/R_g$$

2.4 SIMULATION ALGORITHM (see Appendix 4 for program)

2.4.1 Description

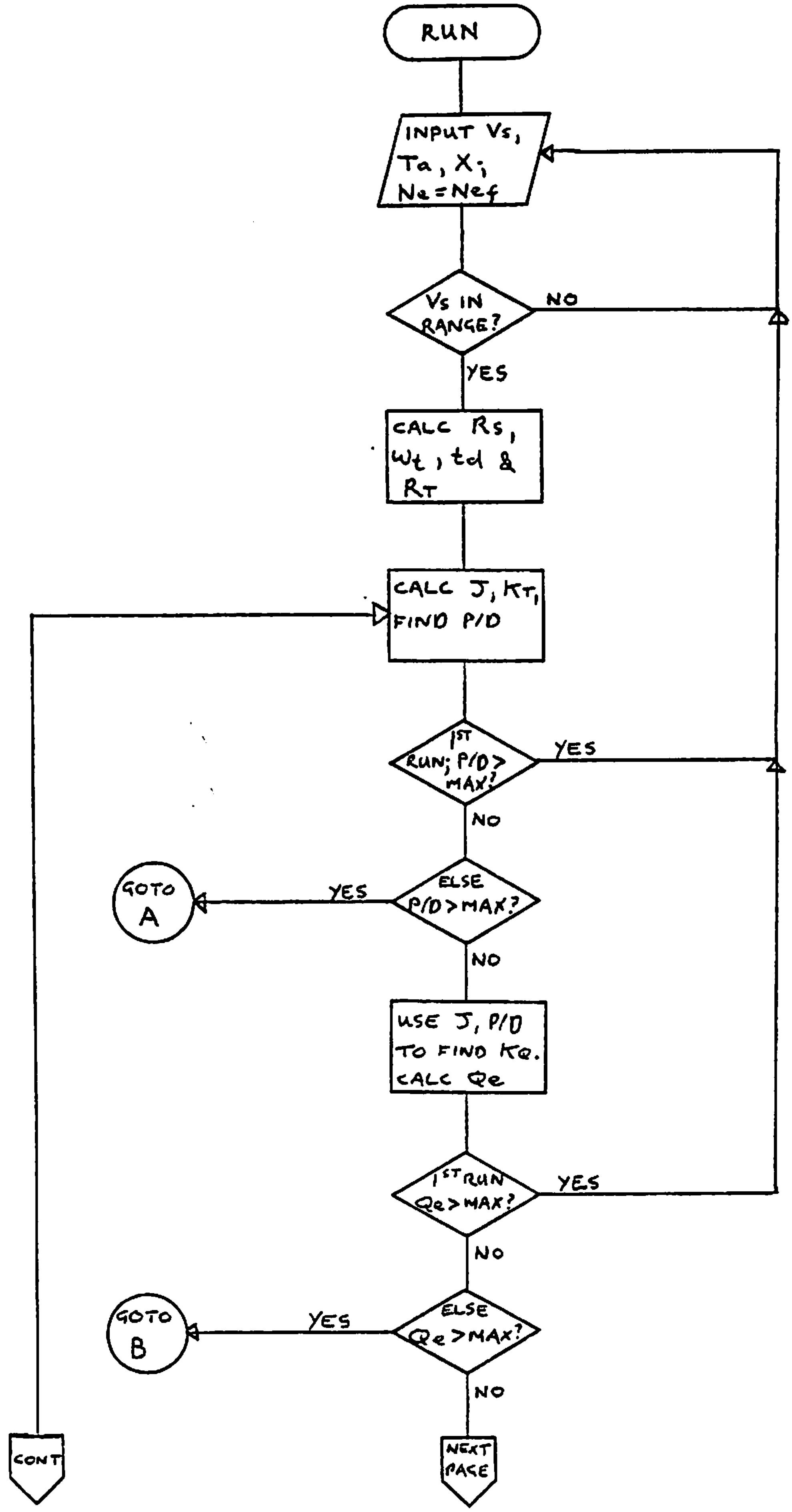
N_e is initially set at full RPM, V_s and T_a are inputed. V_s, W_t and t_d are calculated from equation (2) and R_s is also evaluated from V_s and R_T found. The propeller simulation starts (2.3.1.3) finding P/D from the K_T-J chart and K_Q from the K_Q-P/D-J data. Referring the hydrodynamic torque to the engine, the engine power (P_B) is calculated, and from P_B and N_e the mass fuel flow (FF) is found.

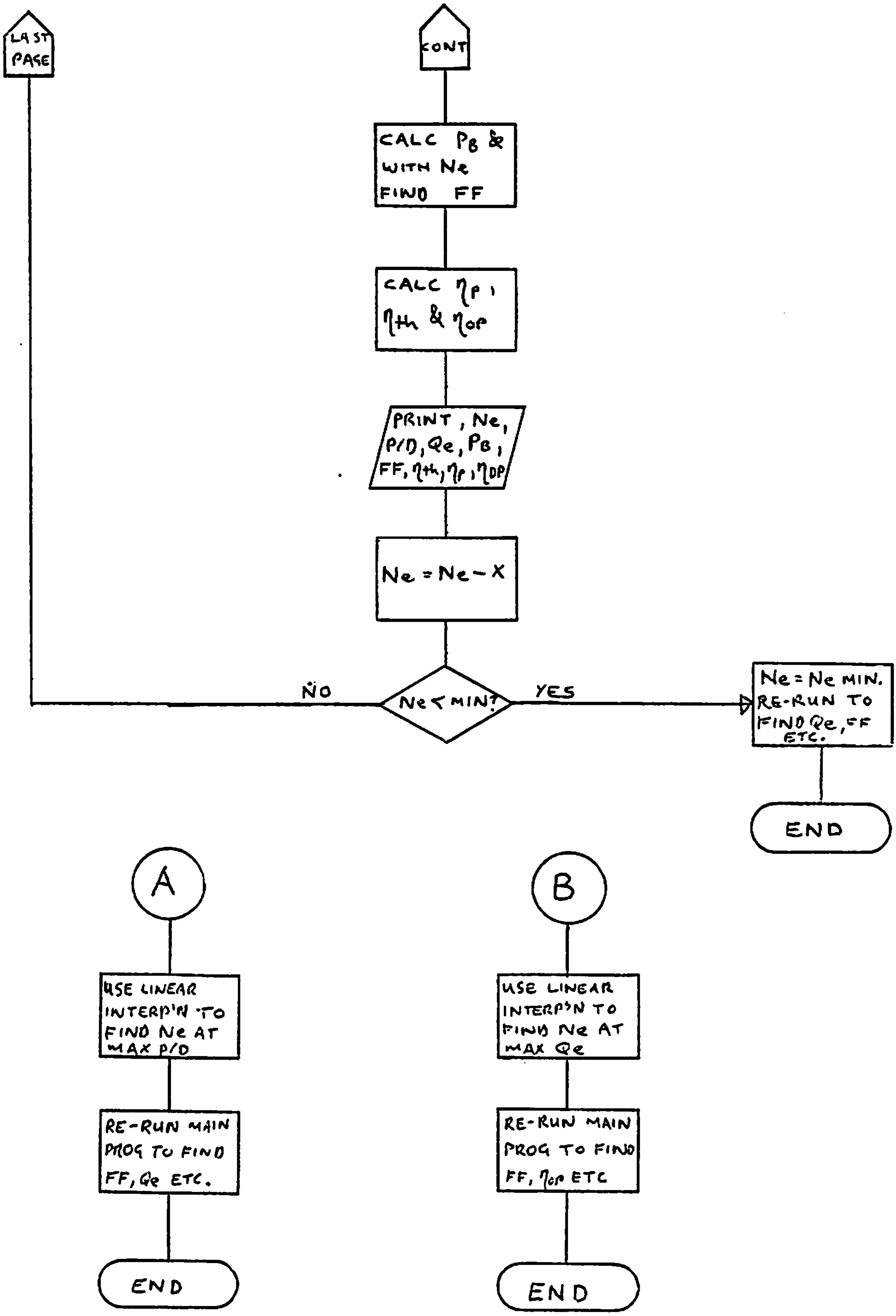
Finally, ηth, ηp, and overall propulsive efficienty (ηop = ηth x ηp) is calculated and N_e decreased by an inputed RPM increment (X). This continues until maximum engine torque or propeller pitch is encountered. The simulation was then run for constant V_s and varying T_a over the working range for towing and free-running. This then provides a reference of ship/propulsion plant limits and performance at the various working conditions (see 4.1).

The next stage was to use the model to determine the optimum settings of N_e and P/D for a particular R_T and V_s. The ship-speed resistance routine and additional resistance input were deleted and the inputs now become V_s, R_T and N_e. The program was then altered into a stepwise minimisation (of FF) program with rationalised values of the lower and upper case R_T, and near optimum N_e taken from the simulation runs. As N_e was incremented by one for accuracy, the latter was of use in keeping the program running time down. R_T was incremented by 5 kN from the lowest value and a three-dimensional matrix of optimum P/D and N_e for V_s and K_T was constructed (Table 3.6, Appendix 3).

FIGURE 4 - FLOW CHART FOR THE SHIP SIMULATION

(See Appendix 4 for program listing)




LAST PAGE
CONT
CALC PB & WITH Ne FIND FF
CALC ηP, ηth & ηOP
PRINT, Ne, P/D, Qe, PB, FF, ηth, ηP, ηOP
Ne = Ne − X
Ne < MIN?
NO
YES
Ne = Ne MIN. RE-RUN TO FIND Qe, FF ETC.
END
A
USE LINEAR INTERP'N TO FIND Ne AT MAX P/D
RE-RUN MAIN PROG TO FIND FF, Qe ETC.
END
B
USE LINEAR INTERP'N TO FIND Ne AT MAX Qe
RE-RUN MAIN PROG TO FIND FF, ηOP ETC
END

3. THE CONTROL SYSTEM PROGRAM

The objective of the control system is to minimise fuel flow (FF) at the required ship speed (V_s), and under the prevailing operational and environmental conditions. The required ship speed (V_s) would be the operating V_s manually set the skipper. In order for the system to define the operating conditions, various monitoring inputs wuld be required.

The system was designed as to require a minimum of monitoring inputs, and includes:

1. Ship speed (V_s)
2. Engine speed (N_e)
3. Propeller pitch (P/D)
4. Fuel flow (FF)

From these, the system uses an inherent ship simulation to determine the appropriate engine speed (N_e) and propeller pitches (P/D) in an iteration search to find the optimum settings.

The control system program works on the principle of maintaining the required ship speed with a calculated, constant required propeller thrust (R_T). N_e and P/D are automatically set outputs from the system.

The control program was designed under a number of basic assumptions and considerations, and these are defined in the next section.

3.1 PROGRAM CONSIDERATIONS AND BASIC SPECIFICATION ASSUMPTIONS

Assumptions

(i) A two lever system is used.

(ii) All inputs are accurately monitored and outputs are correctly set.

(iii) The control program ship model represents the 'real' ship.

(iv) There are no disallowed regions due to torsional vibration or excessive propeller cavitation.

(v) The prime mover is considered as a unit with no power-take-offs (although minimum RPM is defined as for the lowest value compatible with continuous AC power generation).

(vi) The system is valid for steady-state operation only, with dynamic considerations accounted for by time lags as discussed later (5.2.1).

(vii) The function relating engine speed (N_e) to fuel flow (FF) is an unimodal 'dipped' relationship for constant ship speed (V_s) and constant required propeller thrust (R_T).

(viii) For constant V_s there is no variation in wake and thrust deduction fractions (W_t and t_d respectively) with pitch and loading.

Requirements

(i) The control program must be able to find the minimum operating condition with the minimum number of iterations.

(ii) For an 'on-board' system, the program must be able to minimise with constant ship speed, allowing for discontinuities between the control program ship model and real system performance.

(iii) The minimum of monitoring equipment is desired for financial viability of the system. The system does however require an accurate shaft speed counter, pitch indicator, fuel rack position indicator and ship speed log.

(iv) The system must not operate outside the allowable operation region of the engine, ie. maximum torque, minimum and maximum engine RPM. (These constraints plus maximum pitch must also be simulated in the model).

Basic Specification

The control program will be implemented by an on-board computer, programmed in a high-level language eg. Fortran (or assembler if speed of processing is critical). Analogue to digital converters will be used to convert the inputs from:-

(i) A photo-electric tachometer (probably acting off the engine flywheel).

(ii) An accurate and regularly maintained ship speed log eg. an electromagnetic or pitometer, for measurement of speed through the water.

(iii) A pitch indicator (probably a position indicator on the yoke lever).

(iv) A fuel rack position indicator or a fuel meter for fuel consumption monitoring. The former would be used to compute fuel flow using the expression:-

$$FF = FRP . \rho_f . PC . N_e . 60/R_{gp}$$

where FRP = fuel rack position (expressed as a fraction of the volume of fuel deliverd)

ρf = density of diesel oil (kg/m^3)

PC = total capacity of fuel pump (m^3)

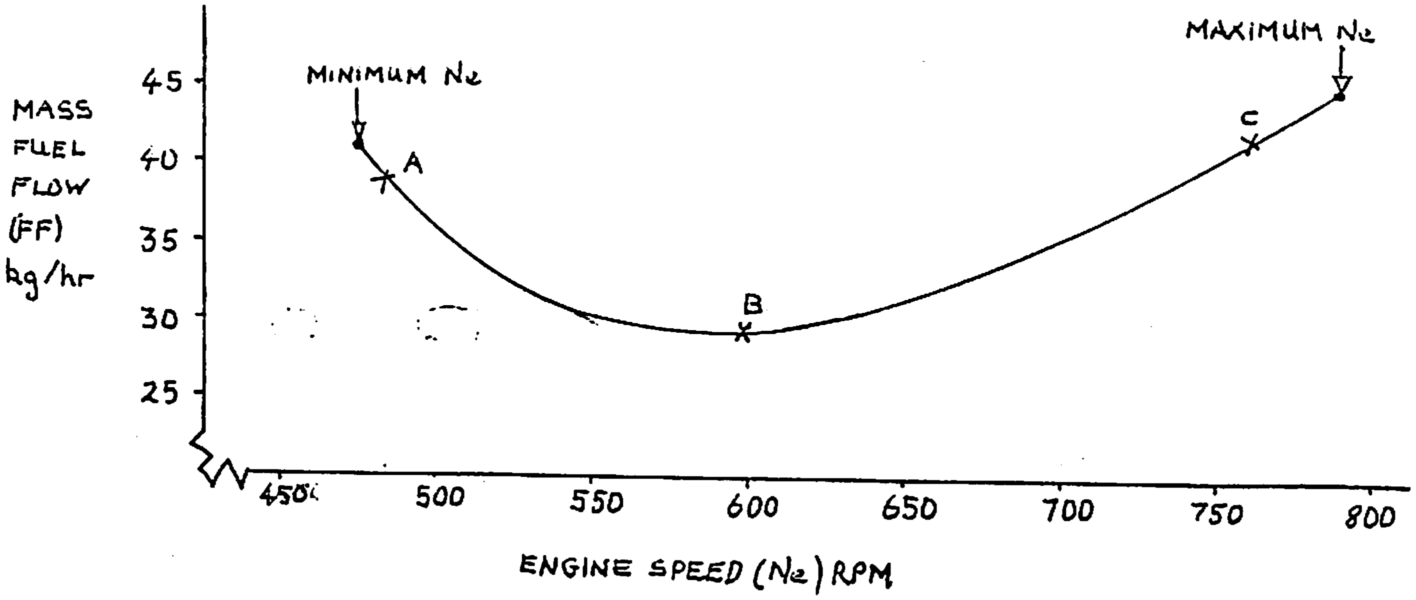
Rgp = reduction gear ratio from engine to fuel pump drive shaft

A digital to analogue converter would be used to process the outputs from the computer, thereby providing the automatic setting signals for pitch and engine RPM. For larger merchant vessels it would be possible to use the existing pneumatic and/or hydraulic actuation systems for automatic setting of demanded pitch and governor set-point. For smaller crafts, in this case fishing vessels, where pitch and engine RPM are mechanically linked to their bridge actuation levers, servo-mechanisms would have to be installed. These would probably be hydraulic (being able to fit in with the ship's hydraulic system), but would increase the capital and maintenance costs of such a system reducing its financial viability (see 5.2.1).

3.2 THE CONTROL PROGRAM ALGORITHM

The control program is basically a minimising line search method which aims to minimise fuel flow (FF) for a particular ship speed (V_s) and required propeller thrust (R_T) by simultaneously altering P/D and N_e. It can be said that in essence $N_e = f(FF)$, so that N_e is used as the search variable with the consequent P/D calculated from the ship simulation to maintain V_s at the required R_T.

Figure 5 - Fuel Flow (FF) Against Engine Speed (N_e) for V_s = 2 knots, T_a = 25 kN and R_T = 36.45 kN



3.2.1 Setting-up the Ship Initial Conditions

This stage corresponds to the skipper setting pitch and engine RPM to obtain the desired ship speed (V_s) under the prevailing operational and environmental conditions. After this, the control program would be initiated and the first stage is to identify the operating conditions from the inputs of N_e, V_s, FF and P/D. Required propeller thrust (R_T) is found by calculating W_t thus giving V_a and allowing J to be calculated, knowing P/D, K_T can now be found and R_T quantified (see figure 6).

This was simulated by using R_T, V_s and N_e as inputs to the ship model and deleting the ship speed resistance routine.

3.2.2 Detection of Position on the Fuel Flow (FF) - Engine Speed (N_e) Curve

The first reference point (N_e2) on the curve would be the theoretical optimum settings stored for the ship speed (V_s) and calculated required propeller thrust (R_T) (see 2.4.1). It must be remembered that for each iteration of N_e and P/D, a time lag must be allowed for any change in V_s (see 5.2.1) (for the purposes of this simulation, this is not implemented). N_e2 is then increased and decreased by an iteration step (IS) (10 RPM was found to be best suited to the model) to find the 'trend' in fuel flow (FF). Considering Figure 5, if the reference N_e2 was at A, then the control system must ensure that maximum torque or minimum N_e are not exceeded by decreasing N_e. At C, maximum N_e must not be exceeded by increasing N_e.

The engine speed set by the skipper will be included as an iteration point if it is within a suitable range of the derived optimum engine speed (N_e2). The range, if too large would distort the trend in fuel flow (FF) and a line fit (see 3.2.3). In this study a range with ±10 and ±20 RPM was found satisfactory.

Considering Figure 5 again; if N_e2 = point A then a decreasing fuel flow (FF) trend will be sensed with increasing engine speed (N_e). This position then starts an increasing stepwise iteration routine in the program. Here the N_e iteration step (IS) is increased by an increment on every execution of this routine, and the fuel flows compared. The increment should not be too large as to distort the trend in FF, and was here found to be 5 RPM. The iteration continues until either a constraint is met (here maximum N_e) or an increase in FF is sensed. The former implies the optimum at a constraint, and the latter that the curve inflection has been found (for the next stage see section 3.2.3).

There is a similar decreasing N_e iteration routine, if, for example, N_e2 = point C, with the constraints being minimum N_e, maximum torque and maximum P/D.

3.2.3 Quadratic Line Fit Minimisation [12]

It can be shown (see Ref. 12) that the minimum x-axis value x_m (here N_e) for a three point interpolating quadratic is:-

$$x_m = \frac{1}{4}(x_1+2x_2+x_3) - \frac{1}{4}(x_3-x_1).\frac{\{(y_2-y_1)/(x_2-x_1)+(y_3-y_2)/(x_3-x_2)\}}{\{(y_3-y_2)/(x_3-x_2)-(y_2-y_1)/(x_2-x_1)\}}$$

where x_m = N_e value of quadratic interpolated FF minimum

x_1 = lower case, $N_e(N_e1)$, x_2 = mid or reference $N_e(N_e2)$ x_3 = upper case N_e (Ne3)

y_1 = fuel flow, at N_e1(FF1), y_2 = fuel flow, at N_e2(FF2). y_3 = fuel flow at N_e3 (FF3)

If N_e2 is at or near the point of inflection, for example Figure 5, point B, then accurate minimum values will be projected by this method. If however, this method was used to project a minimum with the 3 x and y points on the curve slope, then x_m may be extrapolated out of range. Also if an iterative scheme is set-up working from a slope, then divergence from the minimum causing extreme out of range x values, may occur.

This method is only employed when at the curve inflection (ie. $FF1 > FF2$ and $FF2 < FF3$), and the resultant N_e is set and the FF compared with the last FF2. If lower the program ends, if higher N_e2 is reset and the program ended.

After the optimum settings have been found, the control program would then act as a constant ship speed device, although this could be an optional selection by the skipper who may wish to accept a loss in ship speed due to weather or trawl load. The sensitivity or gain of V_s could also be a selected parameter, with larger tolerances giving a greater margin of stability to the system to prevent 'hunting'.

3.3 THE CONTROL/SHIP PROGRAM SIMULATIONS

3.3.1 The 'Ideal' Control System Simulation

This is where the control system enters the ship simulation at the optimum settings and shows how a good theoretical - 'real' system correlaton would achieve minimum FF in the smallest number of iterations (see 4.2).

3.3.2 The Control System Testing Simulation

Here the system does not enter the ship simulation at the stored optimum settings, but the first set engine speed (N_e) (the 'pseudo minimum') is inputed by the user. This was done to test the control system's ability to cope with the various scenarios of being off and to find the optimum N_e. The minimum FF accuracy found by these searches was validated by comparing the FF obtained using the stored optimum settings.

The various search scenarios tests, and are exhibited in the results (4.3), were:-

1. Decreasing and increasing engine speed iteration searches.

2. Minimum fuel flow at a constraint.

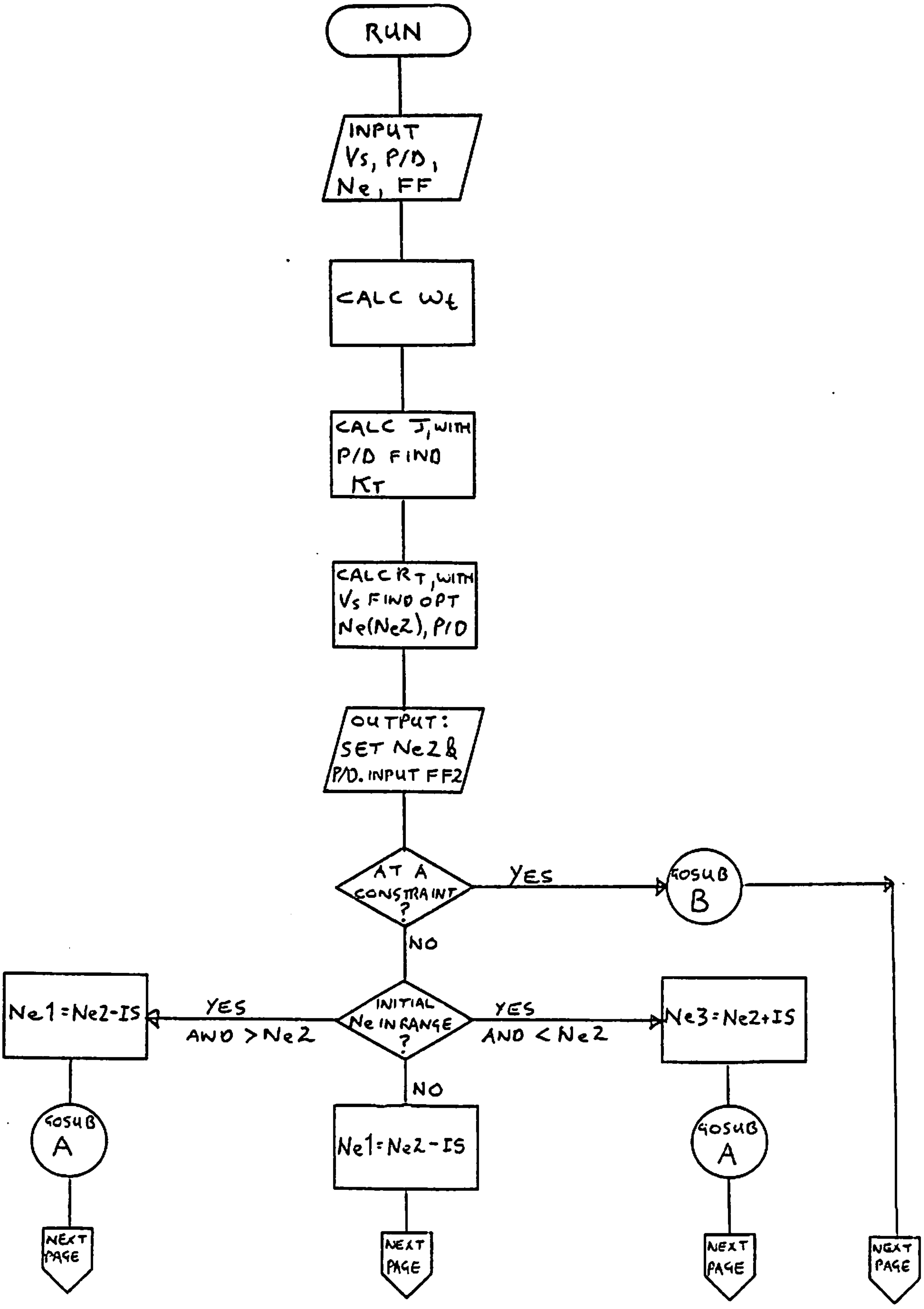
3. Quadratic line fit minimisation.

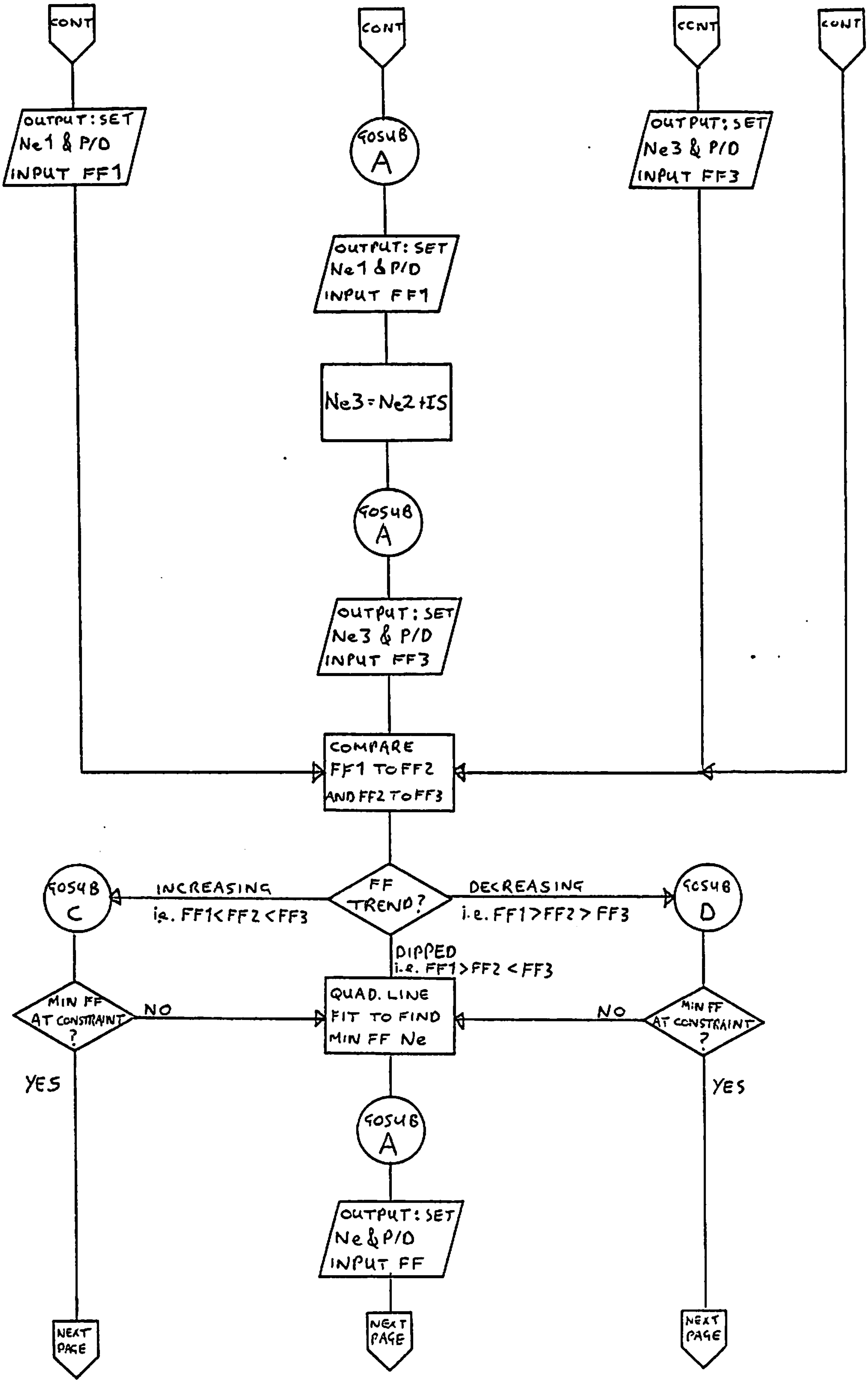
4. The control program's inability to find the minimum fuel flow with the (incorrect) N_e-FF humped function produced at free-running speeds.

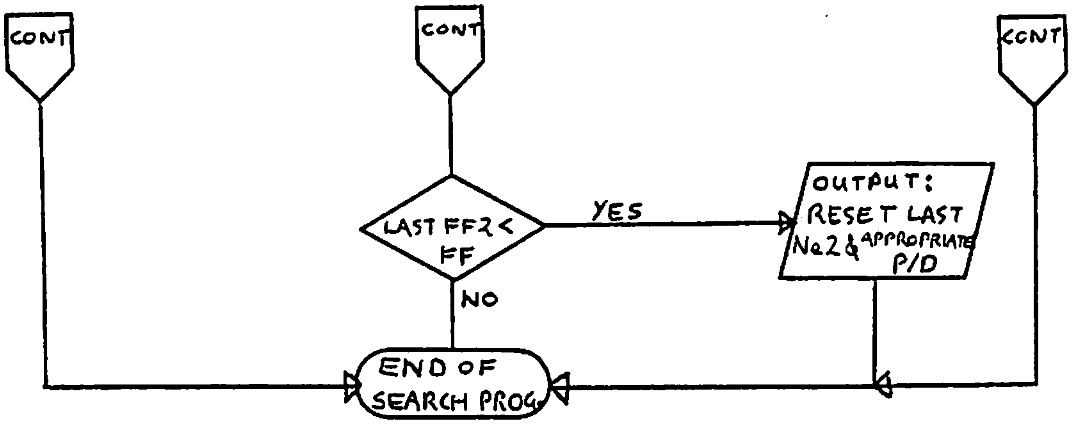
The maximum propeller pitch (P/D) constraint was also lifted to observe the effect on the overall propulsive efficiency.

FIGURE 6 - FLOW CHART FOR THE CONTROL PROGRAM

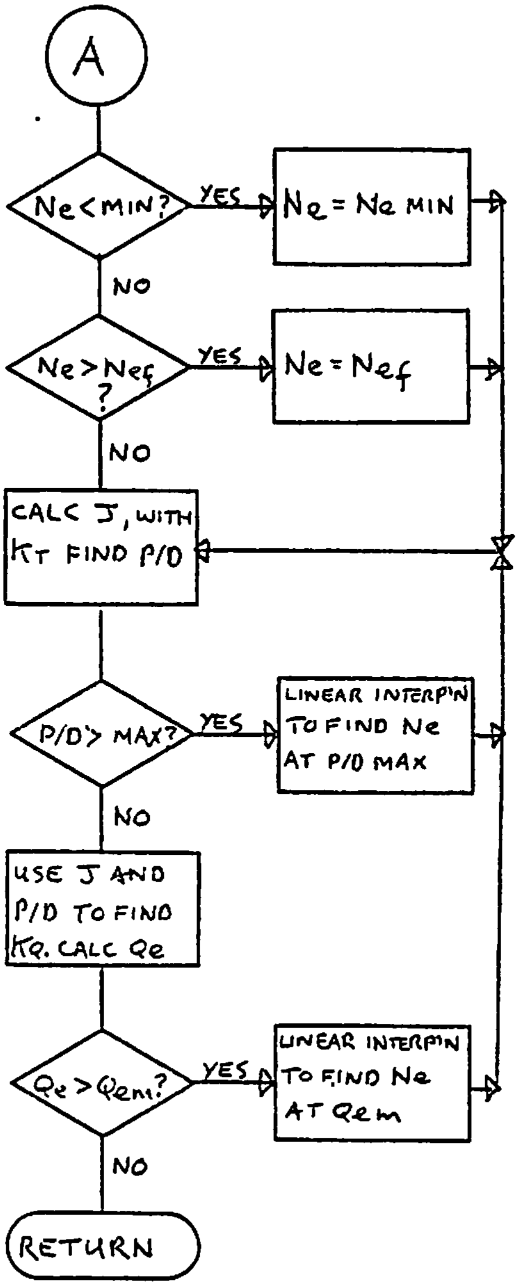
(See Appendix 4 for program listing)

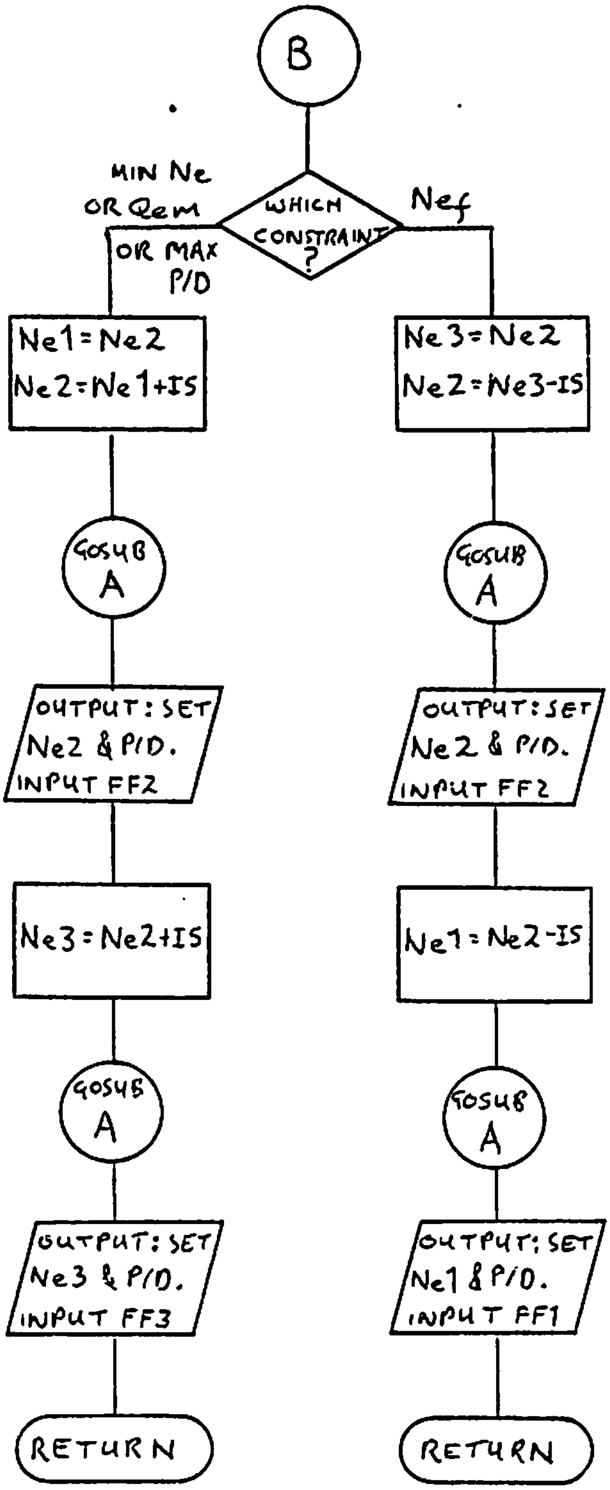


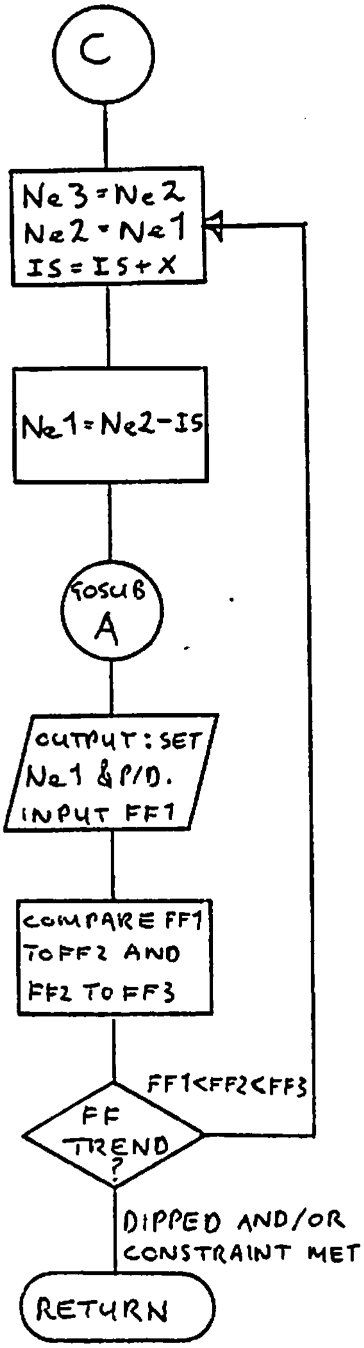

CONT
CONT
CONT
CONT
OUTPUT: SET Ne1 & P/D INPUT FF1
GOSUB A
OUTPUT: SET Ne3 & P/D INPUT FF3
OUTPUT: SET Ne1 & P/D INPUT FF1
Ne3 = Ne2 + IS
GOSUB A
OUTPUT: SET Ne3 & P/D INPUT FF3
COMPARE FF1 TO FF2 AND FF2 TO FF3
FF TREND?
INCREASING i.e. FF1 < FF2 < FF3
DECREASING i.e. FF1 > FF2 > FF3
DIPPED i.e. FF1 > FF2 < FF3
GOSUB C
GOSUB D
MIN FF AT CONSTRAINT ?
NO
QUAD. LINE FIT TO FIND MIN FF Ne
NO
MIN FF AT CONSTRAINT ?
YES
YES
GOSUB A
OUTPUT: SET Ne & P/D INPUT FF
NEXT PAGE
NEXT PAGE
NEXT PAGE

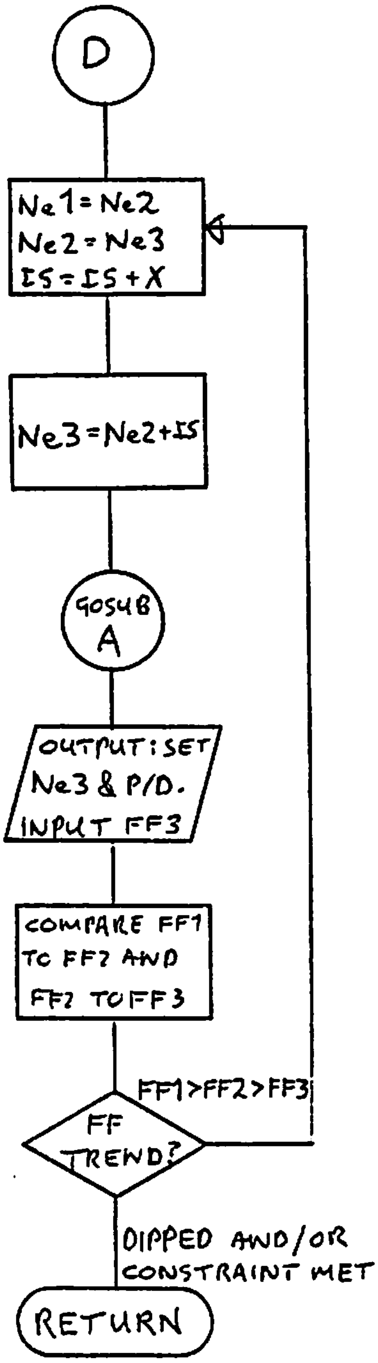


SUBROUTINES






C
Ne3=Ne2
Ne2=Ne1
IS=IS+X
Ne1=Ne2-IS
GOSUB
A
OUTPUT: SET
Ne1 & P/D.
INPUT FF1
COMPARE FF1
TO FF2 AND
FF2 TO FF3
FF
TREND
?
FF1<FF2<FF3
DIPPED AND/OR
CONSTRAINT MET
RETURN


D
Ne1=Ne2
Ne2=Ne3
IS=IS+X
Ne3=Ne2+IS
GOSUB
A
OUTPUT: SET
Ne3 & P/D.
INPUT FF3
COMPARE FF1
TO FF2 AND
FF2 TO FF3
FF
TREND?
FF1>FF2>FF3
DIPPED AND/OR
CONSTRAINT MET
RETURN

4. RESULTS

4.1 FISHING VESSEL SIMULATION EXAMPLES

These are divided into the two operating conditions of towing and free-running. The towing speeds are from 2 knots for the slowest bottom trawl, and up to 5 knots for the high speed manoeuvring of a mid-water trawl.

For trawling the additional resistance (T_a) input would be the total warp load, and from the results (Figures 7 to 10, and Figure 11), the full characteristic dipped engine speed (N_e) fuel flow (FF) function is evident for low trawling speeds.

Under free-running conditions (Figures 1 to 15) discrepancies in the simulation are exhibited by the 'humped' N_e-FF function (this being discussed later in section 5.1). Also, Figure 16, exhibits the effect of allowing the maximum pitch constraint to be removed (also Figure 17).

FIGURE 7 - TRAWLING SIMULATION

```
          M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION

               PROGRAMMED BY G.A.WEBB AUGUST 1983

--------------------------------------------------------------------------
ADDITIONAL THRUST=  25  (kN)

SHIP SPEED = 2 KNOTS          TOTAL THRUST REQUIREMENT = 36.45 kN

WAKE AND THRUST               PROPELLER SPEED OF ADVANCE= 1.47 KNOTS
FRACTIONS = 0.266

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR        QE        EP        FF        PE        TE        OP
 (RPM)   (P/D)     (kNm)     (kW)     (kg/hr)     (%)       (%)       (%)

  790    0.388     2.381     213.5     45.18     12.90     39.33     5.07
  778    0.394     2.530     206.1     43.61     13.37     39.33     5.26
  766    0.399     2.479     198.9     42.23     13.85     39.19     5.43
  754    0.405     2.429     191.8     40.93     14.36     39.01     5.60
  742    0.412     2.380     184.9     39.65     14.89     38.83     5.78
  730    0.418     2.331     178.2     38.42     15.46     38.61     5.97
  718    0.425     2.283     171.6     37.26     16.05     38.34     6.15
  706    0.432     2.237     165.4     36.18     16.65     38.06     6.34
  694    0.438     2.209     160.6     35.30     17.16     37.86     6.50
  682    0.446     2.182     155.8     34.39     17.68     37.71     6.67
  670    0.453     2.154     151.1     33.53     18.22     37.52     6.84
  658    0.461     2.127     146.6     32.70     18.79     37.31     7.01
  646    0.468     2.095     141.7     31.83     19.44     37.05     7.20
  634    0.476     2.081     138.1     31.32     19.94     36.71     7.32
  622    0.484     2.073     135.1     30.90     20.40     36.38     7.42
  610    0.493     2.068     132.1     30.50     20.85     36.05     7.52
  598    0.504     2.069     129.5     30.20     21.26     35.71     7.59
  586    0.515     2.078     127.5     29.92     21.60     35.48     7.66
  574    0.527     2.096     126.0     29.74     21.86     35.27     7.71
  562    0.541     2.125     125.1     29.77     22.03     34.96     7.70
  550    0.557     2.190     126.1     30.20     21.84     34.77     7.59
  538    0.574     2.299     129.5     31.61     21.27     34.10     7.25
  526    0.598     2.436     134.2     33.22     20.53     33.62     6.90
  514    0.623     2.550     137.2     34.70     20.07     32.92     6.61
  502    0.654     2.727     143.3     36.67     19.22     32.53     6.25
  490    0.688     2.927     150.2     39.03     18.34     32.03     5.87
  478    0.723     3.108     155.6     41.15     17.70     31.48     5.57
  475    0.732     3.151     156.7     41.62     17.58     31.34     5.51
```

FIGURE 8 - TRAWLING SIMULATION

```
          M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION

                PROGRAMMED BY G.A.WEBB AUGUST 1983

-------------------------------------------------------------------------
ADDITIONAL THRUST= 35 kN

SHIP SPEED = 3 KNOTS            TOTAL THRUST REQUIREMENT = 50.11 kN

WAKE AND THRUST
FRACTIONS = 0.248               PROPELLER SPEED OF ADVANCE= 2.26 KNOTS

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE       PR        QE        EP        FF        PE       TE       OP
 (RPM)    (P/D)     (kNm)     (kW)     (kg/hr)     (%)      (%)      (%)

  790     0.459     2.953     244.3     51.41     23.83    39.55     9.42
  781     0.464     2.932     239.8     50.46     24.27    39.56     9.60
  772     0.469     2.912     235.4     49.53     24.72    39.57     9.78
  763     0.474     2.910     232.5     48.96     25.04    39.53     9.90
  754     0.480     2.911     229.9     48.47     25.32    39.48    10.00
  745     0.486     2.913     227.3     48.01     25.61    39.40    10.09
  736     0.492     2.916     224.8     47.59     25.90    39.31    10.18
  727     0.498     2.920     222.3     47.19     26.18    39.21    10.27
  718     0.505     2.924     219.9     46.81     26.47    39.10    10.35
  709     0.512     2.936     218.0     46.55     26.70    38.98    10.41
  700     0.520     2.961     217.0     46.48     26.82    38.87    10.42
  691     0.528     2.987     216.2     46.35     26.93    38.82    10.45
  682     0.537     3.014     215.3     46.22     27.04    38.77    10.48
  673     0.546     3.043     214.4     46.11     27.14    38.71    10.51
  664     0.556     3.117     216.7     46.66     26.85    38.66    10.38
  655     0.569     3.241     222.3     47.87     26.18    38.66    10.12
  646     0.582     3.368     227.8     49.06     25.55    38.65     9.87
  637     0.596     3.479     232.1     50.08     25.08    38.58     9.67
  628     0.612     3.576     235.2     50.85     24.75    38.49     9.53
  619     0.628     3.682     238.7     51.66     24.38    38.46     9.38
  610     0.646     3.819     244.0     52.78     23.86    38.47     9.18
  601     0.664     3.958     249.1     53.86     23.37    38.49     8.99
  592     0.684     4.097     254.0     54.90     22.92    38.51     8.82
  583     0.704     4.232     258.4     55.85     22.53    38.51     8.67
  574     0.725     4.358     262.0     56.70     22.22    38.45     8.54
  565     0.745     4.464     264.1     57.56     22.04    38.20     8.42
  556     0.765     4.549     264.9     58.14     21.97    37.92     8.33
  547     0.786     4.627     265.0     58.47     21.96    37.73     8.29
  540     0.800     4.665     263.8     58.29     22.06    37.67     8.31
```

FIGURE 10 - TRAWLING SIMULATION

```
              M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION

                    PROGRAMMED BY G.A.WEBB AUGUST 1983

--------------------------------------------------------------------------
ADDITIONAL THRUST= 51 kN

SHIP SPEED = 5 KNOTS          TOTAL THRUST REQUIREMENT = 71.72 kN

WAKE AND THRUST               PROPELLER SPEED OF ADVANCE= 3.91 KNOTS
FRACTIONS = 0.217

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR       QE       EP       FF       PE       TE       OP
 (RPM)   (P/D)    (kNm)    (kW)    (kg/hr)    (%)      (%)      (%)

 790     0.605    5.311    439.4    88.30    32.89    41.42    13.62
 785     0.614    5.407    444.5    89.29    32.51    41.44    13.47
 780     0.623    5.501    449.4    90.27    32.16    41.43    13.32
 775     0.631    5.595    454.1    91.27    31.82    41.41    13.18
 770     0.640    5.700    459.6    92.39    31.44    41.41    13.02
 765     0.649    5.802    464.8    93.43    31.09    41.41    12.87
 760     0.658    5.902    469.8    94.41    30.76    41.42    12.74
 755     0.667    6.000    474.4    95.32    30.46    41.43    12.62
 750     0.676    6.089    478.2    96.06    30.21    41.44    12.52
 745     0.685    6.166    481.1    96.72    30.03    41.40    12.44
 740     0.693    6.241    483.7    97.32    29.87    41.36    12.36
 735     0.702    6.314    486.0    97.88    29.73    41.33    12.29
 730     0.711    6.383    488.0    98.37    29.61    41.29    12.23
 725     0.720    6.450    489.7    98.80    29.51    41.26    12.17
 722     0.726    6.493    490.7    99.05    29.44    41.24    12.14
```

FIGURE 11 - SHIP SPEED (V_s) AND ADDITIONAL RESISTANCE (T_a) VERSUS FUEL FLOW (FF), ENGINE POWER (P_B) AND ENGINE RPM (N_e)

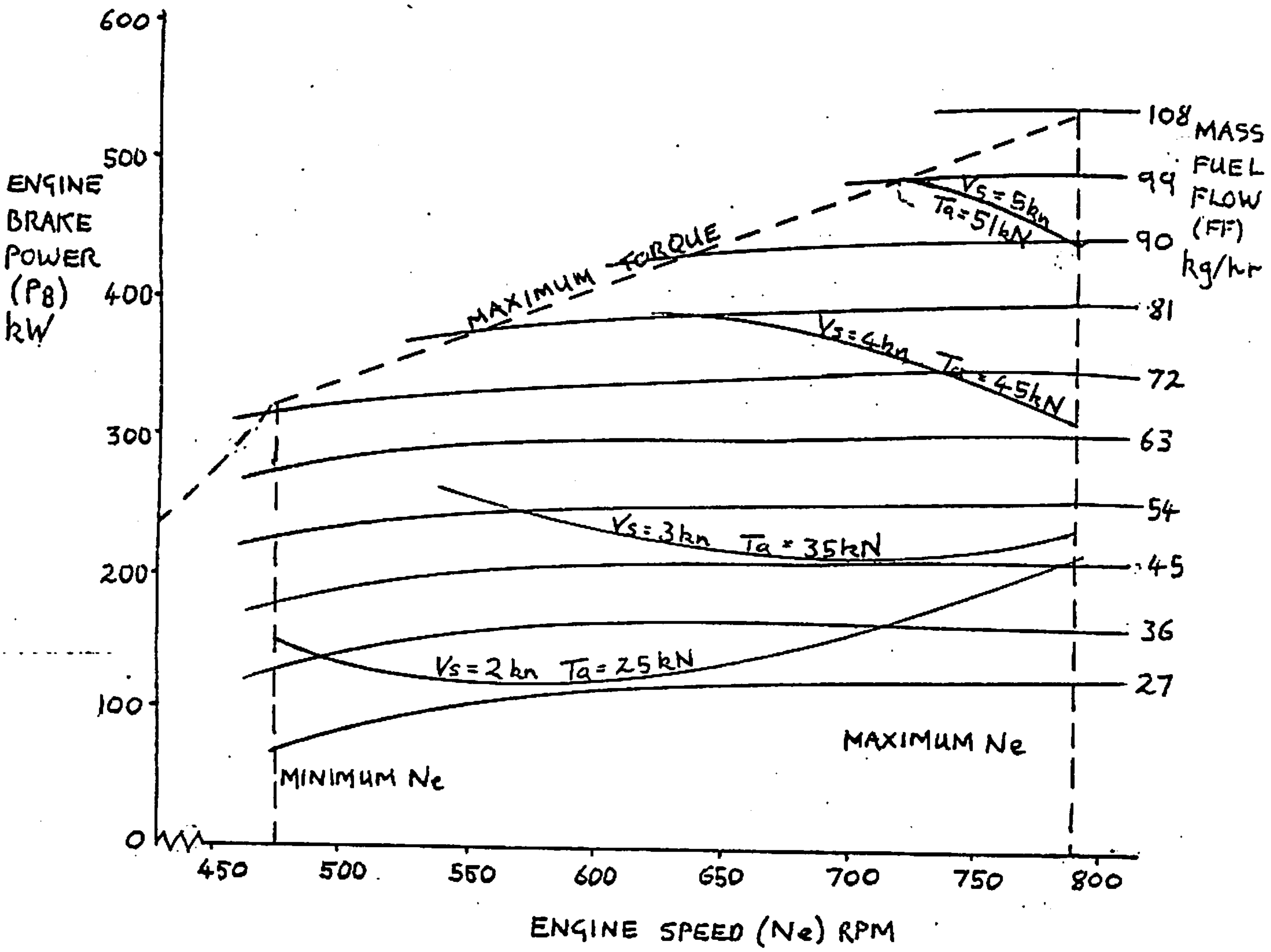


FIGURE 12 - FREE-RUNNING SIMULATION

```
        M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION

               PROGRAMMED BY G.A.WEBB AUGUST 1983

--------------------------------------------------------------------------
ADDITIONAL THRUST= 20 kN

SHIP SPEED = 8 KNOTS          TOTAL THRUST REQUIREMENT = 41.47 kN

WAKE AND THRUST               PROPELLER SPEED OF ADVANCE= 6.51 KNOTS
FRACTIONS = 0.186

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH.DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

 NE       PR        QE        EP        FF        PE        TE        OP
(RPM)    (P/D)     (kNm)     (kW)     (kg/hr)     (%)       (%)       (%)

 790     0.550     3.431     283.8     58.95     48.98     40.08     19.63
 782     0.558     3.525     288.7     59.78     48.16     40.20     19.36
 774     0.567     3.617     293.1     60.52     47.43     40.32     19.12
 766     0.576     3.699     296.7     61.17     46.85     40.38     18.92
 758     0.584     3.757     298.2     61.46     46.62     40.39     18.83
 750     0.592     3.805     298.8     61.59     46.53     40.38     18.79
 742     0.601     3.830     297.6     61.45     46.71     40.31     18.83
 734     0.611     3.859     296.6     61.34     46.87     40.25     18.87
 726     0.621     3.890     295.8     61.26     47.01     40.19     18.89
 718     0.631     3.927     295.3     61.24     47.08     40.13     18.90
 710     0.643     3.982     296.1     61.47     46.96     40.09     18.83
 702     0.655     4.039     296.9     61.70     46.82     40.05     18.75
 694     0.668     4.099     297.9     62.03     46.67     39.98     18.66
 686     0.681     4.155     298.5     62.30     46.58     39.88     18.58
 678     0.695     4.208     298.8     62.52     46.53     39.78     18.51
 670     0.709     4.259     298.8     62.62     46.52     39.72     18.48
 662     0.723     4.304     298.3     62.56     46.60     39.69     18.50
 654     0.738     4.344     297.5     62.45     46.73     39.66     18.53
 646     0.753     4.378     296.2     62.23     46.94     39.61     18.60
 638     0.767     4.401     294.1     61.88     47.28     39.55     18.70
 630     0.782     4.419     291.5     61.46     47.69     39.48     18.83
 622     0.798     4.431     288.6     60.99     48.17     39.39     18.97
 621     0.800     4.432     288.2     60.92     48.24     39.38     18.99
```

FIGURE 13 - FREE-RUNNING SIMULATION

```
                M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION

                     PROGRAMMED BY G.A.WEBB AUGUST 1983

---------------------------------------------------------------------------
ADDITIONAL THRUST= 20 kN

SHIP SPEED = 9 KNOTS          TOTAL THRUST REQUIREMENT = 48.57 kN

WAKE AND THRUST               PROPELLER SPEED OF ADVANCE= 7.39 KNOTS
FRACTIONS = 0.179

NE= ENGINE SPEED (R.P.M.).
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR       QE       EP       FF       PE       TE       OP
 (RPM)   (P/D)    (kNm)    (kW)    (kg/hr)    (%)      (%)      (%)

 790     0.631    4.674    386.7    78.79    47.76    40.85    19.51
 786     0.637    4.703    387.1    78.85    47.71    40.87    19.50
 782     0.642    4.733    387.6    78.92    47.65    40.88    19.48
 778     0.647    4.764    388.1    78.99    47.58    40.90    19.46
 774     0.653    4.795    388.7    79.08    47.52    40.91    19.44
 770     0.659    4.827    389.2    79.22    47.45    40.89    19.41
 766     0.664    4.859    389.7    79.36    47.39    40.88    19.37
 762     0.671    4.891    390.3    79.50    47.32    40.86    19.34
 758     0.677    4.923    390.8    79.62    47.26    40.85    19.31
 754     0.682    4.949    390.8    79.67    47.26    40.83    19.30
 750     0.688    4.975    390.8    79.70    47.26    40.81    19.29
 746     0.694    5.001    390.7    79.72    47.27    40.79    19.28
 742     0.701    5.026    390.5    79.72    47.29    40.78    19.28
 738     0.707    5.050    390.3    79.71    47.32    40.76    19.29
 734     0.713    5.073    390.0    79.68    47.36    40.74    19.29
 730     0.719    5.095    389.5    79.63    47.42    40.72    19.31
 726     0.726    5.116    389.0    79.56    47.48    40.69    19.32
 722     0.732    5.136    388.3    79.49    47.56    40.66    19.34
 718     0.739    5.155    387.6    79.41    47.65    40.63    19.36
 714     0.746    5.173    386.8    79.31    47.75    40.59    19.38
 710     0.753    5.190    385.9    79.20    47.86    40.56    19.41
 706     0.760    5.206    384.9    79.06    47.98    40.52    19.44
 702     0.767    5.221    383.8    78.90    48.12    40.49    19.48
 698     0.773    5.228    382.1    78.63    48.33    40.45    19.55
 694     0.780    5.234    380.4    78.34    48.55    40.42    19.62
 690     0.787    5.239    378.5    78.02    48.79    40.38    19.70
 686     0.794    5.242    376.6    77.68    49.05    40.35    19.79
 683     0.800    5.243    374.8    77.37    49.28    40.32    19.87
```

FIGURE 14 - FREE-RUNNING SIMULATION

```
              M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION

                   PROGRAMMED BY G.A.WEBB AUGUST 1983

-------------------------------------------------------------------------
 ADDITIONAL THRUST= 20 kN

 SHIP SPEED = 10 KNOTS          TOTAL THRUST REQUIREMENT = 56.31 kN

 WAKE AND THRUST                PROPELLER SPEED OF ADVANCE= 8.25 KNOTS
 FRACTIONS = 0.175

 NE= ENGINE SPEED (R.P.M.)
 PR= PROPELLER PITCH DIAMETER RATIO
 QE= ENGINE TORQUE (kNm)
 EP= ENGINE POWER (kW)
 FF= MASS FLOW RATE OF FUEL (kg/hr)
 PE= PROPELLER EFFICIENCY (%)
 TE= ENGINE THERMAL EFFICIENCY (%)
 OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR       QE       EP        FF        PE       TE       OP
 (RPM)   (P/D)    (kNm)    (kW)     (kg/hr)     (%)      (%)      (%)

 790     0.728    6.005    496.8     99.40     48.16    41.60    20.03
 788     0.731    6.015    496.3     99.33     48.20    41.59    20.05
 786     0.734    6.024    495.9     99.25     48.25    41.59    20.06
 784     0.738    6.034    495.4     99.17     48.30    41.58    20.08
 782     0.741    6.043    494.9     99.09     48.35    41.57    20.10
 780     0.744    6.052    494.3     99.00     48.40    41.56    20.12
 778     0.747    6.060    493.7     98.91     48.45    41.55    20.13
 776     0.750    6.069    493.2     98.81     48.51    41.54    20.15
 774     0.753    6.076    492.5     98.70     48.58    41.53    20.18
 772     0.756    6.084    491.8     98.59     48.64    41.53    20.20
 770     0.759    6.091    491.1     98.46     48.71    41.52    20.22
 768     0.762    6.098    490.4     98.34     48.79    41.51    20.25
 766     0.766    6.104    489.6     98.20     48.86    41.50    20.28
 764     0.769    6.110    488.9     98.06     48.94    41.50    20.31
 762     0.772    6.116    488.0     97.91     49.02    41.49    20.34
 760     0.775    6.122    487.2     97.76     49.11    41.48    20.37
 758     0.779    6.127    486.3     97.60     49.19    41.48    20.40
 756     0.782    6.132    485.4     97.43     49.28    41.47    20.44
 754     0.785    6.133    484.2     97.21     49.41    41.47    20.49
 752     0.788    6.134    483.0     96.97     49.53    41.46    20.54
 750     0.791    6.134    481.8     96.74     49.66    41.45    20.59
 748     0.795    6.134    480.5     96.54     49.79    41.43    20.63
 746     0.798    6.134    479.2     96.33     49.93    41.40    20.67
 745     0.800    6.133    478.2     96.18     50.03    41.39    20.71
```

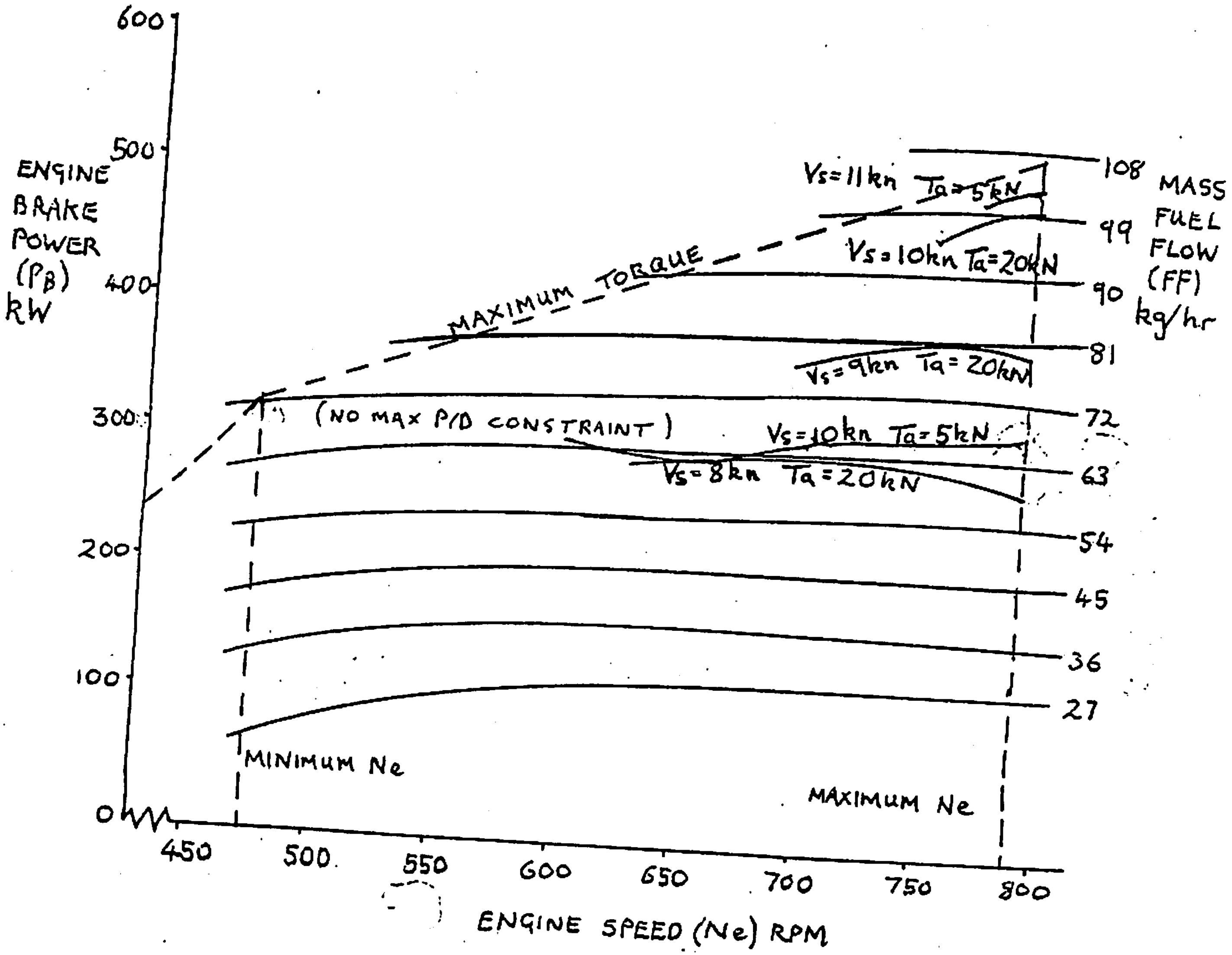
FIGURE 15 - FREE-RUNNING SIMULATION

```
              M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION

                   PROGRAMMED BY G.A.WEBB AUGUST 1983

-------------------------------------------------------------------------------
ADDITIONAL THRUST= 5 kN

SHIP SPEED = 11 KNOTS          TOTAL THRUST REQUIREMENT = 55.73 kN

WAKE AND THRUST                PROPELLER SPEED OF ADVANCE= 9.11 KNOTS
FRACTIONS = 0.172

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

 NE       PR        QE        EP        FF        PE        TE        OP
(RPM)    (P/D)     (kNm)     (kW)     (kg/hr)     (%)       (%)       (%)

 790     0.767     6.212     513.9    102.57     50.84     41.71     21.20
 789     0.769     6.214     513.4    102.47     50.90     41.70     21.23
 788     0.770     6.215     512.8    102.37     50.95     41.70     21.25
 787     0.772     6.216     512.3    102.26     51.01     41.69     21.27
 786     0.773     6.216     511.7    102.16     51.07     41.69     21.29
 785     0.775     6.217     511.1    102.06     51.13     41.68     21.31
 784     0.776     6.218     510.5    101.95     51.18     41.68     21.33
 783     0.778     6.219     509.9    101.84     51.24     41.68     21.36
 782     0.780     6.219     509.3    101.74     51.30     41.67     21.38
 781     0.781     6.220     508.7    101.63     51.37     41.66     21.40
 780     0.783     6.220     508.1    101.52     51.43     41.66     21.42
 779     0.784     6.221     507.5    101.41     51.49     41.65     21.45
 778     0.786     6.221     506.8    101.29     51.56     41.65     21.47
 777     0.787     6.221     506.2    101.18     51.62     41.64     21.50
 776     0.789     6.221     505.6    101.07     51.69     41.64     21.52
 775     0.791     6.221     504.9    100.95     51.75     41.63     21.54
 774     0.792     6.221     504.3    100.84     51.82     41.62     21.57
 773     0.794     6.221     503.6    100.73     51.89     41.61     21.59
 772     0.795     6.221     502.9    100.62     51.96     41.61     21.62
 771     0.797     6.221     502.3    100.50     52.02     41.60     21.64
 770     0.799     6.220     501.6    100.38     52.10     41.59     21.67
 769     0.800     6.220     501.0    100.29     52.15     41.58     21.69
```

FIGURE 16 - SIMULATION RUN WITH MAXIMUM PITCH CONSTRAINT REMOVED

```
            M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION

                 PROGRAMMED BY G.A.WEBB AUGUST 1983

---------------------------------------------------------------------------

ADDITIONAL THRUST= 5 (kN)

SHIP SPEED = 10 KNOTS          TOTAL THRUST REQUIREMENT = 38.13 kN

WAKE AND THRUST                PROPELLER SPEED OF ADVANCE= 8.25 KNOTS
FRACTIONS = 0.175

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE       PR        QE        EP        FF        PE        TE        OP
 (RPM)    (P/D)     (kNm)     (kW)     (kg/hr)     (%)       (%)       (%)

  790     0.607     3.954     327.1     67.22     49.53     40.51     20.06
  781     0.617     3.993     326.6     67.04     49.61     40.55     20.12
  772     0.628     4.029     325.7     66.81     49.74     40.58     20.19
  763     0.639     4.063     324.7     66.53     49.91     40.62     20.27
  754     0.650     4.095     323.3     66.21     50.11     40.65     20.37
  745     0.662     4.124     321.8     65.98     50.36     40.59     20.44
  736     0.674     4.151     320.0     65.79     50.64     40.48     20.50
  727     0.686     4.176     317.9     65.55     50.96     40.37     20.57
  718     0.699     4.198     315.7     65.25     51.33     40.27     20.67
  709     0.712     4.218     313.2     64.90     51.74     40.17     20.78
  700     0.726     4.236     310.5     64.49     52.18     40.08     20.91
  691     0.740     4.251     307.6     64.05     52.68     39.97     21.06
  682     0.754     4.263     304.5     63.58     53.22     39.86     21.21
  673     0.770     4.275     301.3     63.10     53.77     39.75     21.37
  664     0.787     4.289     298.2     62.53     54.33     39.70     21.57
  655     0.804     4.320     296.3     62.21     54.68     39.65     21.68
  646     0.821     4.418     298.9     62.76     54.21     39.64     21.49
  637     0.839     4.510     300.9     63.21     53.85     39.62     21.33
  628     0.858     4.596     302.3     63.56     53.60     39.59     21.22
  619     0.877     4.676     303.1     63.83     53.46     39.53     21.13
  610     0.897     4.749     303.3     64.00     53.41     39.45     21.07
  601     0.918     4.815     303.0     64.05     53.47     39.38     21.06
```

FIGURE 17 - SHIP SPEED (V_s) AND ADDITIONAL RESISTANCE (T_a) VERSUS MASS FUEL FLOW (FF), ENGINE POWER (P_B), ENGINE RPM (N_e)



4.2 THE PROPULSION CONTROL SYSTEM SIMULATION

Only 2 runs are included as this is the ideal situation with the control program finding the optimum immediately. The program properties are, in fact, better exhibited in Section 4.3.

The calculated required propeller thrust is superfluous to this program, as the R_T used is the inputed value. However, this calculation is retained to exhibit:-

1. The correct algorithm sequence.

2. The discrepancies between the line fitted K_T-J data and the data extrapolated for this calculation from the provided K_T-J diagram linear interpolation being used between the four ahead pitches (Table 3.7, Appendix 3).

Figure 18

```
            M.F.V. GLENUGIE IV PROPULSION CONTROL SYSTEM SIMULATION

                   PROGRAMMED BY G.A.WEBB AUGUST 1983

---------------------------------------------------------------------------
ADDITIONAL THRUST= 50 kN

SHIP SPEED = 3.5 KNOTS       TOTAL THRUST REQUIREMENT = 70.02 kN

WAKE AND THRUST              PROPELLER SPEED OF ADVANCE= 2.66 KNOTS
FRACTIONS = 0.240

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR       QE       EP       FF        PE       TE       OP
 (RPM)   (P/D)    (kNm)    (kW)    (kg/hr)    (%)      (%)      (%)

 770     0.574    4.596    370.6    75.73     25.89    40.73    10.55

CONTROL PROGRAM INTIATED

CALCULATED REQUIRED PROPELLER THRUST= 70.42 kN

 784     0.557    4.350    357.1    73.09     26.87    40.67    10.93
 790     0.551    4.278    353.9    72.51     27.11    40.63    11.01

FOUND MININUM FUEL CONSUMPTION
```

Figure 19

```
            M.F.V. GLENUGIE IV PROPULSION CONTROL SYSTEM SIMULATION

                   PROGRAMMED BY G.A.WEBB AUGUST 1983

---------------------------------------------------------------------------
ADDITIONAL THRUST= 35 kN

SHIP SPEED = 8 KNOTS         TOTAL THRUST REQUIREMENT = 59.89 kN

WAKE AND THRUST              PROPELLER SPEED OF ADVANCE= 6.51 KNOTS
FRACTIONS = 0.186

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR       QE       EP       FF        PE       TE       OP
 (RPM)   (P/D)    (kNm)    (kW)    (kg/hr)    (%)      (%)      (%)

 760     0.708    5.833    464.2    93.34     43.26    41.40    17.91

CONTROL PROGRAM INTIATED

CALCULATED REQUIRED PROPELLER THRUST= 60.75 kN

 790     0.661    5.562    460.2    92.27     43.64    41.51    18.11
 780     0.676    5.660    462.3    92.82     43.44    41.46    18.01
 770     0.692    5.749    463.6    93.16     43.32    41.42    17.94
 790     0.661    5.559    459.8    92.21     43.67    41.51    18.13

FOUND MININUM FUEL CONSUMPTION
```

4.3 THE PROPULSION CONTROL SYSTEM TESTING SIMULATION

Here various minimising search scenarios are shown:-

Figure 20 - a decreasing N_e search with penultimately a quadratic fit but finally resetting the previous N_e2.

Figure 21 - an increasing N_e search finding its minimum by quadratic line fit. (Note the increasing iteration steps and inclusion of the initial set N_e in figures 20 and 21).

Figure 22 - an increasing N_e search finding the minimum at maximum N_e.

Figure 23 - a short decreasing N_e search finding the minimum at maximum P/D.

Figure 24 - a quadratic line fit minimisation between 775 RPM and 790 RPM.

Figure 25 - here the humped N_e-FF function given by the simulation causes the program to identify an increasing FF with decreasing N_e. This puts the control program search minimum on the wrong side of the humped function resulting in a discrepancy of 3.69% from the actual minimum FF value.

FIGURE 20 - REDUCING ENGINE SPEED SEARCH

```
          PROPULSION CONTROL SYSTEM - TESTING SIMULATION

                PROGRAMMED BY G.A.WEBB AUGUST 1983

----------------------------------------------------------------------------

SHIP SPEED = 2 KNOTS           TOTAL THRUST REQUIREMENT = 50.00 kN

WAKE AND THRUST                PROPELLER SPEED OF ADVANCE= 1.47 KNOTS
FRACTIONS = 0.266

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR       QE       EP       FF       PE       TE       OP
 (RPM)   (P/D)    (kNm)    (kW)   (kg/hr)    (%)      (%)      (%)

 790     0.446    2.990    247.4    52.05    15.27    39.56    6.04

CONTROL PROGRAM INTIATED

CALCULATED REQUIRED PROPELLER THRUST= 50.86 kN

ENTER PSEUDO MINIMUM ENGINE R.P.M.? 780

 780     0.452    2.965    242.2    50.95    15.60    39.56    6.17
 770     0.457    2.939    237.0    49.86    15.94    39.56    6.31
 755     0.465    2.888    228.3    48.15    16.55    39.47    6.53
 735     0.475    2.842    218.7    46.40    17.27    39.24    6.78
 710     0.491    2.816    209.4    44.80    18.04    38.91    7.02
 630     0.513    2.822    201.0    43.28    18.80    38.66    7.27
 645     0.545    2.889    195.1    42.44    19.36    38.27    7.41
 605     0.600    3.288    208.3    45.83    18.14    37.83    6.86
 654     0.536    2.869    196.5    42.67    19.23    38.33    7.37
 645     0.545    2.889    195.1    42.44    19.36    38.27    7.41

OFF MINIMUM FUEL CONSUMPTION BY 0.35%
```

FIGURE 21 - INCREASING ENGINE SPEED SEARCH

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            PROPULSION CONTROL SYSTEM - TESTING SIMULATION

                  PROGRAMMED BY G.A.WEBB AUGUST 1983

---------------------------------------------------------------------------

SHIP SPEED = 2 KNOTS            TOTAL THRUST REQUIREMENT = 70.00 kN

WAKE AND THRUST                 PROPELLER SPEED OF ADVANCE= 1.47 KNOTS
FRACTIONS = 0.266

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE       PR        QE        EP        FF        PE        TE        OP
 (RPM)    (P/D)     (kNm)     (kW)     (kg/hr)     (%)       (%)       (%)

  680     0.652     5.117     364.4     75.39     14.51     40.23     5.84

CONTROL PROGRAM INTIATED

CALCULATED REQUIRED PROPELLER THRUST= 69.56 kN

ENTER PSEUDO MINIMUM ENGINE R.P.M.? 690

  690     0.632     4.869     351.8     72.89     15.03     40.18     6.04
  700     0.613     4.677     342.8     71.06     15.43     40.16     6.20
  715     0.590     4.469     334.7     69.10     15.81     40.31     6.37
  735     0.565     4.201     323.3     66.46     16.36     40.50     6.62
  760     0.541     4.018     319.7     65.57     16.54     40.59     6.71
  790     0.518     3.948     326.6     67.12     16.19     40.51     6.56
  759     0.542     4.020     319.5     65.52     16.55     40.59     6.72

OFF MINIMUM FUEL CONSUMPTION BY 0.69%
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FIGURE 22 - MINIMUM FUEL FLOW AT MAXIMUM ENGINE SPEED

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        PROPULSION CONTROL SYSTEM - TESTING SIMULATION

               PROGRAMMED BY G.A.WEBB AUGUST 1983

--------------------------------------------------------------------------

SHIP SPEED = 3 KNOTS          TOTAL THRUST REQUIREMENT = 75.00 kN

WAKE AND THRUST               PROPELLER SPEED OF ADVANCE= 2.26 KNOTS
FRACTIONS = 0.248

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR       QE       EP       FF        PE       TE       OP
 (RPM)   (P/D)    (kNm)    (kW)    (kg/hr)    (%)      (%)      (%)

  750    0.612    5.200    408.4    82.93    21.33    40.99     8.74

CONTROL PROGRAM INTIATED

CALCULATED REQUIRED PROPELLER THRUST= 75.29 kN

ENTER PSEUDO MINIMUM ENGINE R.P.M.? 740

  740    0.628    5.337    413.6    83.98    21.06    41.00     8.64
  730    0.644    5.522    422.2    85.67    20.64    41.02     8.46
  765    0.591    4.992    399.9    81.25    21.78    40.97     8.92
  785    0.567    4.691    385.6    78.57    22.59    40.85     9.23
  790    0.562    4.622    382.3    78.00    22.78    40.80     9.30

FOUND MINIMUM FUEL CONSUMPTION
```

FIGURE 23 - MINIMUM FUEL FLOW AT MAXIMUM PITCH

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          PROPULSION CONTROL SYSTEM - TESTING SIMULATION

                PROGRAMMED BY G.A.WEBB AUGUST 1983

----------------------------------------------------------------------------

SHIP SPEED = 11 KNOTS        TOTAL THRUST REQUIREMENT = 50.00 kN

WAKE AND THRUST              PROPELLER SPEED OF ADVANCE= 9.11 KNOTS
FRACTIONS = 0.172

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE      PR       QE       EP       FF       PE       TE       OP
 (RPM)   (P/D)    (kNm)    (kW)    (kg/hr)    (%)      (%)      (%)

 790     0.729    5.630    465.8    93.40    50.33    41.51    20.89

CONTROL PROGRAM INTIATED

CALCULATED REQUIRED PROPELLER THRUST= 50.50 kN

ENTER PSEUDO MINIMUM ENGINE R.P.M.? 780

 780     0.743    5.653    461.8    92.72    50.77    41.45    21.05
 770     0.758    5.663    456.7    91.81    51.34    41.40    21.26
 755     0.782    5.663    447.8    90.21    52.36    41.31    21.63
 744     0.800    5.651    440.3    88.93    53.25    41.21    21.94

FOUND MINIMUM FUEL CONSUMPTION
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FIGURE 24 - QUADRATIC LINE FIT MINIMISATION

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          PROPULSION CONTROL SYSTEM - TESTING SIMULATION

                PROGRAMMED BY G.A.WEBB AUGUST 1983

--------------------------------------------------------------------------

SHIP SPEED = 4 KNOTS           TOTAL THRUST REQUIREMENT = 65.00 kN

WAKE AND THRUST                PROPELLER SPEED OF ADVANCE= 3.07 KNOTS
FRACTIONS = 0.232

NE= ENGINE SPEED (R.P.M.) .
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

 NE      PR       QE       EP       FF       PE       TE       OP
(RPM)   (P/D)    (kNm)    (kW)    (kg/hr)    (%)      (%)      (%)

 765    0.564    4.226    338.5    69.26    30.38    40.69    12.36

CONTROL PROGRAM INTIATED

CALCULATED REQUIRED PROPELLER THRUST= 64.58 kN

ENTER PSEUDO MINIMUM ENGINE R.P.M.? 775

 775    0.554    4.105    333.2    68.31    30.87    40.60    12.53
 785    0.544    4.032    331.4    68.03    31.03    40.55    12.58
 790    0.539    4.009    331.6    68.10    31.01    40.53    12.57
 785    0.544    4.032    331.4    68.03    31.03    40.55    12.58

OFF MINIMUM FUEL CONSUMPTION BY 0.13%
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FIGURE 25 - THE ENCOUNTERING OF A HUMPED FUEL FLOW ENGINE SPEED CHARACTERISTIC

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          PROPULSION CONTROL SYSTEM - TESTING SIMULATION

                 PROGRAMMED BY G.A.WEBB AUGUST 1983

----------------------------------------------------------------------------

SHIP SPEED = 10 KNOTS         TOTAL THRUST REQUIREMENT = 40.00 kN

WAKE AND THRUST               PROPELLER SPEED OF ADVANCE= 8.25 KNOTS
FRACTIONS = 0.175

NE= ENGINE SPEED (R.P.M.)
PR= PROPELLER PITCH DIAMETER RATIO
QE= ENGINE TORQUE (kNm)
EP= ENGINE POWER (kW)
FF= MASS FLOW RATE OF FUEL (kg/hr)
PE= PROPELLER EFFICIENCY (%)
TE= ENGINE THERMAL EFFICIENCY (%)
OP= OVERALL PROPULSIVE EFFICIENCY (%)

  NE       PR        QE        EP        FF        PE        TE        OP
 (RPM)    (P/D)     (kNm)     (kW)     (kg/hr)     (%)       (%)       (%)

 790      0.615     4.059     335.8     68.92     50.61     40.56     20.53

CONTROL PROGRAM INTIATED

CALCULATED REQUIRED PROPELLER THRUST= 39.92 kN

ENTER PSEUDO MINIMUM ENGINE R.P.M.? 790

 780      0.628     4.118     336.4     68.97     50.52     40.60     20.51
 770      0.641     4.195     338.3     69.25     50.24     40.66     20.43
 790      0.615     4.059     335.8     68.92     50.61     40.56     20.53

OFF MINIMUM FUEL CONSUMPTION BY 3.69%
```

5. DISCUSSION

5.1 THE SHIP SIMULATION

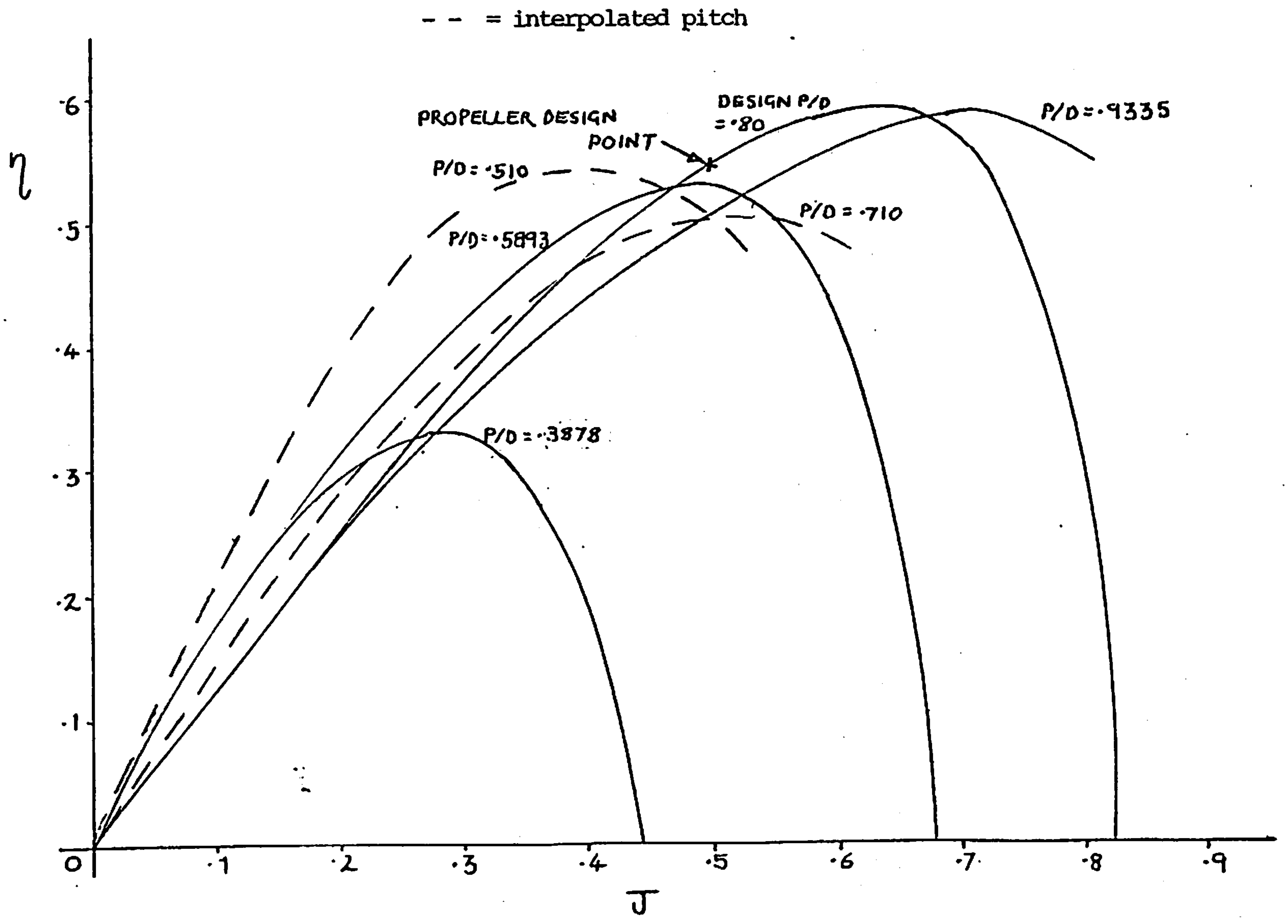
The simulation exhibited problems arising when representing continuous data using linearised digital techniques. This was exagerated in this study by the fact that only information on four ahead pitches were given in the open water propeller charts. Also, even though astern pitches were tested, J was not taken to bollard pull conditions (ie. J = 0) (although this was probably due to the primary interest in spindle torques of the experiments [11]). Initially, intermediate pitches were calculated for the K_T-J by linear interpolation between the model data pitches of 0, 0.3878, 0.5893 and 0.800. The same procedure was used for forming the P/D for K_Q and J matrix. This led to extreme gains and losses in propeller efficiency (η) at the intermediate pitches (P/D), so to counteract this, curves were fitted for K_T and K_Q against P/D for constant J (Figures 34 & 35, Appendix 2). A short experimentation with mathematical curve fitting proved difficult due to the irregularity of the functions produced, but it is considered that this approach should not be discounted for further work.

It was found that using data extrapolated from the curve fitted Figures 34 & 35 to increase the matrix sizes and decrease the errors of linear interpolation, gave unsatisfactory results. From Figure 26, it can be seen that the selected curve fitted pitches give distorted efficiencies. P/D = 0.51 shows a larger maximum than 0.5893, and P/D = 0.71 is lower maximum than 0.5893, whereas the inverse of both should be true. Now

$$\eta = \frac{J}{2\pi} \frac{K_T}{K_Q} \qquad (3)$$

For a particular J, K_T must be overestimated and/or K_Q underestimated for an unusual gain in η, and vice-versa for a loss in η. It is suggested that the errors are mainly due to the especially non-linear characteristics of the K_Q chart. These being a combination of curve fitting and linear interpolation errors, and incorrect extrapolation of P/D lines from J = 0 to 0.3.

FIGURE 26 - PROPELLER EFFICIENCY (η) VERSUS ADVANCE COEFFICIENT (J)



For typical CPP model data J would be extended to zero, but it is common practice to only test a few selected ahead P/D ratios. The model showed extreme sensitivity to changes in N_e and P/D, and in order for a more representative simulation to be developed for use in the control program the following procedure is proposed:-

In order to rationalise interpolated P/D performance the efficiency characteristics should first be plotted as in Figure 26 for the given P/D performances. A curve should then be fitted through the maximum efficiencies (ηm). This could be done mathematically, as from other data, the function produced is regular and, for example, a square root fit could be appropriate. Also mathematical fitting of the K_T-P/D curves for constant J could be attempted as this is a more regular function than for K_Q-P/D for constant J. Here a cubic fit would be appropriate as there are four x & y reference points, ie. model tested pitch-diameter ratios. It should be noted that an inclusion of a past design P/D may distort any function fitted as this is a discontinuity of the physical system (see Figures 27 & 28).

If relationships are then set-up between ηm and P/D, and J_{OPT} and P/D from the efficiency chart, then the following procedure may be used:-

1. For a particular P/D obtain ηm from ηm = f(P/D)

2. Find J_{OPT} value for P/D from J_{OPT} = f(P/D)

3. Obtain K_T from derived function of

$$K_T = f(P/D) \text{ for constant } J$$

4. Find K_Q from rearranging equation (3).

$$K_Q = \frac{J}{2\pi} \frac{K_T}{\eta}$$

This is then repeated for different pitch ratios but only goes part the way to solving the data interpolation problems as we only have one point of K_Q-J for the chosen P/D. As the lines of constant P/D have little curvature, then points about the K_Q at ηm would be enough to fit in a line of constant P/D by hand. Now there are two places where $\eta = 0$ and K_Q can be expressed as a function of P/D.

(i) When $\eta = 0$ and $J = 0$

and as $\eta = f(P/D)$

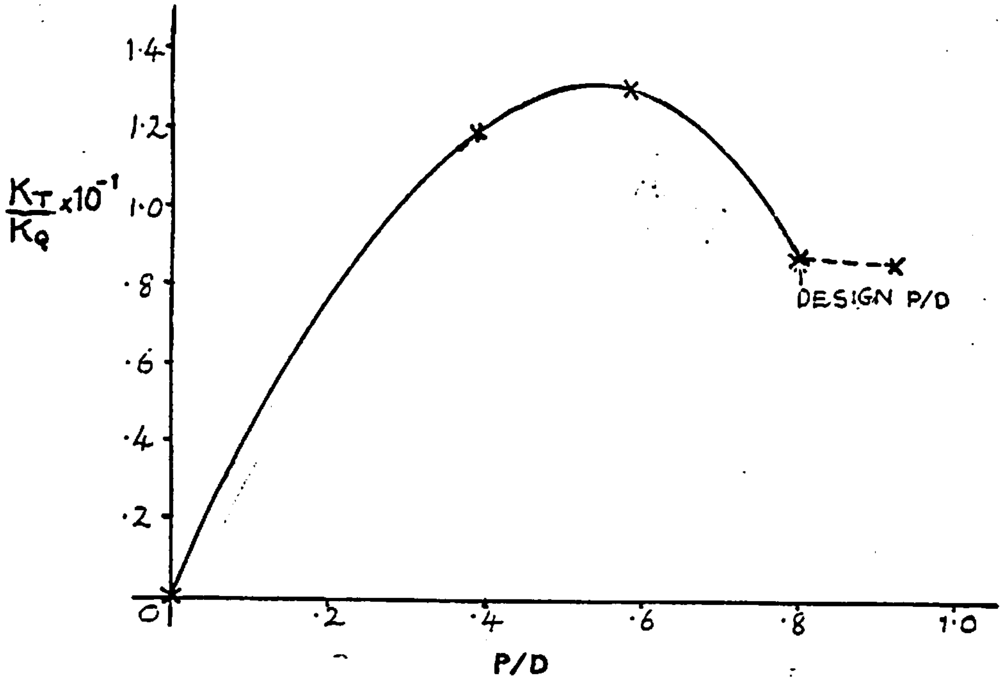
Thus $\frac{K_T}{K_Q} = f(P/D)$ (ignoring $1/_{2\pi}$)

This is plotted or functioned by using the given P/D ratios as shown in Figure 27.

Figure 27 - K_T/K_Q against P/D for $\eta = 0$ and $J = 0$

x = given P/D data

- - = past design P/D discontinuity



From this diagram the K_T/K_Q can be extrapolated for the selected P/D ratios and K_Q found by finding the value of K_T from the K_T-P/D constant J chart or function.

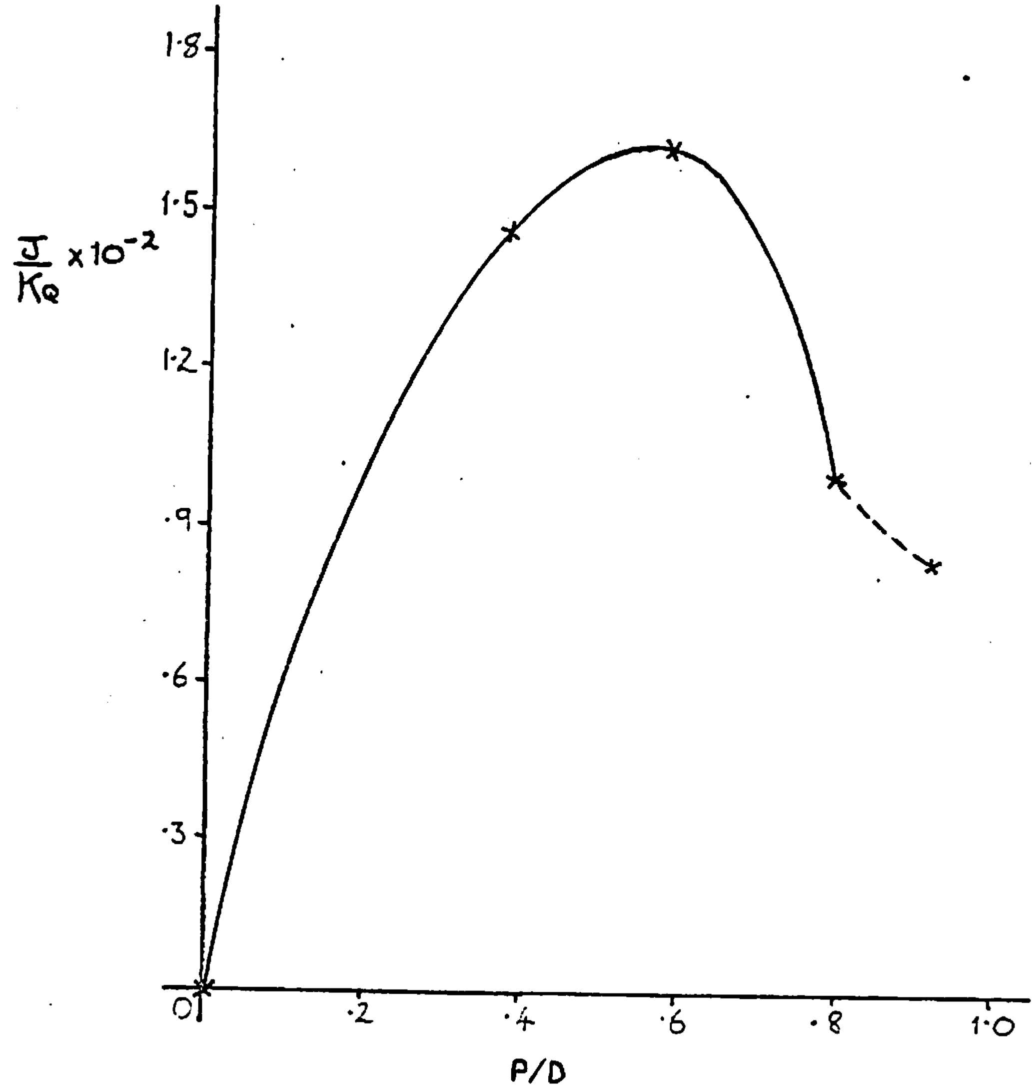
(ii) The second case is when $\eta = 0$ and $K_T = 0$ and now

$$\frac{J}{K_Q} = f(P/D)$$

Figure 28 - J/K_Q Against P/D for $\eta = 0$ and $K_T = 0$

x = given P/D data

- - = past design P/D discontinuity



Extrapolating or calculating the values of J/K_Q for various P/D ratios, K_Q can be found by the appropriate J value from constant J, K_T-P/D functions (since $K_T = 0$ and P/D is known).

More K_Q values for intermediate P/D ratios could be found by line fitting between the found intermediate P/D-K_Q values and the provided higher and lower P/D values.

The slope of a P/D line for K_Q-J may be checked by differentiating η.

Now $\eta = \frac{J}{2\pi} \frac{K_T}{K_Q}$

Differentiating w.r.t. J

$$\frac{d\eta}{dJ} = \frac{1 . K_T}{2\pi K_Q} + \frac{dK_T}{dJ} \frac{. J . 1}{2\pi K_Q} - \frac{dK_Q}{dJ} \frac{. J . K_T}{2\pi K_Q^2}$$

at maximum , $\frac{d\eta}{dJ} = 0$, and multiplying by 2π

and K_Q we get

$$0 = K_T + \frac{dK_T}{dJ} . J - \frac{dK_Q}{dJ} \frac{K_T}{K_Q} . J$$

thus $$\frac{dK_Q}{dJ} = \frac{K_T + \frac{dK_T}{dJ} . J}{J . \frac{K_T}{K_Q}} \qquad \text{——— (4)}$$

eg. for P/D = 0.80, $J_{OPT} = 0.625$

$K_T = 0.109$, $K_Q = 0.0178$

$$\frac{dK_T}{dJ} = \frac{0.071 - 0.163}{0.2} = -0.46$$

Using equation (4)

$$\frac{dK_Q}{dJ} = -0.047$$

From the K_Q - J chart

$$\frac{dK_Q}{dJ} = -0.046$$

Discretion should be used in correlating the two gradients, as equation (4) is sensitive to small changes in J, and an approximate agreement, eg. allowing 5% for extrapolation and number rounding errors, should suffice.

After plotting the now derived intermediate P/D ratios on the K_Q-J diagram, η should be plotted. The efficiency characteristics then can be correlated with the given P/D efficiencies and discrepancies altered by adjusting the K_T and/or K_Q value accordingly.

In order to generate an accurate simulation the matrixed produced of P/D for K_T and J, and K_Q for P/D and J, should be as large as possible around the 'working' P/D region. For this simulation it was between 0.3878 and 0.8000 (although past design pitches should be included). Interpolation should be by mathematical line fit to reduce compounded linear approximation errors such as was produced in this study.

Other improvements for the simulation could be in the propulsion coefficients employed ie. wake and thrust deduction fractions (W_t & t_d). The equation supplied by Lackenby and Parker [4] was for a steady-state velocity dependent relationship from standard hull series tests. Although hull form was taken into account, full size correlation is not known as this is considered to be a 'grey area' of understanding. Lewis [13] showed that relative rotative factor (ηr) was approximately constant at unity (ie. one) under towing and free-running conditions, thereby agreeing with the assumption made here. Yazalsi [14] showed that at high Froude numbers (greather than 0.13) W_t and t_d did not vary with P/D and agreed with Lewis [13] that at low Froude numbers they did vary with P/D. Lewis states that at low ship speeds and high thrust, W_t and t_d are dependent on P/D, n, and propeller thrust as well as V_s. He also gives methods for determining these from full size data.

The data used was not sufficient to be employed in this study but if incorporated into a ship simulation an iteration would have to be set-up. This would be to determine the appropriate values of K_T, P/D and J, under varying t_d and W_t with n and P/D.

Using a ship simulation in the control program has produced an inherent weakness in the system. This is due to the need for simulation accuracy to minimise search time. Although in this system it is seen as unavoidable, the need for ship simulation accuracy is fraught by a lack of basic information.

This is especially true for fishing vessels in which case a lack of comprehensive engine performance data appears to be available (as experienced by the author, with respect to one particular engine manufacturer). More generally a lack of compatible CPP performance data exists due to the non-existence of a standard series.

To overcome these problems, approximations would have to be made: for the engine Schanz [1] gives formulae; or optimum settings being determined purely by maximum propeller efficiency. For the propeller, standard fixed pitch series data would have to be employed approximating for a loss in propeller efficiency due to increased hub diameter and blade thickness. The varying radial pitch distributions of a CPP with P/D will cause errors in simulating the propeller by using FPP data, but the magnitude of these are not known.

5.1.1 Ship Simulation Results

As previously discussed, the results did not give a correct simulation of performance due to interpolation distortions. However, general trends can be observed. The characteristic dipped N_e-FF function was obtained for trawling but the curve is exagerated due to the initial loss and gain at the N_e-FF curve inflection of propeller efficiency (η).

However, it can be seen from the results that for this propulsion unit the optimum settings ie. maximum overall propulsive efficiency (ηop), are generally dictated by maximum propeller efficiency.

This was due to the near linear fuel flow characteristics of the main engine (Figure 33, Appendix 1). It must be remembered that engine thermal efficiency (ηth) is dictated by the loading of the propeller on the engine, and that for a more variable fuel flow (FF) characteristic, a higher power does not necessarily mean a higher fuel flow. This leads to a greater interaction between ηth and ηp, and consequently the optimum settings of P/D and N_e.

For trawling the value of J was confined to between 0.075 and about 0.3. Now for constant V_s and R_T the variation in K_T with J is given by:-

$$J = \frac{V_a}{nD_p} \quad \text{and} \quad K_T = \frac{R_T}{\rho\, n^2 D_p^4}$$

$$\text{thus } K_T = \frac{R_T \cdot J^2}{\rho \cdot V_a^2 \cdot D_p^2}$$

Inserting typical values

where $\rho = 1025\ \text{kg/m}^3$ $\qquad$ $Dp = 1.875\ \text{m}$

$V_a = 1.2\ \text{ms}^{-1}$ $(V_s \approx 3\ \text{knots})$ $\qquad$ $R_T = 5 \times 10^4 N$

$$K_T \approx 10 . J^2 \qquad \text{———— (5)}$$

This explains why for small changes in n and hence J, there is a large increase in K_T and thus the appropriate P/D. These changes in P/D will be reflected in the fuel flow (FF) by the especially non-linear characteristics of the K_Q-J chart.

$$\text{ie.} \quad P_B = \frac{2\pi . n . Q_p}{\eta tr}$$

and $FF \propto P_B$

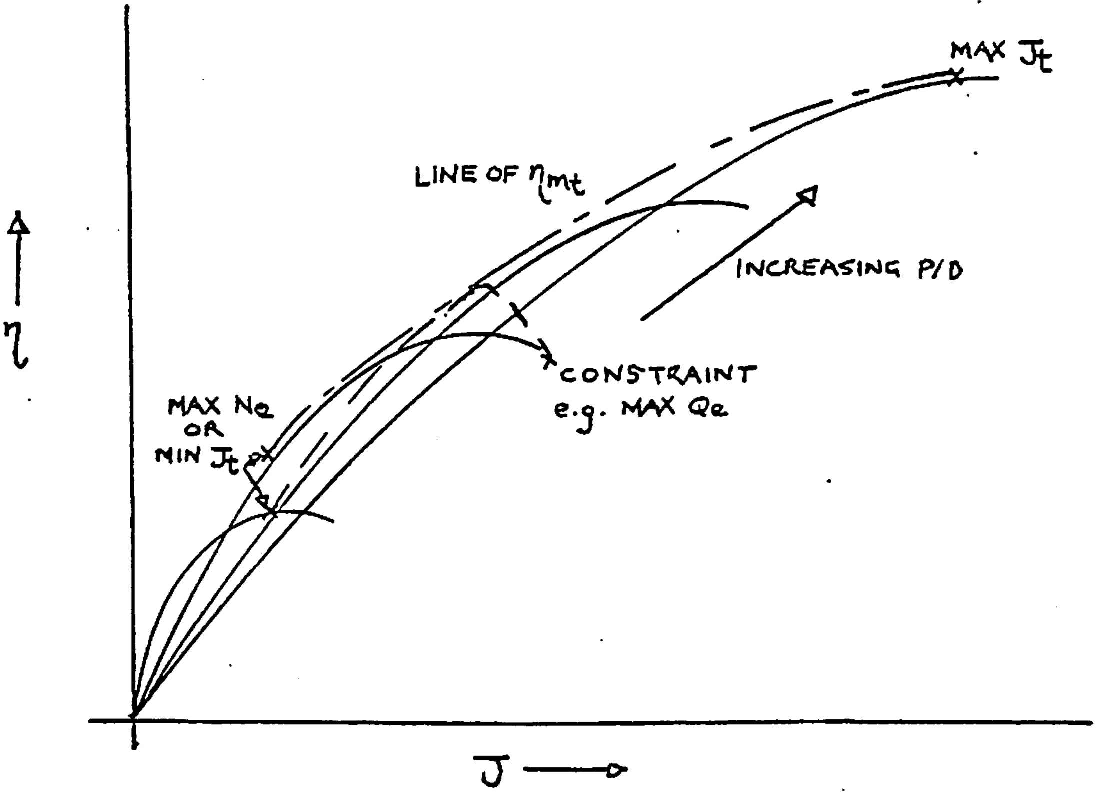
The operating J range under typical conditions is between 0.11 and 0.18 where P/D = 0.80. This narrowness in the range of J accounts for the sensitivity of the simulation to large changes in P/D, K_T and K_Q for small increments of J.

However, it is in the trawling mode that generally the widest range of N_e (and subsequent variation in FF) is available. This is because at higher speeds of advance, the N_e range is limited by the maximum P/D. To obtain the required V_s, the initial P/D at maximum N_e is relatively high, so the variation in N_e is limited by the small range in P/D.

To explain the dipped N_e-FF function the engine characteristics can be initially ignored and the trawling mode considered. As the simulation reduced N_e from full engine speed (N_{ef}), then P/D increased along with (for constant V_s and R_T) until there was a decreasing trend in η with greater P/D ratios. This is shown graphically in Figure 29 and the maximum trawling efficiency (ηmt) being achieved where the value of trawling J (J_t) encounters the extreme LHS efficiency characteristic.

Figure 29 - An Example of the Variation of η-J with P/D and N_e at Constant R_T and V_s Trawling

-- = representative variation line



Rewriting equation (4) (page 66), in mathematical terms the variation is represented by:-

$$\frac{d\eta}{dJ} = \frac{K_T + \frac{dK_T}{dJ}.J - \frac{dK_Q}{dJ}.\frac{J.K_T}{K_Q}}{2\pi K_Q}$$

so when $\frac{d\eta}{dJ}$ is positive, $K_T - \frac{dK_Q}{dJ}.\ J.\frac{K_T}{K_Q}$ is greater than $\frac{dK_T}{dJ}.\ J.$

Note that $\frac{dK_T}{dJ}$ and $\frac{dK_Q}{dJ}$ are negative for the considered P/D ratios.

When $\frac{d\eta}{dJ}$ is negative, then the relationship is vice-versa.

At ηmt then $\frac{d\eta}{dJ} = 0$, thus J_{OPT} is given by

$$J_{OPT} = \frac{K_T}{\left[\frac{dK_Q}{dJ}.\frac{K_T}{K_Q} - \frac{dK_T}{dJ}\right]}$$

If ηm is to be considered, perhaps for lack of engine data, then the following method may be used to find the N_e and P/D associated with the R_T and V_a:-

1. The maximum obtainable (shown by the ηmt line) is expressed as a function of P/D and J_{OPT}.

2. The line is plotted on the K_T-J and K_Q-J characteristics.

3. K_T is expressed as a function of J as in equation (5) (page 69) and iterated to find the values of K_T, J and P/D at the ηm line.

4. The values of P/D and J are entered at the K_Q-J diagram to ensure that maximum torque (Q_{em}) is not exceeded. If so, then K_T (and J) would have to be iteratedly reduced to find the N_e and P/D at Q_{em}.

The constraints of the system can be said to be divided into hard and soft constraints. The hard constraints are Q_{em}, N_{ef} and minimum N_e; whereas the maximum P/D can be considered a soft constraint as this is only there to stop unnecessary overloading of the engine. Physically, this usually takes the form of a stop on the yoke lever and can be removed. The maximum P/D constraint was removed from the simulation and interpolated P/D ratios were not unusually distorted due to the linearity of the P/D variation from 0.80 to 0.9335.

The results showed that no further gain in overall propulsive efficiency (η_{op}) was possible, and this is due to fact that increasing P/D past design pitch there is a decrease in propeller efficiency (η). It should not be ruled out however, that η_{op} could be increased in past design P/D if a greater increase in η_{th} may be achieved (see Figure 2, for example) relative to the loss in η.

Fuel savings from worst to best settings of N_e and P/D for trawling, were at most 34% and on average around 25%. The former figure is considered to be a distortion error, but the latter is thought to be representative, agreeing with results obtained by Bennett [6]. In fact, Newage Propeller Systems Limited [9] quote savings in fuel of 20% for a two-pitch propeller system relative to a FPP. This can be substantiated by comparing the η at 0.80 and at an equivalent single trawling pitch used for a two-pitch system. This will be the P/D to absorb full engine power at full RPM, at a maximum trawling speed eg. 5 knots. Using the K_Q-J chart this is about 0.73 P/D, and assuming J_t = 0.10 for a typical value then

when $J_t = 0.10$

for P/D = 0.80, $\eta = 0.120$

This is for a CPP and a FPP will have a propeller efficiency (η) about 2% due to increased hub size and blade thickness.

thus $\eta = 0.12 \times 1.02 = 0.122$
for P/D = 0.73
$\eta = 0.156$

Thus there is a gain of 22% in propeller efficiency and a reduction of engine power of the same magnitude. There will be a corresponding reduction in fuel flow (FF) if engine power (P_B) & FF.

The use of a two-pitch system is attractive in the sense that it does not allow extreme off optimum running of P/D. It can be said that this system offers a greater reliability of a lower fuel consumption relative to a misused CPP, but it does not give the high manoeuvring and reversing ability of the CPP. There will also be losses in ηop from the optimum N_e and P/D settings changing with V_a and R_T. However, as discussed in the introduction, this is not at present achievable in practice.

The Newage two-pitch propeller system has been fitted on a number of British fishing vessels but has been unpopular due to mechanism reliability problems. In principle, it does offer on the whole a better aid to lower fuel consumption than would a CPP system using random settings of N_e and P/D. Only with an optimising control system could the CPP be guaranteed to show lower fuel consumption.

5.2 THE CONTROL PROGRAM

In testing with the ship simulation, the program found the minimum fuel flow within +0.5%, and would perform better with a less accute engine speed (N_e) - fuel flow (FF) curve inflection caused by the distorted P/D efficiencies. The iteration step (IS) of 10 RPM was found by experimenting, as a too large step distorts the program's FF referencing, and a too small step results in excess iterations.

On an iteration search from being initially referenced off the minimum, the iteration step (IS) was increased by 5 RPM. This decreased the number of iterations and was found not to distort fuel flow referencing or quadratic line fit.

The quadratic line fit performed fairly well, but due to the sharp inflecton of the N_e-FF curves, the lowest FF was not always found. The sharper inflection is not considered typical as a more gradual typical function would hope to give better results. This line fit method was used as it was summised that the simulation derived optimum settings would not be far from the actual minimum values arising in the real system.

Other line search methods such as Fibonacci search and golden section (see reference 2) used extreme value iteration. These would not be as efficient as quadratic fit in this case, and it could be alarming to a skipper to hear his engine RPM rising to maximum and then lowered to minimum!

The humped N_e-FF function produced at free-running was due to simulation errors and is not considered to be a scenario to be dealt with. It is realised, however, that discontinuities may occur in the real system but the iteration step should be large enough to nullify these.

5.2.1 The Control System

This control system works on a steady state principle, unlike dynamic analogue controllers, and its stability will depend on the accuracy of the inputs and the tolerances or gains allowed for fluctuations in signals from these. Therefore, working on a steady state principle, all dynamic effects must be allowed to settle.

The governing dynamic or transient variation is the change in ship speed due to incorrect system settings of N_e and P/D. Initialising the system to monitor ship speed (V_s) will be after an allowance for the time lag due to setting of P/D, as the N_e lag is very small and is a characteristic of the system used. This may be in the order of a minute, after which V_s is sampled from the speed log, say every second, and averaged over 10 secs. From this program, it can monitor the change in V_s with time ie. dV_s/dt.

Now for a change in V_s

$$M + AVM.\ \frac{dV_s}{dt} = \Delta R_T$$

where

M = mass of the ship (kg)

AVM = added virtual mass (about 10%)

ΔR_T = difference in propeller thrust to resistance

So knowing M and AVM, ΔR_T can be calculated by averaging dV_s/dt over say 3 minutes and R_T incremented by ΔR_T and the program re-run. If the settings were the first derived system optimums, then the new value of R_T would demand new optimum N_e and P/D. If this was not the case, then the variation in V_s could be due to differences in real and simulated wake and thrust deduction fractions (W_t and td), and the new R_T results only in the program finding a new P/D. The allowance for a change in V_s is obviously a stability problem as it must be carried out for every iteration. To aid stability an inherent minimum tolerance or gain for sampled average V_s would be needed to prevent system hunting. Further increases in tolerance for monitoring of V_s after the minimum FF has been found, could be an adjustable input.

Ideally, if the system was fitted on a new ship, then simulation derived optimums could be correlated to the physical trials performance. Since the market for such a system lies in existing CPP fittings, then the program could be programmed to 'learn' the real ship optimums as they are found. This could be accomplished by the system storing the located real system optimum settings in a second matrix for V_s and R_T, along with the model derived optimums.

The use of a fuel rack position (FRP) sensor correlated with N_e is suggested as an alternative to a fuel meter; reducing system first cost and maintenance (and probably increasing reliability) of fuel flow monitoring. As the engine ages the ideal FF obtained by the equation from FRP will obviously differ from the real FF, but this will not matter as all FF comparisons are relative.

The use of an accurate N_e monitoring device (a photo-electric tachometer is suggested) is desirable due to inaccuracies inherent in engine manufacturers equipment and the accuracies demanded here.

P/D measurement by correlating yoke lever position to P/D or pitch angle, is not seen as a problem and is commonly employed on larger vessels.

As with any monitoring device the output is only as accurate as the input, therefore regular servicing requirements of the monitoring equipment would be mandatory.

The system has been specified so that the minimum of monitoring equipment is required, and the temptation of expanding the equipment to include a shaft torque meter and thrust meter has been avoided for reasons of system cost and reliability.

Detection and prevention of exceedence of maximum engine torque can be achieved in several ways:-

1. The use of a secondary flyball mechanism on the engine governor.

2. Correlating FF to N_e at maximum Q_e.

3. Using the simulation derived maximum Q_e.

4. Using installed engine monitoring equipment of cylinder pressure for maximum B.M.E.P, and/or correlating exhaust gas temperature, and/or water jacket temperature, and/or checking for N_e drooping.

For larger vessels this is already accounted for, but for smaller crafts the answer may lie in a combination of the suggested techniques, as it is important that continuous operation never exceeds this constraint. Pitch trimming would be required if Q_{em} was exceeded and N_e altered to maintain V_s by the optimisation control program.

This project did not take into account variable or constant power take-offs from the main engine. To account for this, further monitoring equipment would be necessary to quantify the amount of power taken-off by the auxiliaries. This would require the ship simulation to be run and the control program to act on the model to derive the optimum settings. The auxiliary power requirement would then be added to the simulation derived propeller loading when the iterative search commences.

Due to the fact that the time required for optimisation to be established could be between 15 to perhaps 40 minutes, then its at sea application is to a long term steady-state V_s mode of operation. There is here perhaps, the need for a choice of open loop control ie. only setting the program optimums, and the closed loop control search. So not only is the initialising of the system operated by the skipper but also its mode of minimisation.

The real test of any shipboard control system is its ability to cope with a crash astern manoeuvre. As this system is in control of the manoeuvring operators then disengagement is to be implemented immediately by any movement of the N_e or P/D controls at the bridge or engine room. Alternatively, the program could be disengaged at the system terminal. This will then allow for execution of emergency actions.

Further program improvements could include the engine load-speed droop characteristics, disallowed regions for torsional vibration and/or severe propeller cavitation.

Generally, the applicability of such a control system to a CPP installed fishing vessel will depend on the availability of data defining the propulsion plant characteristics, and the fishing method employed. For mid-water (pelagic) trawling the system finds its application by ensuring a constant ship speed (V_s) required to maintain the trawl at its set depth. Also it is more likely to have a longer duration of constant steady-state conditions ie. trawl load, compared to a bottom (demersal) trawl. The demersal trawl load will vary according to the types of sea-bed conditions encountered and for this case, an open loop control mode would be appropriate.

Purse seiners (surrounding net type fishing method) require very high powers for high free-running speed and for a very large hydraulic system drive load when hauling. These types of vessel usually employ a CPP and the system could be applicable, not only at free-running, but during the sometimes prolonged reduced speed searches for fish shoals.

On smaller CPP installations the system may not be economically or otherwise acceptable, and computer software could be produced using estimates for inputs, and deriving optimum settings from maximum propeller efficiency as a guide to operation.

The profitability of the fishing operation today is being diminished by falling catches and high operational costs (fuel being about 50% of these). The former can only be improved by the enforcement of legislation, but the latter could be considerably reduced by the refining of the present 'courseness' of operations.

These include towing the gear at its optimum design speed with the assistance of an accurate speed log, and steaming at an economic free-running speed. Figure 3 showed the typically steep speed-resistance curve for a modern fishing vessel form. A reduction from design V_s of half a knot reduces fuel consumption by 14%, and one knot by 23%. Clearly any reduction in this speed must be correlated to lost revenue per day for example, and this sort of calculation lends itself to computer software.

The role of computers is already widespread in the shipping world and it cannot be long before it becomes a vital aid to the fishing vessel owner and skipper.

5.2.1.1 Other ship type applications

In the merchant field the most obvious application is to the tug with its similar towing and high free-running modes. Also, for example, if the tug is to be used in an integrated barge pushing (or towing) application it effectively becomes a small ship. Fuel flow may be minimised in this role or when the tug is separated and free steaming.

For passenger vessels such as liners or ferries; schedules are usually maintained by the use of a combination of ship speeds on route; and the

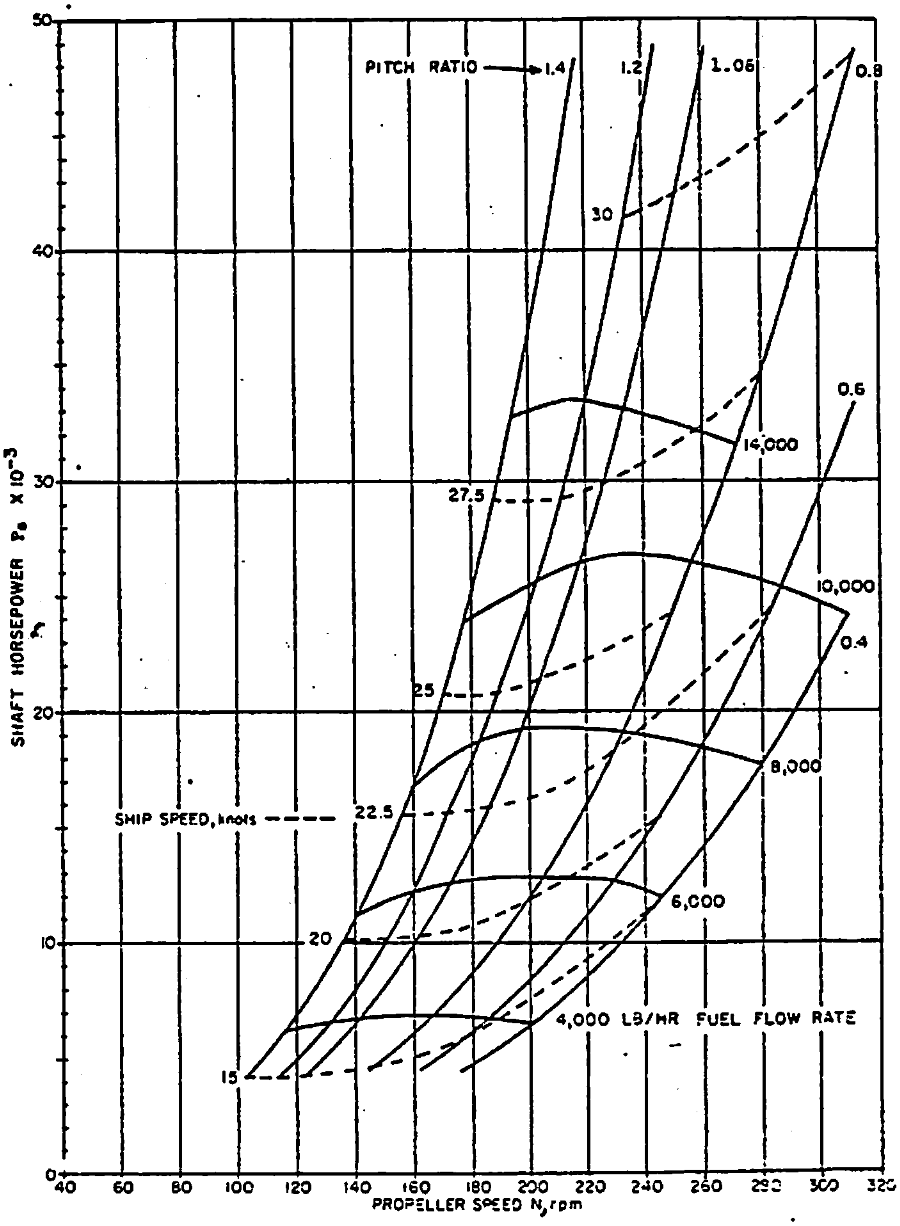
system is pertinent for this application.
For vessels altering their economic speed eg. container ships, or generally any ship required to achieve and maintain a particular speed using a CPP, then the control system is applicable.

A more recently developed ship type in which the CPP is almost ubiquitously fitted, is the oil rig supply vessel. These are used in sea and/or ice conditions, and as with the aforementioned ship types are fitted with very large engine powers. The percentage savings in fuel consumption appropriated with the proposed control system may not be as large as with a smaller towing vessel, but the fuel cost savings will be proportionally increased.

The use of a combinator system on some of these ship types but this would not cause any application problems. It is recommended that for future merchant ship combinator design, that the operational line or schedule be drawn through the maximum overall propulsive efficiency lines. These may be derived from the proposed ship simulation. It must be remembered that these derived 'optimum' settings are only for one ship resistance characteristic, but this is the limitation of using a single lever control system.

The naval use of CP propellers has become extensive, due to increasing faith in its reliability, and the necessary application in combined prime mover units eg. CODOG (combined diesel or gas turbine), CODAG, COGOG used on type 21 and 22 frigates. Rubis [3] carried out a simulation for a COGAG destroyer machinery system and Figure 30 shows the high-speed-range steady-state characteristics.

Figure 30 - The High-Speed-Range SHP versus Ship Speed, Propeller Speed and Fuel Flowrate for a COGAG Destroyer



In theory, eg. at 22.5 knots the difference in best to worst fuel flow is 28% (7000 lb/hr) to 9800 lb/hr). In reality the limits on a P/D-N_e iteration would be cavitation with the resulting underwater noise, and the special limit characteristics of the gas turbines. Generally, these systems work on a combinator system with a linear relationship between ship speed (V_s) and lever position. This does not account for optimum settings, which would be located under cruising conditions using the control minimisation. Due to the inefficiencies of gas turbines under part load and the need to conserve fuel for combat purposes, the system offers great advantages to naval application.

6. CONCLUSIONS

It was found that by using model CPP data in a digital simulation, significant errors were generated by linear interpolation. A method was therefore proposed for overcoming the lack of data provided from model CPP tests, to rectify simulation errors. The variation in fuel flow, for constant ship speed and required propeller thrust, under trawling conditions was thereby realistically found to be around 25%.

However, minimisation of fuel flow under changing resistance, hull, propeller and engine conditions in the real system would require a control system.

A control program was therefore developed and tested for its minimisation properties, and observed to satisfy various search requirements and constraints, locating the optimum within 0.5%.

A control system package was thereby proposed which could have an application for a large range of ship types.

With regard to fishing vessels, it was considered that compared to FPP, a two-pitch propeller system would be a more reliable way of achieving lower fuel consumption than the uninformed use of a CPP.

It was recommended that for future merchant ship CPP combinator design, that a ship simulation be used to locate the optimum settings. From this, the pitch and engine speed schedule may be derived for maximum overal propulsive efficiency, but this will only be for one hull condition.

6.1 RECOMMENDATIONS FOR FUTURE WORK

The fishing vessel simulation should be re-run using the propeller performance data extrapolation method described. Simulation runs could also be carried out on different ship types to determine the fuel savings possible using such a control system.

More pitch angle settings should be used in cavitation tunnel tests due to the peculiarity of below design P/D performance.

Correlation of full size to simulation performance and optimum settings prediction could also be carried out.

The economic validity of the proposed control system package should also be analysed for two lever and combinator CPP systems. Finally, the economic merits of a two-pitch propeller system relative to an optimised, and non-optimised CPP system for fishing vessels should be investigated.

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APPENDIX 1

Propeller and Engine Performance Figures

FIGURE 31 - K_T-J DIAGRAM WITH EXTRAPOLATED P/D LINES (USING 5 COMPONENT DYNAMOMETER RESULTS) [11]

- - = extrapolated P/D line

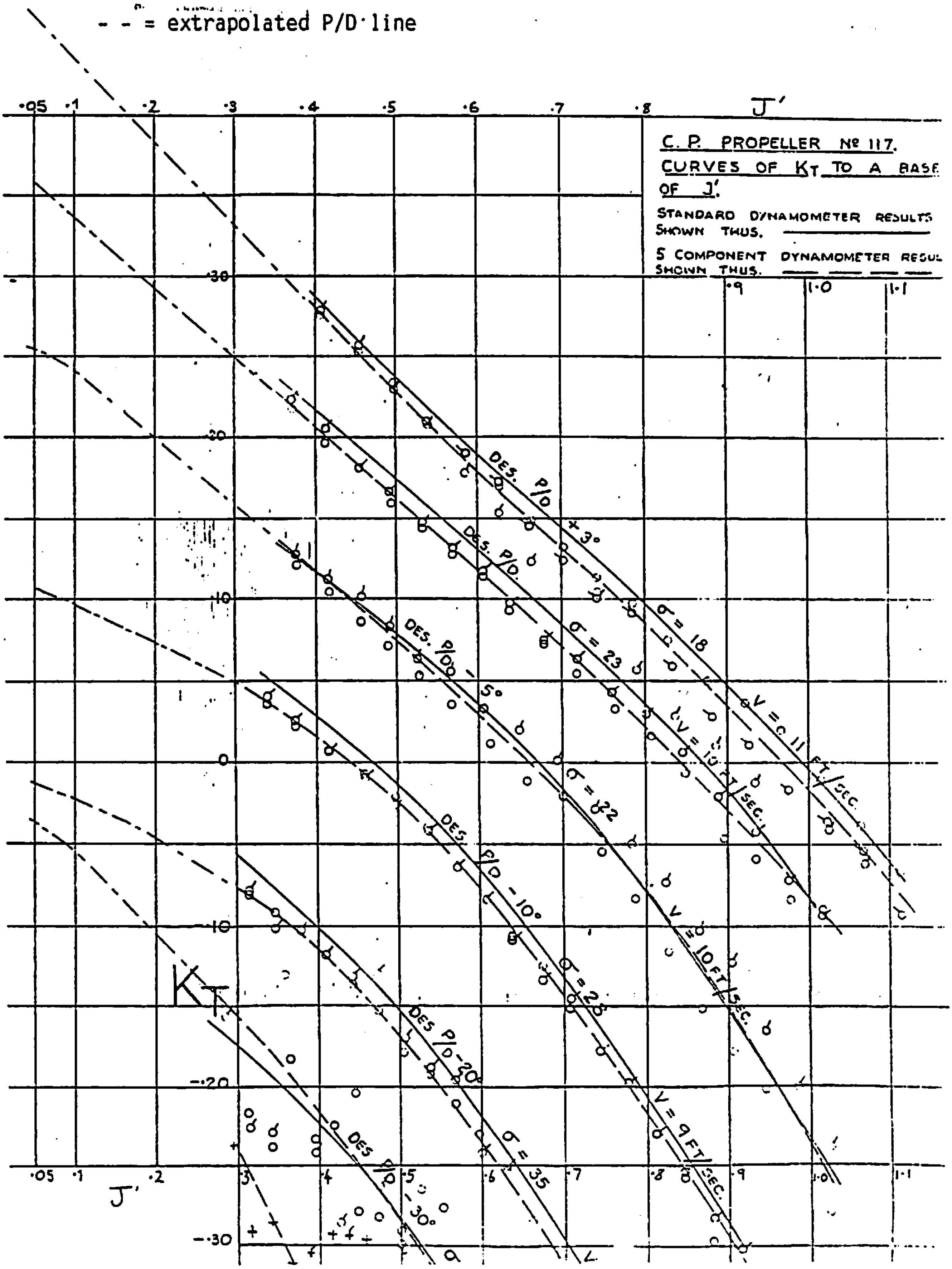
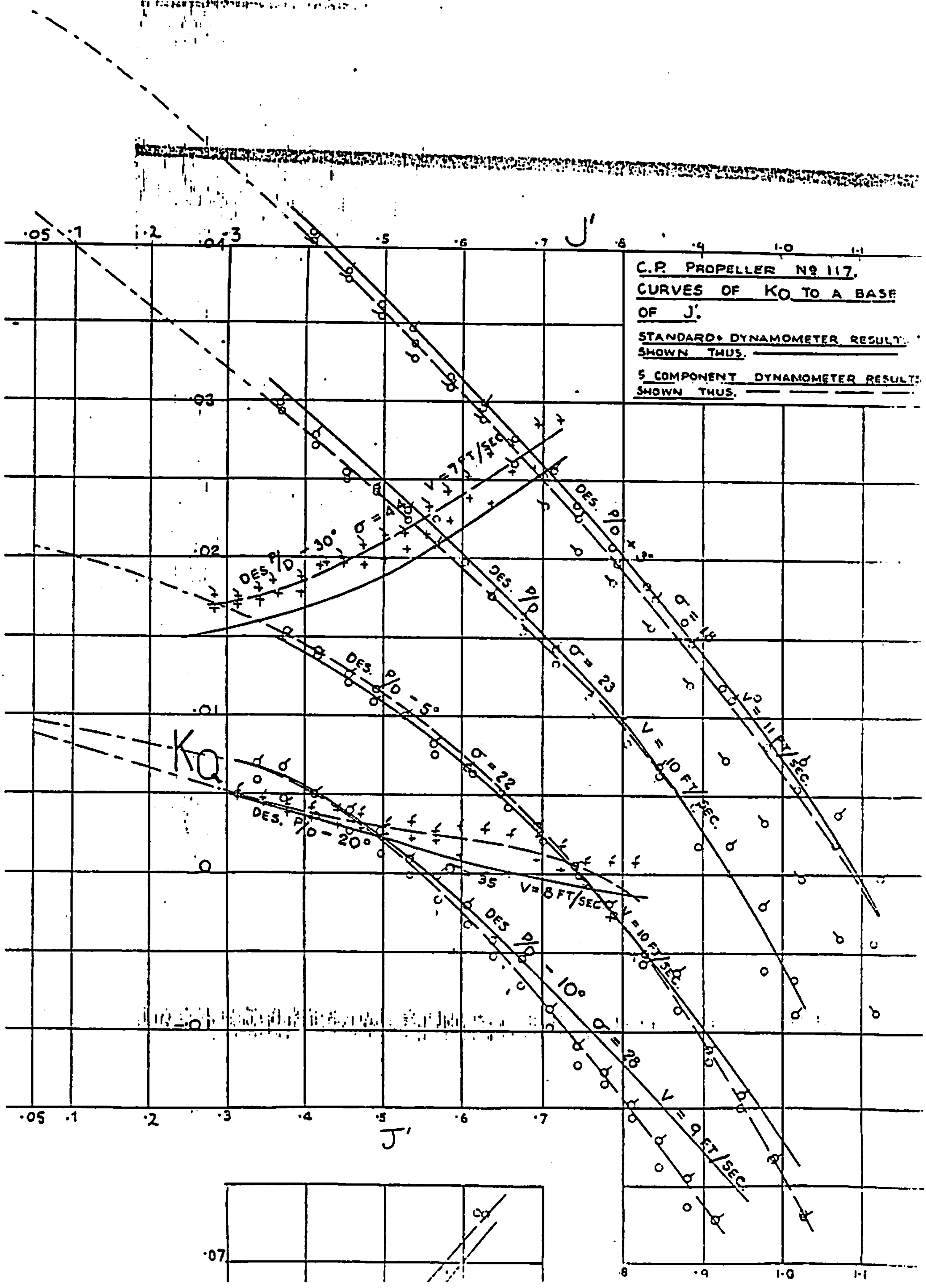
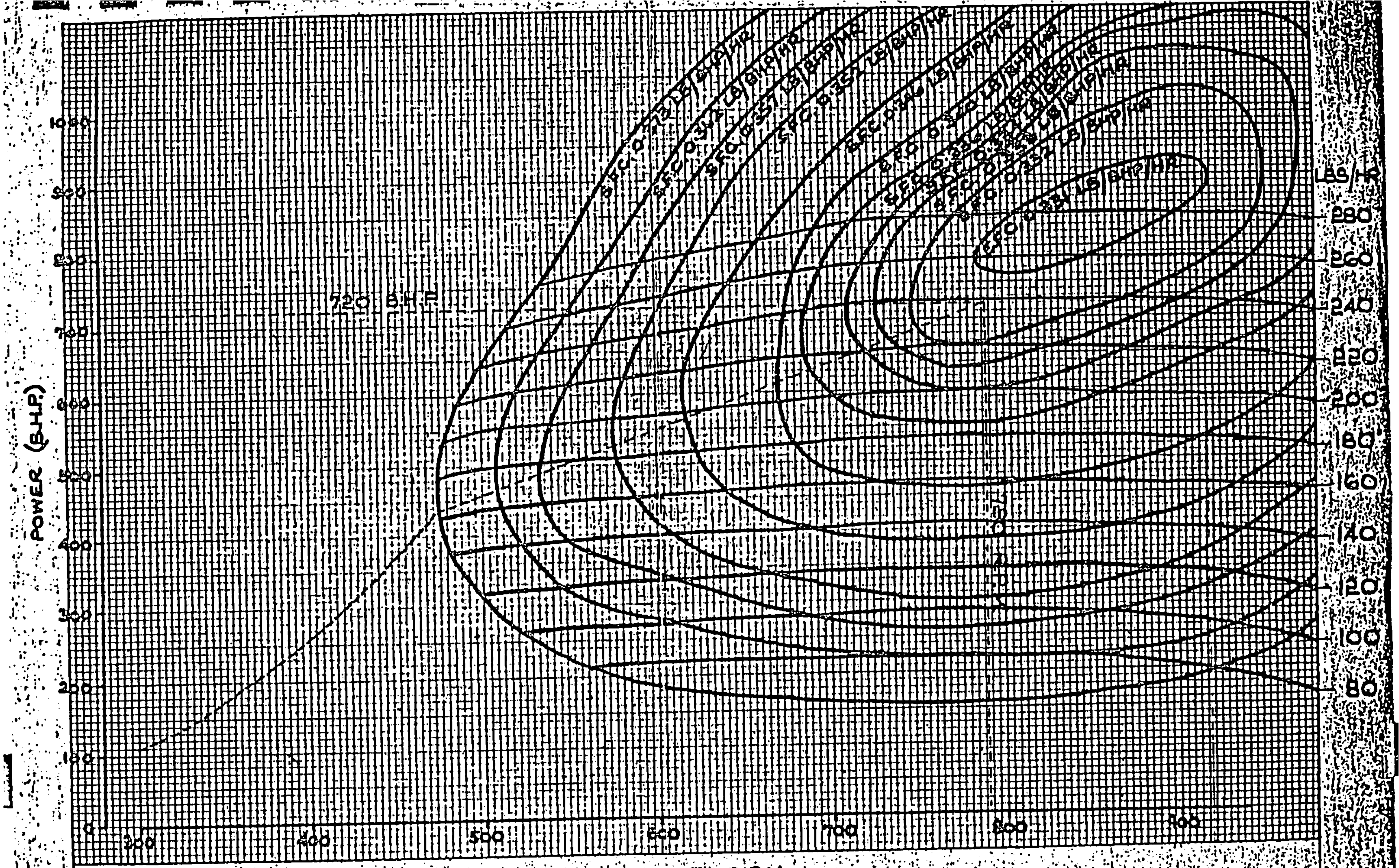


FIGURE 32 - K_Q-J DIAGRAM WITH EXTRAPOLATED P/D LINES (USING 5 COMPONENT DYNAMOMETER RESULTS) [11]

- - = extrapolated P/D line





ENGINE R.P.M.

ESLG MK II ENGINE CARPET CURVES, BROWN BOVERI VTR 200 TURBOCHARGER BUILD MZ 84AS268 IV CH6IAW3P

FUEL CONSUMPTION CURVES)

REPORT NO.	DATE	CURVE NO.	FIG NO33

APPENDIX 2

Fitted Propeller Data Extrapolation Figures

FIGURE 34 - K_T AGAINST P/D FOR CONSTANT VALUES OF J WITH FITTED CURVES

x = given P/D performance

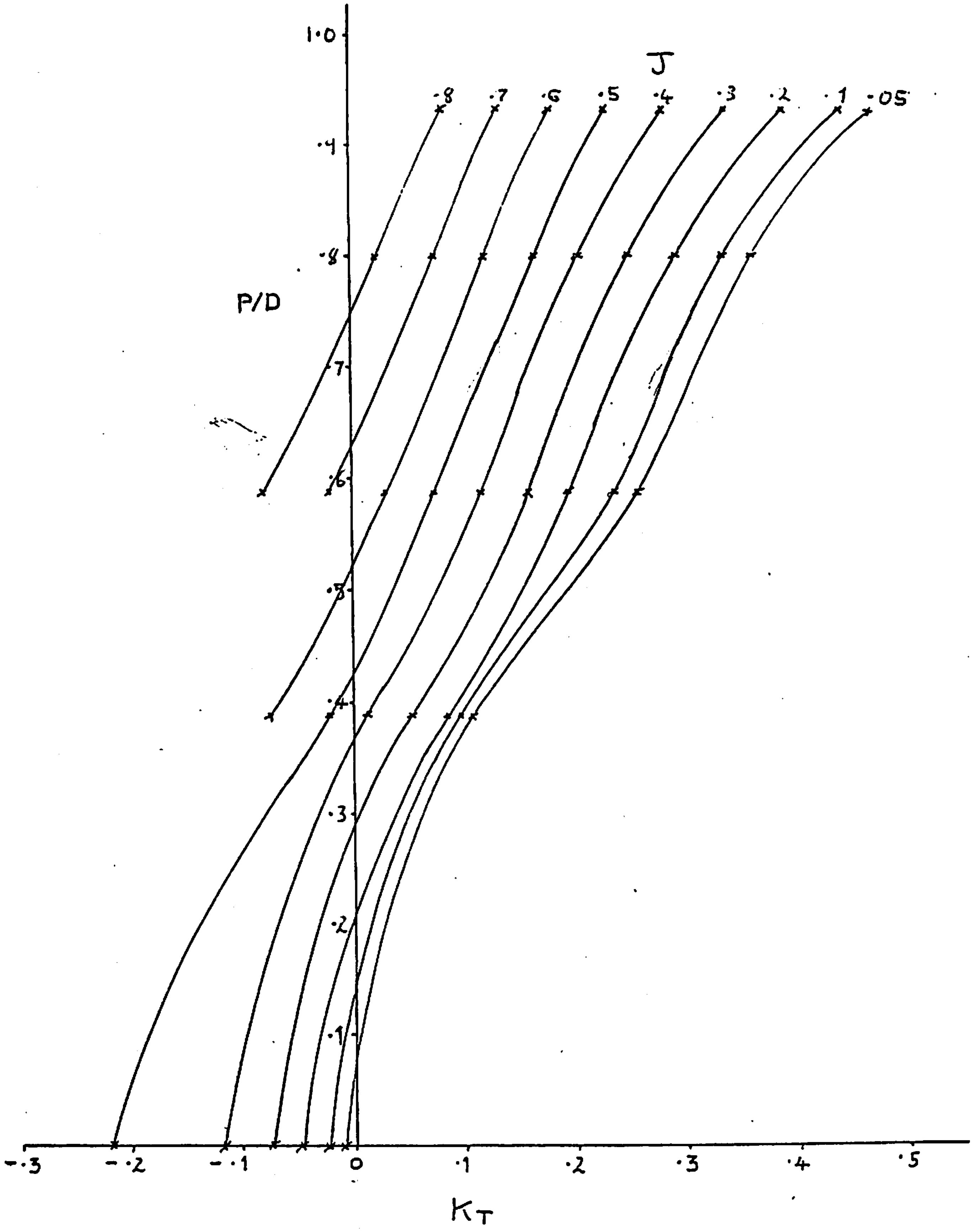
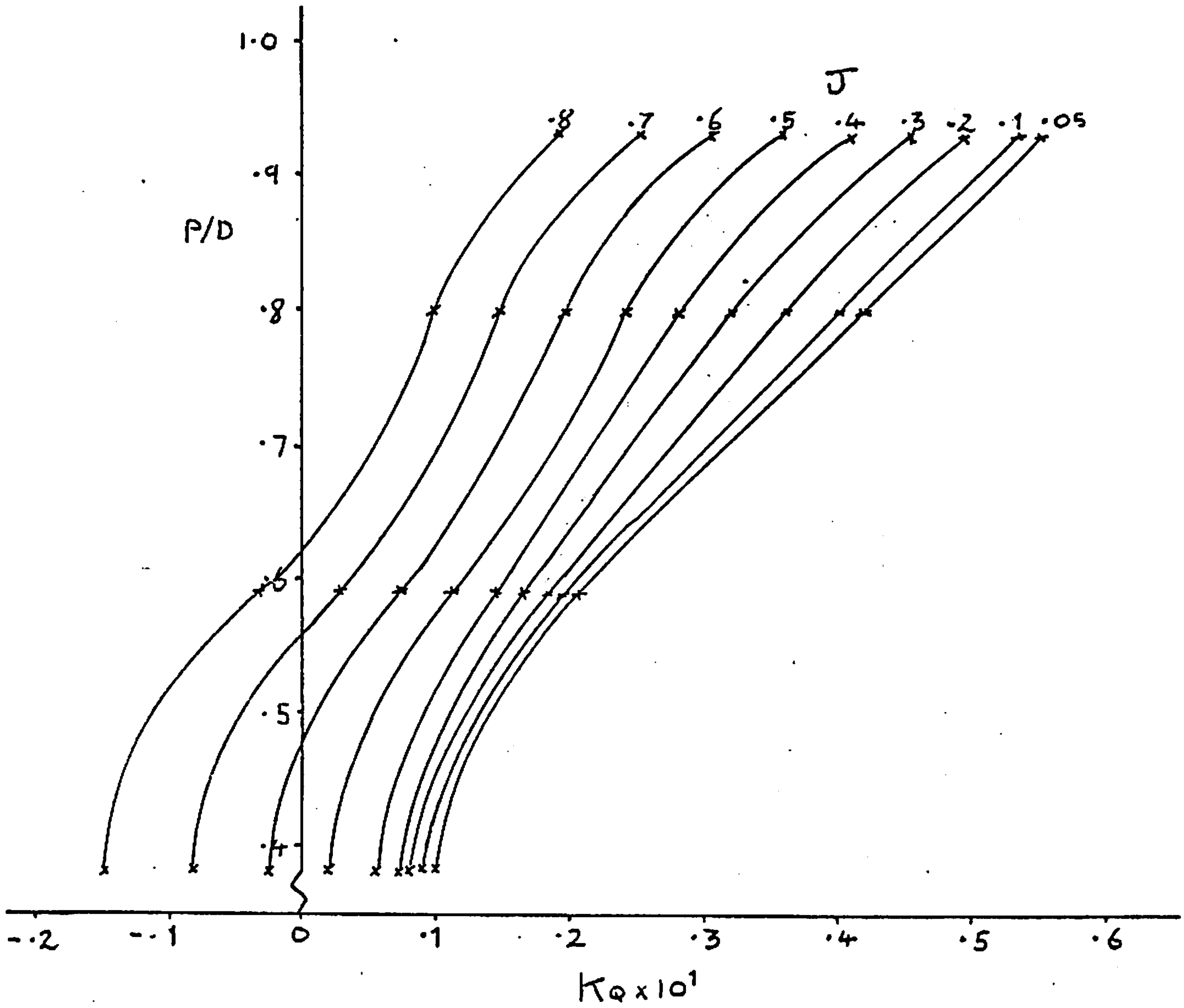


FIGURE 35 - K_Q AGAINST P/D FOR CONSTANT VALUES OF J WITH FITTED CURVES

x = given P/D performance



APPENDIX 3

Tables of Extrapolated Data

TABLE 3.1- Residuary Resistance Coefficient (C_r) Against Ship Speed (V_s) Extrapolated From Ridgely-Nevitt [2]

V_s(knots)	C_r
1	8.53
2	7.49
3	4.33
4	2.87
5	2.31
6.4	2.1
7.3	2.31
8.2	2.82
9.1	3.55
10	3.97
10.5	5.62
11	5.8
11.5	6.45

TABLE 3.2 - Calculated Ship Speed (V_s) Against Resistance (R_s)

V_s(knots)	R_s(kN)
2	1.75
3	2.69
4	3.72
5	5.14
6	7.07
7	9.67
8	13.76
9	19.86
10	26.47
11	41.14
11.458	47.84

TABLE 3.3 - Extrapolated Feasible Values of Propeller Pitch-Diameter Ratio (P/D) for Various Propeller Thrust Coefficient (K_T) and Propeller Advance Coefficient (J)

	J								
P/D	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
K_T 0.07	.315	.340	.365	.425	.490	.530	.680	.800	.903
0.10	.374	.390	.411	.475	.550	.649	.760	.815	.956
0.125	.412	.430	.451	.539	.611	.715	.818	.920	-
0.15	.449	.464	.494	.570	.675	.771	.874	-	-
0.175	.475	.495	.540	.631	.735	.830	.926	-	-
0.200	.510	.528	.590	.697	.791	.880	-	-	-
0.225	.540	.565	.659	.751	.840	.925	-	-	-
0.250	.575	.615	.720	.800	.885	-	-	-	-
0.275	.624	.680	.770	.840	.925	-	-	-	-
0.300	.680	.745	.810	.876	-	-	-	-	-
0.325	.740	.800	.845	.915	-	-	-	-	-
0.350	0.790	.835	.880	0.95	-	-	-	-	-
0.375	0.830	.865	.914	-	-	-	-	-	-
0.400	0.865	.890	.942	-	-	-	-	-	-
0.425	0.842	.915	-	-	-	-	-	-	-
0.450	0.920	.940	-	-	-	-	-	-	-
0.465	0.9335	-	-	-	-	-	-	-	-

These values are extrapolated from figure 34.

TABLE 3.4 - Extrapolated Feasible Values of Propeller Torque Coefficient (K_Q) for Various Advance Coefficients (J) and Pitch-Diameter Ratios (P/D)

	J								
$K_Q \text{x} 10^{1}$	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
P/D 0	0.0884	0.0780	0.065	0.055	0.052	-	-	-	-
*0.3878	0.0997	0.0925	0.083	0.073	.055	0.020	.025	.077	0.145
0.4300	0.110	0.101	0.090	0.083	-	-	-	-	-
0.4700	0.125	0.116	0.105	0.095	0.075	-	-	-	-
0.5100	0.145	0.138	0.126	0.114	0.094	-	-	-	-
0.5500	0.173	0.163	0.151	0.136	0.115	0.081	-	-	-
*0.5893	0.2070	0.2000	0.186	0.169	0.145	0.115	.075	0.029	.030
0.6300	0.245	0.232	0.217	0.195	0.169	0.140	-	-	-
0.6700	0.285	0.271	0.250	0.225	0.195	0.167	-	-	-
0.7100	0.325	0.310	0.284	0.252	0.221	0.191	0.150	-	-
0.7500	0.366	0.350	0.317	0.282	0.247	0.213	0.170	0.125	-
*0.8000	0.4200	0.4000	0.360	0.320	0.280	0.239	0.194	0.145	0.099
0.8400	0.464	0.437	0.397	0.355	0.311	0.265	0.218	0.170	-
0.8700	0.492	0.468	0.427	0.383	0.340	0.290	0.239	0.191	-
0.9000	0.521	0.500	0.46	0.416	0.371	0.317	0.266	0.216	0.160
*0.9335	0.5500	0.535	0.495	0.455	0.408	0.357	0.305	0.250	0.192

Values marked * are extrapolated from figure 32, otherwise are from figure 35.

TABLE 3.5 - ENGINE PERFORMANCE DATA MATRIX OF FUEL FLOW (FF) FOR VARIOUS ENGINE SPEEDS (N_e) AND ENGINE BRAKE POWERS (P_B)

		N_e (RPM)													
	FF(lb/hr)	475	500	525	550	575	600	625	650	675	700	725	750	775	790
P_B (BHP)	150	75	70	65	61	60	59.5	58	57	56.5	56.25	56	55.9	55.8	56
	200	89.8	84.04	80	77	76	75.5	75	74	73.6	73.59	73.25	73.13	73.11	73.12
	250	103.11	99.64	95.64	93.1	92.5	92.31	90	90.5	89.52	89.5	88.89	88.70	88.3	88.51
	300	118.11	115.56	111.89	111.25	109.32	109.09	108.33	107.1	106.74	106.33	105.58	105.03	104.6	104.94
	350	134.61	130.67	128.51	128.42	125.53	124.78	124.12	123.2	123.11	122.21	121.19	121.8	122.04	121.9
	400	151.25	147.25	144.44	142.5	141.19	140	139.5	139.2	138.9	137.78	137.23	136.7	136.53	136.84
	450	168.23	166.23	162.27	160	159.5	159.02	156.67	155.7	155.38	154.84	153.48	152.22	152.89	153.11
	500	187.9	181.28	180	177.65	176.87	175.28	173.32	172.36	171.29	170.89	170.32	169.89	169.23	169.55
	550	-	200	197.47	195.74	194.82	192.5	190.88	188.76	187.23	186.44	185.5	185.06	184.67	184.68
	600	-	-	-	215.13	212.5	210.45	208.1	205.56	204.44	201.6	201.18	200.5	200	199.5
	650	-	-	-	-	-	227.69	225	222.35	219.5	218.5	217.58	216.3	216.26	216
	700	-	-	-	-	-	-	-	240	238	234.08	232.93	232.13	231.33	231.33
	750	-	-	-	-	-	-	-	-	-	-	267.53	265.96	265.35	265

TABLE 3.6 - Optimum Engine Speed (N_e) and Propeller Pitch-Diameter Ratio (P/D) Settings for Various Ship Speeds (V_s) and Required Propeller Thrust (R_T)

N_e(RPM)		V_s(Knots)							
P/D		2	3	4	5	8	9	10	11
R_T(kN)	25	-	-	-	-	669	733	-	-
		-	-	-	-	.549	.529	-	-
	30	-	-	-	-	730	749	618	
		-	-	-	-	.526	.546	.800	-
	35	-	-	-	-	783	778	644	-
		-	-	-	-	.510	.550	.800	-
	40	579	637	665	688	790	790	669	698
		.549	.516	.510	.520	.539	.573	.800	.800
	45	610	675	701	730	790	666	693	721
		.549	.513	.510	.510	.573	.800	.800	.800
	50	640	669	725	761	770	689	717	744
		.549	.550	.518	.509	.620	.800	.800	.800
	55	670	699	747	789	790	710	739	766
		.550	.548	.526	.510	.627	.800	.800	.800
	60	698	730	752	790	790	733	760	-
		.549	.545	.550	.536	.662	.800	.80	-
	65	724	759	779	790	790	-	-	-
		.550	.543	.550	.564	.697	-	-	-
	70	750	778	790	790	-	-	-	-
		.550	.549	.564	.593	-	-	-	-
	75	774	790	790	790	-	-	-	-
		.550	.562	.596	.631	-	-	-	-
	80	790	790	790	-	-	-	-	-
		.558	.587	.628	-	-	-	-	-
	85	790	790	-	-	-	-	-	-
		.582	.617	-	-	-	-	-	-
	90	790	-	-	-	-	-	-	-
		.610	-	-	-	-	-	-	-

TABLE 3.7 - Extrapolated Values of Propeller Thrust Coefficient (K_T) for Various Propeller Advance Coefficients (J) and Pitch-Diameter Ratios (P/D) from figure 31

	J								
K_T	0.09	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
P/D 0	-.010	-.022	-.048	-.075	-.115	-	-	-	-
.3878	.110	.099	.077	.050	.015	-.024	-.075	-.141	-.215
.5893	.255	.237	.199	.159	.115	.075	.030	-.021	-.077
.8000	.355	.335	.294	.250	.205	.163	.120	.071	.022
.9335	.464	.440	.389	.335	.280	.228	.179	.132	.085

TABLE 3.8 - Calculated Values of Propeller Efficiency(η) for Various Propeller Advance Coefficients (J) and Pitch-Diameter Ratios (P/D)

	J							
η	0.05	0.2	0.3	0.4	0.5	0.6	0.7	0.8
P/D .3878	.088	.295	.327	.174	-	-	-	-
.47	.106	.409	.478	.509	.398	-	-	-
.51	.110	.404	.503	.542	.517	0	-	-
.55	.106	.379	.492	.543	.540	.310	-	-
.5893	.098	.341	.449	.505	.519	.382	-	-
.71	.077	.275	.388	.467	.517	.490	-	-
.8	.066	.260	.373	.466	.543	.591	.546	-
.9335	.067	.250	.352	.437	.508	.560	.588	.564

APPENDIX 4

Ship Simulation and Control Program Listings

FIGURE 36

```
10 REM ENGINE/PROPELLER SIMULATION
20 DIM W(50),X(50),Y(50,50),Z(50)
30 PRINT
40 PRINT"         M.F.V. GLENUGIE IV PROPULSION SYSTEM SIMULATION"
50 PRINT"
60 PRINT"              PROGRAMMED BY G.A.WEBB AUGUST 1983"
70 PRINT
80 PRINT
90 PRINT"-------------------------------------------------------------
---------"
100 DP=1.875
110 PRINT"ENGINE SPEED IS 790 (RPM)":NE=790
120 INPUT"ENTER R.P.M. INCREMENTS";X
130 INPUT"ENTER SHIP SPEED (KNOTS)";VS
140 INPUT"ENTER ADDITIONAL THRUST (kN)";TA
150 IF VS<1.5 OR VS>11.458 THEN PRINT"SPEED OUT OF RANGE":GOTO 80
160 REM SHIP SPEED RESISTANCE CALCULATION
170 RN=VS*9110783!
180 CF=((.075/(LOG(RN)/2.302585-2)^2)+.0001328)*1.05
190 X1=VS
200 N$="RCDATA"
210 GOSUB 320
220 CR=Y1*.001
230 CT=CR+CF
240 WT=.30837-.023073*VS+9.7029E-04*VS^2
250 TD=WT
260 RS=(VS^2*CT*34.86897*1.2+TA)
270 RT=RS/(1-TD)
280 VA=VS*.5148*(1-WT)
290 NP=NE/150
300 GOTO 430
310 REM 2-D INTERPOLATION SUBROUTINE
320 OPEN"I",£1,N$
330 FOR I=1 TO 15
340 INPUT£1,X(I),W(I)
350 NEXT
360 CLOSE£1
370 FOR I=1 TO 15
380 IF X(I)>= X1 THEN GOTO 400
390 NEXT
400 Y1=W(I-1)+(W(I)-W(I-1))*(X1-X(I-1))/(X(I)-X(I-1))
410 RETURN
420 REM ROUTINE FOR FIRST EVALUATION OF PROPULSION SYSTEM PARAMETERS
430 XX=VA/NP/DP:ZZ=RT/NP^2/DP^4/1.025:C$="THDATA"
440 GOSUB 590
450 PR=YY
460 IF PR>.8 THEN PRINT"THRUST OUT OF RANGE RENTER":GOTO 80
470 ZZ=YY:XX=VA/NP/DP:C$="TQDATA"
480 GOSUB 590
490 QE=YY*NP^2*DP^5*.04182
500 IF QE>6.493 THEN PRINT"THRUST OUT OF RANGE RENTER":GOTO 80
```

```
510 ZZ=QE*NE*.140375:XX=NE:C$="ENGMAP"
520 GOSUB 590
530 EP=ZZ*.746:FF=.45*YY
540 PE=RT*VA*100/EP
550 TE=EP*8.3237/FF
560 OP=TE*PE*.01
570 GOTO 910
580 REM 3-D INTERPOLATION SUBROUTINE
590 OPEN "I",£1,C$
600 INPUT£1, N1,N2
610 FOR I=1 TO N1
620 INPUT£1, X(I)
630 NEXT I
640 FOR J=1 TO N2
650 INPUT£1, Z(J)
660 NEXT J
670 FOR I=1 TO N1
680 FOR J=1 TO N2
690 INPUT£1, Y(I,J)
700 NEXT J
710 NEXT I
720 CLOSE £1
730 IF XX < X(1) GOTO 780
740 IF XX > X(N1) GOTO 780
750 IF ZZ < Z(1) GOTO 780
760 IF ZZ > Z(N2) GOTO 780
770 GOTO 790
780 PRINT"VALUE OUT OF RANGE":GOTO 80
790 FOR I=1 TO N1
800 IF XX < X(I) GOTO 820
810 NEXT I
820 FOR J=1 TO N2
830 IF ZZ < Z(J) GOTO 850
840 NEXT J
850 R1=(XX-X(I-1))/(X(I)-X(I-1))
860 R2=(ZZ-Z(J-1))/(Z(J)-Z(J-1))
870 Y1=Y((I-1),(J-1))+R1*(Y(I,(J-1))-Y((I-1),(J-1)))
880 Y2=Y((I-1),J)+R1*(Y(I,J)-Y((I-1),J))
890 YY=Y1+R2*(Y2-Y1)
900 RETURN
910 REM STEADY STATE SCHEDULE PROGRAM
920 PRINT
930 PRINT"SHIP SPEED =";VS;"KNOTS","TOTAL THRUST REQUIREMENT =";:PRINT USING "££

£.££ ";RT;:PRINT "kN"
940 PRINT
950 PRINT"WAKE AND THRUST","PROPELLER SPEED OF ADVANCE=";:PRINT USING "££.££ ";V

A/.5148;:PRINT"KNOTS"
960 PRINT"FRACTIONS =";:PRINT USING " £.£££";WT
970 PRINT
980 PRINT"NE= ENGINE SPEED (R.P.M.)"
990 PRINT"PR= PROPELLER PITCH DIAMETER RATIO"
1000 PRINT"QE= ENGINE TORQUE (kNm)"
1010 PRINT"EP= ENGINE POWER (kW)"
1020 PRINT"FF= MASS FLOW RATE OF FUEL (kg/hr)"
1030 PRINT"PE= PROPELLER EFFICIENCY (%)"
1040 PRINT"TE= ENGINE THERMAL EFFICIENCY (%)"
1050 PRINT"OP= OVERALL PROPULSIVE EFFICIENCY (%)"
1060 PRINT
```

FIGURE 37

```
10 REM PROPULSION CONTROL SYSTEM TESTING SIMULATION
 20 DIM V(50,50),W(50),X(50),Y(50,50),Z(50)
 30 PRINT
 40 PRINT"         PROPULSION CONTROL SYSTEM - TESTING SIMULATION"
 50 PRINT"
 60 PRINT"                PROGRAMMED BY G.A.WEBB AUGUST 1983"
 70 PRINT
 90 PRINT
 100 PRINT"-------------------------------------------------------------------
 ----------"
 105 DP=1.875
 110 INPUT"ENTER ENGINE SPEED (RPM)";NE:NE1=NE
 120 INPUT"ENTER SHIP SPEED (KNOTS)";VS
 130 INPUT"ENTER REQUIRED PROPELLER THRUST (kN)";RT
 140 IF VS<1.5 OR VS>11.458 THEN PRINT"SPEED OUT OF RANGE":GOTO 90
 150 WT=.30837-.023073*VS+9.7029E-04*VS^2
 160 TD=WT
 170 VA=VS*.5148*(1-WT)
 175 REM 1ST CALC'N OF PROPULSION SYSTEM PARAMETERS
 180 NP=NE/150
 190 XX=VA/NP/DP:ZZ=RT/NP^2/DP^4/1.025:C$="THDATA"
 200 JJ=XX
 210 GOSUB 350
 220 PR=YY
 230 IF PR>.8 THEN PRINT"THRUST OUT OF RANGE RENTER":GOTO 90
 240 ZZ=YY:XX=VA/NP/DP:C$="TQDATA"
 250 GOSUB 350
 260 QE=YY*NP^2*DP^5*.04182
 270 IF QE>6.493 THEN PRINT"THRUST OUT OF RANGE RENTER":GOTO 90
 280 ZZ=QE*NE*.140375:XX=NE:C$="ENGMAP"
 290 GOSUB 350
 300 EP=ZZ*.7460001:FF=.45*YY:FF1=FF
 310 PE=RT*VS*51.48/EP
 320 TE=EP*8.3237/FF
 330 OP=TE*PE*.01
 340 GOTO 670
 345 REM 3-D INTERPOLATION SUBROUTINE
 350 OPEN "I",£1,C$
 360 INPUT£1, N1,N2
 370 FOR I=1 TO N1
 380 INPUT£1, X(I)
 390 NEXT I
 400 FOR J=1 TO N2
 410 INPUT£1, Z(J)
 420 NEXT J
 430 FOR I=1 TO N1
 440 FOR J=1 TO N2
 450 INPUT£1, Y(I,J)
 460 NEXT J
 470 NEXT I
 480 CLOSE £1
 490 IF XX < X(1) GOTO 540
 500 IF XX > X(N1) GOTO 540
```

```
510 IF ZZ < Z(1) GOTO 540
520 IF ZZ > Z(N2) GOTO 540
530 GOTO 550
540 PRINT"VALUE OUT OF RANGE":GOTO 90
550 FOR I=1 TO N1
560 IF XX < X(I) GOTO 580
570 NEXT I
580 FOR J=1 TO N2
590 IF ZZ < Z(J) GOTO 610
600 NEXT J
610 R1=(XX-X(I-1))/(X(I)-X(I-1))
620 R2=(ZZ-Z(J-1))/(Z(J)-Z(J-1))
630 Y1=Y((I-1),(J-1))+R1*(Y(I,(J-1))-Y((I-1),(J-1)))
640 Y2=Y((I-1),J)+R1*(Y(I,J)-Y((I-1),J))
650 YY=Y1+R2*(Y2-Y1)
660 RETURN
670 PRINT
680 PRINT"SHIP SPEED =";VS;"KNOTS","TOTAL THRUST REQUIREMENT =";:PRINT USING "££

£.££ ";RT;:PRINT "kN"
690 PRINT
700 PRINT"WAKE AND THRUST","PROPELLER SPEED OF ADVANCE=";:PRINT USING "££.££ ";V

A/.5148;:PRINT"KNOTS"
710 PRINT"FRACTIONS =";:PRINT USING " £.£££";WT
720 PRINT
730 PRINT"NE= ENGINE SPEED (R.P.M.)"
740 PRINT"PR= PROPELLER PITCH DIAMETER RATIO"
750 PRINT"QE= ENGINE TORQUE (kNm)"
760 PRINT"EP= ENGINE POWER (kW)"
770 PRINT"FF= MASS FLOW RATE OF FUEL (kg/hr)"
780 PRINT"PE= PROPELLER EFFICIENCY (%)"
790 PRINT"TE= ENGINE THERMAL EFFICIENCY (%)"
800 PRINT"OP= OVERALL PROPULSIVE EFFICIENCY (%)"
810 PRINT
820 PRINT"  NE    ";"   PR    ";"     QE    ";"     EP    ";"     FF    ";"     PE

";"     TE    ";"     OP    "
830 PRINT" (RPM)  ";"  (P/D)  ";"    (kNm)  ";"    (kW)   ";"   (kg/hr)";"      (%)

";"     (%)   ";"     (%)   "
840 PRINT
850 GOSUB 870
860 GOTO 940
870 PRINT NE;
880 PRINT USING "     £.£££   ";PR;
890 PRINT USING "    £.£££";QE;
900 PRINT USING "      £££.£   ";EP;
910 PRINT USING "   £££.££";FF;
920 PRINT USING "      ££.££";PE;TE;OP
930 RETURN
940 REM CONTROL PROGRAM
950 IS=10
960 PRINT
970 PRINT"CONTROL PROGRAM INTIATED"
980 XX=JJ
990 ZZ=PR
1000 C$="JPRDATA"
```

```
1010 GOSUB 350
1020 RTR=YY*NP^2*DP^4*1.025
1030 PRINT
1040 PRINT"CALCULATED REQUIRED PROPELLER THRUST= ";:PRINT USING"££.££";RTR;:PRIN

T" kN"
1050 PRINT
1060 INPUT"ENTER PSEUDO MINIMUM ENGINE RPM";NEIN
1070 PRINT
1080 IF NEIN=NE1 THEN NE2=NE1:FF2=FF1:GOTO 1140
1090 NE2=NEIN
1100 NE=NE2
1110 GOSUB 1180
1120 FF2=FF
1130 GOSUB 870
1140 IF NE=790 GOTO 1780
1150 IF PR>.79 GOTO 2100
1160 IF QE>6.49 GOTO 2100
1170 GOTO 1350
1175 REM CALC'N OF PROPULSION SYSTEM PARAMETERS
1180 NP=NE/150
1190 XX=VA/NP/DP
1200 ZZ=RT/NP^2/DP^4/1.025
1210 C$="THDATA":GOSUB 350
1220 PR=YY
1230 ZZ=PR
1240 C$="TQDATA"
1250 GOSUB 350
1260 QE=YY*NP^2*DP^5*.04182
1270 XX=NE:ZZ=QE*NE*.140375
1280 C$="ENGMAP"
1290 GOSUB 350
1300 EP=ZZ*.746:FF=.45*YY
1310 PE=RT*VS*51.48/EP
1320 TE=EP*8.3237/FF
1330 OP=TE*PE*.01
1340 RETURN
1350 IF NE1>=NE2+IS AND NE1<=NE2+2*IS THEN NE3=NE1 ELSE 1530
1360 IF NE3=790 THEN FF3=FF1:GOTO 1920
1370 FF3=FF1
1380 NE1=NE2-IS
1390 NE=NE1:GOSUB 1180
1400 IF PR>.799444 THEN GOSUB 2720:GOTO 1420
1410 IF QE>6.492444 THEN GOSUB 2850 ELSE 1480
1420 GOSUB 870
1430 NE1=NE
1440 FF1=FF
1450 IF FF1<FF2 AND FF2<FF3 THEN FFE=FF1:GOTO 3030
1460 IF FF1>FF2 AND FF2>FF3 GOTO 2400
1470 IF FF1>FF2 AND FF2<FF3 GOTO 2940
1480 GOSUB 870
1490 FF1=FF
1500 IF FF1>FF2 AND FF2<FF3 GOTO 2940
```

```
1510 IF FF1>FF2 AND FF2>FF3 GOTO 2400
1520 IF FF1<FF2 AND FF2<FF3 GOTO 2560
1530 IF NE1<=NE2-IS AND NE1>=NE2-2*IS THEN NE1=NE1 ELSE 1680
1540 NE3=NE2+IS
1550 IF NE3>=790 THEN NE3=790 ELSE 1620
1560 NE=NE3:GOSUB 1180
1570 GOSUB 870
1580 FF3=FF
1590 IF FF1<FF2 AND FF2<FF3 GOTO 2560
1600 IF FF1>FF2 AND FF2>FF3 THEN FFE=FF3:GOTO 3030
1610 IF FF1>FF2 AND FF2<FF3 GOTO 2940
1620 NE=NE3:GOSUB 1180
1630 GOSUB 870
1640 FF3=FF
1650 IF FF1>FF2 AND FF2<FF3 GOTO 2940
1660 IF FF1<FF2 AND FF2<FF3 GOTO 2560
1670 IF FF1>FF2 AND FF2>FF3 GOTO 2400
1680 NE3=NE2+IS
1690 IF NE3>=790 THEN NE3=790 ELSE 1740
1700 NE=NE3:GOSUB 1180
1710 GOSUB 870
1720 FF3=FF
1730 GOTO 1920
1740 NE=NE3:GOSUB 1180
1750 GOSUB 870
1760 FF3=FF
1770 GOTO 1380
1780 NE3=NE2:FF3=FF2
1790 NE2=NE3-IS:NE=NE2
1800 GOSUB 1180
1810 IF PR>.799444 THEN GOSUB 2720:GOTO 1850
1820 IF QE>6.492444 THEN GOSUB 2850 ELSE 1900
1830 GOSUB 870
1840 IF FF<FF3 THEN FFE=FF:GOTO 3030
1850 IF FF>FF3 THEN NE=NE3
1860 GOSUB 1180
1870 GOSUB 870
1880 FFE=FF
1890 GOTO 3030
1900 GOSUB 870
1910 NE2=NE:FF2=FF
1920 NE1=NE2-IS
1930 NE=NE1:GOSUB 1180
1940 IF PR>.799444 THEN GOSUB 2720:GOTO 1960
1950 IF QE>6.492444 THEN GOSUB 2850 ELSE 2050
1960 NE1=NE:FF1=FF
1970 GOSUB 870
1980 IF FF1>FF2 AND FF2>FF3 THEN NE=NE3
1990 IF FF1<FF2 AND FF2<FF3 THEN FFE=FF1:GOTO 3030
2000 IF FF1>FF2 AND FF2<FF3 GOTO 2940
```

```
2010 GOSUB 1180
2020 GOSUB 870
2030 FFE=FF
2040 GOTO 3030
2050 GOSUB 870
2060 NE1=NE:FF1=FF
2070 IF FF1>FF2 AND FF2>FF3 THEN NE=NE3:GOTO 2010
2080 IF FF1>FF2 AND FF2<FF3 GOTO 2940
2090 IF FF1<FF2 AND FF2<FF3 GOTO 2560
2100 NE1=NE2:FF1=FF2
2110 NE2=NE1+IS
2120 IF NE2>=790 THEN NE2=790 ELSE 2190
2130 NE=NE2:GOSUB 1180
2140 GOSUB 870
2150 IF FF<FF1 THEN FFE=FF:GOTO 3030
2160 IF FF>FF1 THEN NE=NE1:GOTO 2170
2170 FFE=FF
2180 GOTO 3030
2190 NE=NE2:GOSUB 1180
2200 FF2=FF
2210 GOSUB 870
2220 NE3=NE2+IS
2230 IF NE3>=790 THEN NE3=790 ELSE 2340
2240 NE=NE3:GOSUB 1180
2250 GOSUB 870
2260 FF3=FF
2270 IF FF1<FF2 AND FF2<FF3 THEN NE=NE1
2280 IF FF1>FF2 AND FF2<FF3 GOTO 2940
2290 IF FF1>FF2 AND FF2>FF3 THEN FFE=FF3:GOTO 3030
2300 GOSUB 1180
2310 GOSUB 870
2320 FFE=FF
2330 GOTO 3030
2340 NE=NE3:GOSUB 1180
2350 GOSUB 870
2360 FF3=FF
2370 IF FF1<FF2 AND FF2<FF3 THEN NE=NE1:GOTO 2300
2380 IF FF1>FF2 AND FF2<FF3 GOTO 2940
2390 IF FF1>FF2 AND FF2>FF3 GOTO 2400
2395 REM INCREASING RPM SEARCH
2400 NE1=NE2:FF1=FF2
2410 NE2=NE3:FF2=FF3:IS=IS+5
2420 NE3=NE2+IS
2430 IF NE3>=790 THEN NE3=790 ELSE 2500
2440 NE=NE3:GOSUB 1180
2450 GOSUB 870
2460 FF3=FF
2470 IF FF1<FF2 AND FF2<FF3 THEN NE=NE1:GOTO 2300
2480 IF FF1>FF2 AND FF2<FF3 GOTO 2940
2490 IF FF1>FF2 AND FF2>FF3 THEN FFE=FF3:GOTO 3030
2500 NE=NE3:GOSUB 1180
```

```
2510 GOSUB 870
2520 FF3=FF
2530 IF FF1<FF2 AND FF2<FF3 THEN NE=NE1:GOTO 2300
2540 IF FF1>FF2 AND FF2<FF3 GOTO 2940
2550 IF FF1>FF2 AND FF2>FF3 GOTO 2400
2555 REM DECREASING RPM SEARCH
2560 NE3=NE2:FF3=FF2
2570 NE2=NE1:FF2=FF1:IS=IS+5
2580 NE1=NE2-IS
2590 NE=NE1:GOSUB 1180
2600 IF PR>.799444 THEN GOSUB 2720:GOTO 2620
2610 IF QE>6.492444 THEN GOSUB 2840 ELSE 2670
2620 NE1=NE:FF1=FF
2630 GOSUB 870
2640 IF FF1<FF2 AND FF2<FF3 THEN FFE=FF1:GOTO 3030
2650 IF FF1>FF2 AND FF2<FF3 GOTO 2940
2660 IF FF1>FF2 AND FF2>FF3 THEN NE=NE3:GOTO 2300
2670 GOSUB 870
2680 FF1=FF
2690 IF FF1>FF2 AND FF2>FF3 THEN NE=NE3:GOTO 2300
2700 IF FF1>FF2 AND FF2<FF3 GOTO 2940
2710 IF FF1<FF2 AND FF2<FF3 GOTO 2560
2715 REM MAX PITCH CONSTRAINT SUBROUTINE
2720 IF PR>.799444 AND PR<.8 THEN PR=.8
2730 P2=PR
2740 NX=NE:NE=NE2
2750 NP=NE/150
2760 XX=VA/NP/DP
2770 ZZ=RT/NP^2/DP^4/1.025
2780 C$="THDATA"
2790 GOSUB 350
2800 P1=YY
2810 N%=NX+(NE2-NX)*(P2-.8)/(P2-P1)
2820 NE=N%
2830 GOSUB 1180
2840 RETURN
2845 REM MAX TORQUE CONSTRAINT SUBROUTINE
2850 IF QE>6.492444 AND QE<6.493 THEN QE=6.493
2860 Q2=QE
2870 NX=NE:NE=NE2
2880 GOSUB 1180
2890 Q1=QE
2900 N%=NX+(NE2-NX)*(Q2-6.493)/(Q2-Q1)
2910 NE=N%
2920 GOSUB 1180
2930 RETURN
2940 NEMIN=.25*(NE1+2*NE2+NE3)-.25*(NE3-NE1)*((FF2-FF1)/(NE2-NE1)+(FF3-FF2)/(NE3
-NE2))/((FF3-FF2)/(NE3-NE2)-(FF2-FF1)/(NE2-NE1))
2950 N%=NEMIN:NE=N%
2960 IF NE>790 THEN NE=790
2970 GOSUB 1180
2980 IF QE>6.492444 THEN GOSUB 2850
2990 IF PR>.799444 THEN GOSUB 2720
3000 FFE=FF
```

```
[illegible]
```

```
3010 GOSUB 870
3020 IF FFE>FF2 THEN NE=NE2:GOTO 2300
3025 REM ACTUAL MINIMUM SETTINGS ROUTINE
3030 XX=VS:ZZ=RT:C$="OPTSETDATA"
3040 GOSUB 3130
3050 NE=YY
3060 GOSUB 1180
3070 FFMIN=FF
3080 DEVN=(1-FFMIN/FFE)*100
3090 PRINT
3100 IF DEVN<=.004 THEN PRINT"FOUND MINIMUM FUEL CONSUMPTION":GOTO 90
3110 PRINT"OFF MINIMUM FUEL CONSUMPTION BY";:PRINT USING"££.££";ABS(DEVN);:PRINT
"%"
3120 GOTO 90
3125 REM 3-D INTERPOLATION SUBROUTINE FOR PITCH & RPM
3130 OPEN "I",£1,C$
3140 INPUT£1, N1,N2
3150 FOR I=1 TO N1
3160 INPUT£1, X(I)
3170 NEXT I
3180 FOR J=1 TO N2
3190 INPUT£1, Z(J)
3200 NEXT J
3210 FOR I=1 TO N1
3220 FOR J=1 TO N2
3230 INPUT£1, Y(I,J)
3240 INPUT£1, V(I,J)
3250 NEXT J
3260 NEXT I
3270 CLOSE £1
3280 IF XX < X(1) GOTO 3330
3290 IF XX > X(N1) GOTO 3330
3300 IF ZZ < Z(1) GOTO 3330
3310 IF ZZ > Z(N2) GOTO 3330
3320 GOTO 3340
3330 PRINT"VALUE OUT OF RANGE"
3340 FOR I=1 TO N1
3350 IF XX < X(I) GOTO 3370
3360 NEXT I
3370 FOR J=1 TO N2
3380 IF ZZ < Z(J) GOTO 3400
3390 NEXT J
3400 R1=(XX-X(I-1))/(X(I)-X(I-1))
3410 R2=(ZZ-Z(J-1))/(Z(J)-Z(J-1))
3420 Y1=Y((I-1),(J-1))+R1*(Y(I,(J-1))-Y((I-1),(J-1)))
3430 Y2=Y((I-1),J)+R1*(Y(I,J)-Y((I-1),J))
3440 YY=Y1+R2*(Y2-Y1)
3450 V1=V((I-1),(J-1))+R1*(V(I,(J-1))-V((I-1),(J-1)))
3460 V2=V((I-1),J)+R1*(V(I,J)-V((I-1),J))
3470 VV=V1+R2*(V2-V1)
3480 RETURN
```