# Development of Equipment Health Monitoring(EHM) System of Naval Ship Propulsion


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May 2013

# Development of Equipment Health Monitoring(EHM) System of Naval Ship Propulsion

**Major Project**

Submitted in partial fulfillment of the requirements

for the degree of

**Master of Technology in Mechanical Engineering (Design Engineering)**

By

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**May 2013**

# Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Mechanical Engineering (Design Engineering) at Nirma University and has not been submitted elsewhere for a degree.

2. Due acknowledgement has been made in the text to all other material used.

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## Undertaking for Originality of the Work

I **Jitendra Ujwal Mahajan**, Roll No.**11MMED06**, give undertaking that the Major Project entitled **"Development of Equipment Health Monitoring(EHM) System of Naval Ship Propulsion"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Mechanical Engineering (Design Engineering)**, under Institute of Technology of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere, it will result in serve disciplinary action.

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This is to certify that the Major Project Report entitled **Development of Equipment Health Monitoring(EHM) System of Naval Ship Propulsion** submitted by Mr.Jitendra Ujwal Mahajan (11MMED06), towards the partial fulfilment of the requirements for the award of degree of **Master of Technology in Mechanical Engineering** in the field of **Design Engineering** of Nirma University, Ahmedabad is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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# Acknowledgements

I would like to thank my guide Prof. M.M.Chauhan, who has been instrumental in fostering interest and enthusiasm in all my research endeavors. I look to him for guidance in all my future undertakings.

I also wish to thank the sponsors, Larsen & Toubro- Marine Switchboards and Control System and Industry guide Mr.Makarand Patil in carrying out this project. I would also like to thank Mr. R.S.Mahajan,GM,Larsen & Toubro- Marine Switchboards and Control System and Mr. Alok Bhagawat, Sr.DGM,Larsen & Toubro- Marine Switchboards and Control System for their valuable inputs during the project.

My sincere thanks and gratitude to **Dr. D S Sharma**, PG coordinator of Design Engineering Group and Professor, Mechanical Engineering Department, Institute of Technology, Nirma University, Ahmedabad and **Dr. R N Patel**, Head of Mechanical Engineering Department, Institute of Technology, Nirma University, Ahmedabad encouragement and motivation throughout the dissertation work. I also thanks the faculty members of Mechanical Engineering Department for their support during this work.

I would also like to thank **Dr. K.Kotecha**, Director, Institute of Technology, Nirma University for allowing me to carry out my project work in industry. I am thankful to Nirma University for providing all kind of required resources.

I extent my heartfelt thanks to my parents for their motivation, moral support and encouragement through out my dissertation work.

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# Abstract

Current project proposes newly developed EHM system of naval ship propulsion. Manufacturer of the equipments of propulsion system have provided experimental data for different power and speed. Using least square regression, a curve is fitted in this data and an equation is derived. This equation gives the value of the parameter for any input value of power and speed. Actual trial data is obtained from customer. Trial data means actual parameter values obtain from various channels during test sailing of ship. Trial data is different than manufacturing data due to unpredictable loses and measuring errors. The equations are modified as per actual trial data to accommodate these loses. This analysis is done with the help of least square regression.

The final modified equations are validated using different trial data. These final equations are used in EHM system. This model will give the predicted value of parameters, which will compare with the actual value obtain from sensor; If the actual value exceed the limit then alarm is generated. This alarm will intimate the operator that the particular system is not functioning properly.

Preceding further a feedback system is design for temperature and pressure, which will automatically control these parameters. A flowchart is proposed to developed EHM system.

A mathematical model for vital component of propulsion system is developed based on the literature review. These model find out the output parameters like efficiencies, torque transferred, power transferred etc which monitor the performance of the vital components of propulsion system. This model can also be incorporated in EHM system to monitor the overall performance of the equipment.

**Keywords:-** Equipment Health Monitoring, Least Square Method, Numerical Analysis, Performance Parameters, Propulsion Control System

# Contents

# List of Tables

# List of Figures

# Abbreviations

EHM ........ Equipment Health Monitoring
MA ........ Model Anaysis
SA ........ Simple Analysis
FPP ........ Fixed Pitch Propeller
CPP ........ Controllable Pitch Propeller
LSM ........ Least Square Method
CAC ........ Charge Air Cooler
LO ........ Lubricating oil
GB ........ Gear Box
SW ........ Sea Water

# Chapter 1

# Introduction

## 1.1 Preliminary Remarks

The Equipment Health Monitoring(EHM) system is the mathematical model of the various parameters which will monitor the performance of the components of the system. Each model specification provides a detailed functional description of the equipment to be modeled. list of model inputs and outputs and details of the modeling algorithms used to generate output signals based on input signals. The data from the model (which represents perfect operation of the machinery) and the actual data from the vessels running machinery are then compared. Obviously, the actual machinery will never run perfectly as per the ideal parameter settings, however it should be within certain permissable limit. When the EHM system compares the data, it takes into account the tolerances.

## 1.2 Objective

The vital activity of EHM is to monitor the performance of the equipment. The EHM monitors the functions of the principal propulsion systems for the purpose of:

a. Analyzing the deviation of parameters from expected range.

b. Comparison of trends against idealized or expected behaviour.

c. Predicting failures based on deviation from expected behaviour.

d. Help to plan the maintenance of the equipments.

## 1.3 Methodology

In order to develop the EHM, the effective mathematical model is needed to develop. Current project proposes two models.

First model is based on the data given by manufacturer and trial data obtain during the actual sailing of the ship. The least square method is used to fit this data and obtain the governing equation which will be used to predict the value of parameter. This model will produce the predicted value of output parameters like pressure, temperature and discharge. Actual trial data is used to optimize the equations using least square regression in which the constants are modified to fit the actual trial data. These equations can be used to develop the EHM system. The flowchart is presented which will describe the methodology.

The second model is based on the efficiency calculation of the various components of propulsion system. The formulation is developed in computer application which will calculate the efficiency of the components. This model can also be added to the EHM in order to monitor the overall performance of the propulsion system.

## 1.4 Ship Propulsion System

Ship propulsion system is that part of ship concerned by the design and selection of main propulsion plant equipments and machineries. The main role of this plant is to produce enough power to overcome the ship resistance and to generate the needed electric power for the various applications onboard the ship.[1] The main components of a propulsion system are shown in figure 1.1.

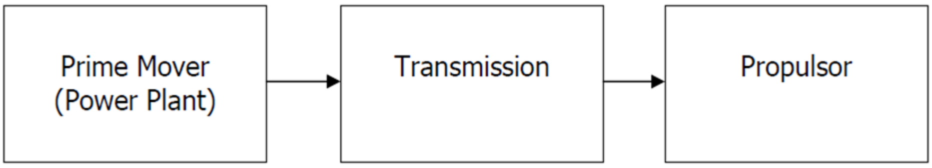


Figure 1.1: Ship Propulsion System Layout [1]

### 1.4.1 Prime Mover

The function of the prime mover is to deliver mechanical energy to the propulsor. Diesel Engine is the most widely used prime mover in the shipping industries due to its low fuel consumption compare to other prime mover like gas turbine, steam engine etc.

### 1.4.2 Transmission

Transmission is a sub-system of the propulsion system. It is a system itself built up from components such as shafts, gearboxes and bearings. The transmission's functions are:

a. To transfer the mechanical energy generated from the prime mover to the propulsor.

b. To transfer the thrust generated by the propulsor to the ship's hull.

Shaft transfer the torque from gearbox to propeller. losses occurred in shaft are very less. GB is the vital component of transmission system. The main function of GB is to reduce the speed and increase the torque. Losses occurred in GB is maximum in transmission system. Bearings are used in transmission to support the propeller shaft. Losses in bearings are very less.

### 1.4.3 Propulsor

The propulsor converts the rotating mechanical power delivered by the engine into translating mechanical power to propel the ship. The propulsor should generate the thrust more than the ship resistances.

The most common propulsor is the propeller. In general, two types of propeller are distinguished,

a. Fixed Pitch Propeller (FPP)

b. Controllable Pitch Propeller (CPP)

The pitch of the FPP, although not constant along the radius of the blades, it is fixed in any point, since the blades are rigidly attached to the hub. The amount of thrust developed by the propeller is controlled by the rotational speed of the propeller. Stopping and reversing the ship require special measures. It must be possible to change the direction of rotation of the propeller in either the gearbox or the engine.

CPP consists of a hub with the blades mounted on separately, so that they can rotate, thus changing their pitch. The shaft is hollow and contains a control system, mainly hydraulic, that can adjust the pitch angle of the blades. Adjusting the position of the blades changes the angle of attack in the flow, thus changing the thrust without changing the rotational speed. This has major advantages with respect to manoeuvrability of the ship.

Hence CPP is used instead of FPP due to its thrust changing characteristic.

## 1.5 Curve Fitting Techniques

Curve fitting techniques are used to map the experimental and trial data and give a equation of the curve. This equation predicts the output value for any input value. This is explained in below paragraphs.

### 1.5.1 Curve Fitting

In applied mathematics and engineering sciences we come across experiments and problems, which involve two variables or more variables.

For example, it is known that the speed V of a ship varies with the horsepower P of an engine according to the formula . Here a and b are the constants to be determined. For this purpose several sets of readings of speeds and the corresponding horsepower's can be taken. The problem is to find the best values for a and b using the observed values of V and P. Thus, the general problem is to find a suitable relation or law that may exist between the variables X and Y from a given set of observed values ($X_i$,$Y_i$). Such a relation connecting X and Y is known as empirical law. For above example, X = V and Y = P.

The process of finding the equation of the curve of best fit, which may be most suitable for predicting the unknown values, is known as curve fitting. Therefore, curve fitting means an exact relationship between two or more variables by algebraic equations. There are following methods for fitting a curve.[15]

a. Graphic method

b. Method of group averages

c. Method of moments

d. Principle of least square.

Out of above 4, least square method is most suitable and precise for our problem.

### 1.5.2 Least Square Regression

The Method of Least Squares is a procedure to determine the best fit line or surface to data. Sara A et al [21] gives basic information about LSM. The proof uses simple calculus and linear algebra. The basic problem is to find the best fit straight line Y = aX + b, surface Z= aX + bY + c given that, for $\eta\epsilon\{1....N\}$,the pairs $(X_N Y_N, Z_N)$

are observed. The method easily generalizes to finding the best fit of the form $Y = a_1 f_1(X) + ..... + c_k f_k(X)$,it is not necessary for the functions $f_k$ to be linearly in X.[18]

### 1.5.3 Basics Of Least Square Method

For given data $(X_1,Y_1)....(X_N,Y_N)$, we may define the error associated to Y = aX + b by,

$$E(a,b) = \sum_{n=1}^{N}(Y_n - (aX_(n) + b))^2 \tag{1.1}$$

This is just N times the variance of the data set $Y_1-(aX_1+b), ....Y_n-(aX_N+b)$. It makes no difference whether or not we study the variance or N times the variance as our error, and note that the error is a function of two variables.The goal is to find values of a and b that minimize the error. In multivariate calculus we learn that this requires us to find the values of (a, b) such that

$$\frac{\partial E}{\partial a} = 0 \tag{1.2}$$

and

$$\frac{\partial E}{\partial b} = 0 \tag{1.3}$$

Differentiating E(a, b) yields

$$\frac{\partial E}{\partial a} = \sum_{n=1}^{N} 2(Y_n - (aX_n))(-X_n) \tag{1.4}$$

$$\frac{\partial E}{\partial b} = \sum_{n=1}^{N} 2(Y_n - (aX_n))(1) \tag{1.5}$$

Setting $\frac{\partial E}{\partial a} = 0$ and $\frac{\partial E}{\partial b} = 0$ and dividing by 2 yields

$$\sum_{n=1}^{N}(Y_n - (aX_n))(X_n) = 0 \tag{1.6}$$

$$\sum_{n=1}^{N}(Y_n - (aX_n)) = 0 \tag{1.7}$$

We have obtained that the values of a and b which minimize the error by solving following equation

$$(\sum_{n=1}^{N} X_n^2)a + (\sum_{n=1}^{N} X_n)b = \sum_{n=1}^{N} X_n Y_n \tag{1.8}$$

$$(\sum_{n=1}^{N} X_n)a + (\sum_{n=1}^{N})b = \sum_{n=1}^{N} Y_n \tag{1.9}$$

Similarly equations for quadratic least square method are

$$(\sum_{n=1}^{N} 1)a + (\sum_{n=1}^{N} X_n)b + (\sum_{n=1}^{N} X_n^2)c = \sum_{n=1}^{N} Y_n \tag{1.10}$$

$$(\sum_{n=1}^{N} X_n)a + (\sum_{n=1}^{N} X_n^2)b + (\sum_{n=1}^{N} X_n^3)c = \sum_{n=1}^{N} X_n Y_n \tag{1.11}$$

$$(\sum_{n=1}^{N} X_n^2)a + (\sum_{n=1}^{N} X_n^3)b + (\sum_{n=1}^{N} X_n^4)c = \sum_{n=1}^{N} X_n^2 Y_n \tag{1.12}$$

## 1.6 Equipment Health Monitoring (EHM)

The EHM system uses software model to replicate the function of machinery. The model is designed to replicate the machinery running perfectly (an idealized model). The model then outputs parameters such as efficiencies, pressures and temperatures in the same format as the data from the actual machinery fitted to the vessel. The dynamic analysis of the propulsion system is carried out to monitor the functions of the main components of the propulsion system. The data from the model (which represents perfect operation of the machinery) and the actual data from the vessels running machinery are then compared.

Using the comparison data, EHM system predicts the following points

a. Failures based on deviation from expected behaviour.

b. Monitor the performance of the components of propulsion system.

c. Analyzing the deviation of parameters from expected range as an aid to planned maintenance.

EHM system can can be developed in two way

a. Model Based Analysis

b. Simple Analysis

### 1.6.1 Model Based Analysis(MA)

MA requires the close co-operation of the equipment manufacturer to provide detailed information on the dynamic response of the hardware. To model a specific parameter it is necessary to know all the dependent variables and the effects each variable has on the modelled parameter. Should this information not be available it may be possible to monitor the as-fitted hardware onboard, and generate models from this data. It will be necessary for the equipment manufacturer to confirm that the hardware is meeting its optimal operating conditions to confirm that the models will represent the ideal values.

### 1.6.2 Simple Analysis(SA)

SA is often much more simple than MA and as such needs less manufacturer supplied data to operate successfully. SA can often be successfully implemented using simple mathematical statements.

# Chapter 2

# Literature Review

## 2.1 Introduction

The effectiveness of the EHM system is mainly depends on the mapping of manufacturing data using regression techniques. various literatures are referred to decide regression technique. For efficiency base model, performance parameters of the main components of the propulsion system need to calculate. This chapter explains the various literature reviewed for formulating the analysis.

## 2.2 Least Square Method

For using the curve fitting to compute equations which are used to predict the output parameter based on input data, various literatures are reviewed for formulation.

Miller [15] give the basic information and advantages of using least square method for mathematical regression problems. The least square method performs the following tasks,

a. Reduce noise and smooth data

b. Find the mathematical relationship or function among variables

c. Use that function to perform further data processing, such as error compensation

d. Estimate the variable value between data samples

e. Estimate the variable value outside the data sample range

Rui Sun et al [16] gives input on primary function determination. The primary function selection makes great influence to the fitting precise and computing efficiency, and become a key point in curve fitting. Many researchers prefer to determine the primary function according to the source data. In mechanical and electronic engineering practice, standard 2-parameter, 3-parameter polynomial distribution and exponential distribution are the conventional choices, which should be chosen according to the underlying failure time. If reconditions cannot be satisfied, primary distributions or primary functions selection method are not suitable. In this situation, general primary function should be used for curve fitting procedure. Polynomial is a common general primary function.

$$Y = f(X) = a_0 + a_1 X + ..... + a_n X^n \tag{2.1}$$

Parameter n should be determined in fitting procedure.

Simoncelli et al [20] explains about optimization using least square method. Least squares (LS) problems are optimization problems in which the objective (error) function may be expressed as a sum of squares. Such problems have a natural relationship to distances in Euclidean geometry, and the solutions may be computed analytically using the tools of linear algebra.

Kozan et al, [17] have done the curve fitting technique for engine experimental data for engine speed, torque and sweep cam angle. And for mapping these data Author use quadratic least square method. Author has used two stages modeling for fix the engine experimental data. Following flowchart is used to predict the output parameters.

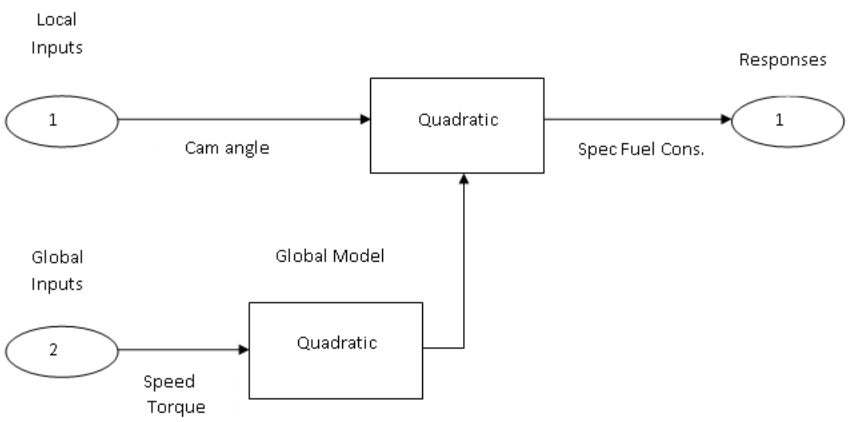


Figure 2.1: Stage engine data mapping [17]

## 2.3 Diesel Engine Parameters

Rajput [2] has proposed that engine performance is an indication of the degree of success of the engine performs its assigned task i.e. the conversion of the chemical energy contained in the fuel into the useful mechanical work. The performance of an engine is evaluated on the basis of the following:

a. Specific Fuel Consumption.

b. Brake Mean Effective Pressure.

c. Specific Power Output.

d. Specific Weight.

e. Exhaust Smoke and Other Emissions.

For the evaluation of an engine performance few more parameters are chosen and the effect of various operating conditions, design concepts and modifications on these parameters is studied. The basic performance parameters are the following:

a. Power and Mechanical Efficiency.

b. Mean Effective Pressure and Torque.

c. Specific Output.

d. Fuel-air Ratio.

e. Specific Fuel Consumption.

f. Thermal Efficiency and Heat Balance.

g. Exhaust Smoke and Other Emissions.

h. Specific Weight.

Power is defined as the rate of doing work and is equal to the product of force and linear velocity or the product of torque and angular velocity.

Thus, the measurement of power involves the measurement of force (or torque) as well as speed. The force or torque is measured with the help of a dynamometer and the speed by a tachometer.

Chybowski [3] has compared the analytical and experimental result for the mean effective pressure and effective power produce by engine. It is crucial for both the general estimation of the engine working parameters value reflecting the engine's operational condition and for comparing its current condition with the previous one (recorded during the last check of the engine performance) or its state during the trials at the engine test bed. In the paper the basic methods of torque engine load estimation have been presented. In fact for the main propulsion engines more and more often torquemeters have been installed. However, there have still existed many vessels without such equipment. In such cases the presented methods are applied.

Indicated power is given by

$$P_i = C_1 \times p_i \times n[W] \tag{2.2}$$

Where, $C_1$ is the cylinder constant taking into consideration the piston area, its stroke and number of ignitions assigned for one crank shaft revolution, $p_i$ is mean indicated pressure [Pa],$n$ is speed of the crank shaft [s-1]

The mean effective pressure can be determined in relation to

$$P_i = P_i C_2 [Pa] \tag{2.3}$$

Due to the estimation approximate torque value T and effective power Pe can be calculated as follow

$$T = C_1 \times P_e [Nm] \tag{2.4}$$

$$P = C_1 \times P_e \times n[W] \tag{2.5}$$

Ishiodu and Ogbonnaya [5] has mentioned the following guideline in order to evaluate engine performance

a. Calculation of heat losses to jackets during the working cycle.

b. Knowledge of the heat absorbed by the walls of the combustion chamber.

c. Power train, smoothness, quietness.

d. Gear rather than noise when running a reduced engine performance.

e. Author has provided a comprehensive study of performance of MDE for proactive condition monitoring. This was brought to fruition using software named MDEPEA written in visual basic programming language. MDEPEA stands for Marine Diesel Engine Performance Evaluation and Analysis.

Benvenuto and Compora [4] has formulate the diesel engine model to use for fault simulation and secondly to analyze and compare the influence of engine governor logic.

Ahmad [6] has used Arial dynamometer to measure brake, friction and indicated power instead of brake dynamometer. He has plot following plots to represent many properties of engine.

The friction power (KW) versus the rotational speed (RPM) is as shown in figure 2.2 It explains that the friction power proportion to the consumed current.

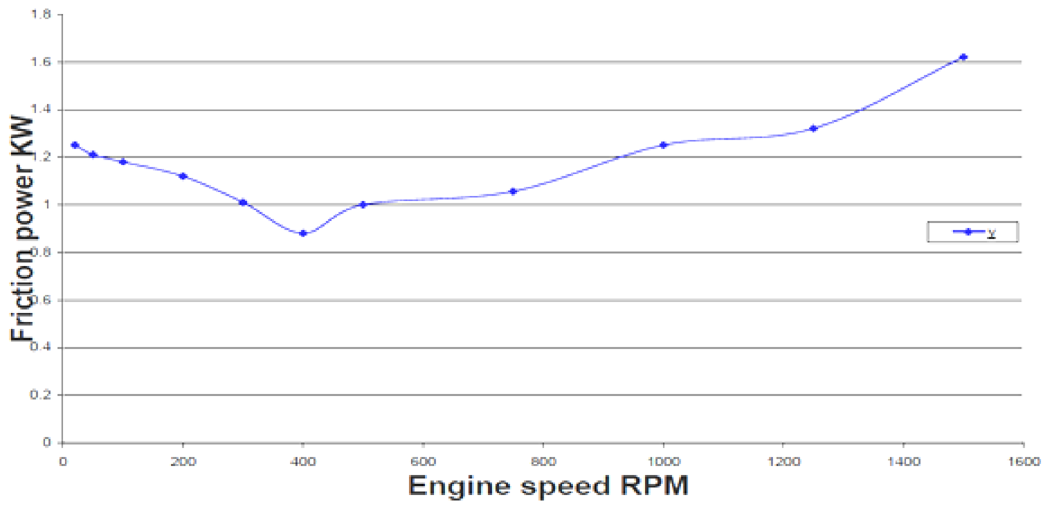


Figure 2.2: Friction Power Vs Engine Speed [6]

The brake power (KW) versus the effective pressure (bar) of compressed air which is used as a load on the diesel engine is as shown in figure 2.3.

The most characterized property of this aerial dynamometer; where the brake power produced by the diesel engine is a function of the effective pressure of the compressor. So that the brake power increases as the pressure increases but the relation is not linear.

Three kinds powers indicated, brake, friction powers versus the engine speed (RPM) is as shown in figure 2.4. It shows a comparison with whole kinds of powers, so that it represents the small difference between indicated and brake power.

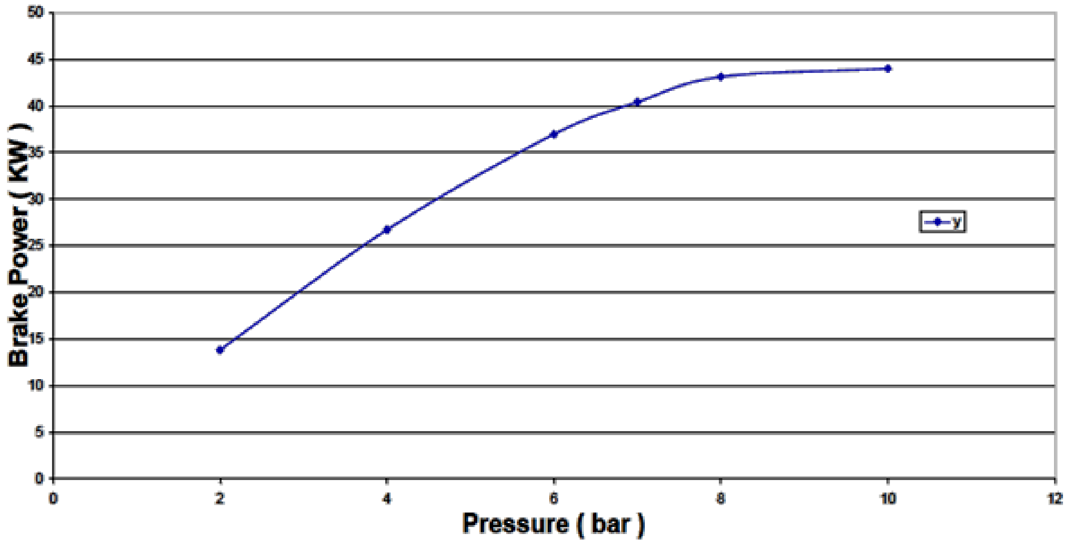


Figure 2.3: Brake Power Vs Pressure [6]

## 2.4 Gearbox Parameter

El-Gohary and El-Sherif [1] mentioned marine gearboxes consist of meshing teeth on pinions and wheels, which transfer power from a drive shaft (primary) to a driven shaft (secondary) and reduce speed.

There are three configurations of gearboxes,

a. Parallel Gear Train

b. Locked Gear Train

c. Epicyclic Gear Train

Parallel configuration is consist of pinion and wheels.

In Locked train because of the high torque to be transmitted, the gas turbine power is split over two parallel gear trains. The gas turbine input pinion meshes with two intermediate gear wheels, which should transmit 50% of the torque each. The intermediate gear wheels are connected by intermediate shafts to secondary pinions,

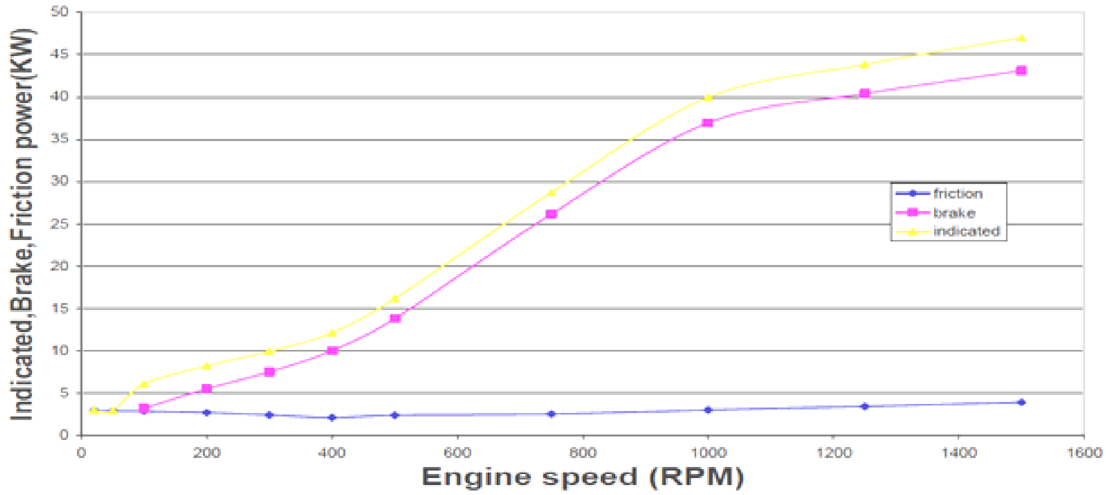


Figure 2.4: IP, FP Vs Engine Speed [6]

which mesh with the main gear wheel. This type of gear transmission is called a locked train.

In an epicyclic system, one or more wheels travel around the outside or inside of another wheel whose axis is fixed. They are referred to as planetary, solar and star gears.

Hohn et al [7] pointed out the loses occurred in the gearbox. Power loss reduction at the end of the power train has a large impact on overall optimization although absolute efficiency in gearboxes and rear axles is already high. Power loss in a gearbox consists of gear, bearing, seal and auxiliary losses. Loses can be separated in

a. No load loses

b. Load dependent loses

No load losses are mainly related to lubricant viscosity and density immersion depth of the components of a sump lubricated gearbox. Load losses depend on transmitted load, coefficient of friction and sliding velocity in the contact areas of the components.

Gear Power Lose- No load gear losses mainly depend on immersion depth in sump lubricated gearboxes as well as on lubricant viscosity.

Load gear loses- The load gear losses in the mesh while power is transmitted follow the basic Coulomb law

$$P_{VZP} = F_R \times V_R \tag{2.6}$$

Where, $P_{VZP}$ is load gear losses, $V_R$ is friction force, $V_R$ is relative velocity.

Kuria and Kihiu [8] has described the contribution of gear loses. Sliding friction contributes about 98% of the total power loss for gear trains operating at relatively low speeds (less than 2000 rpm input speed). Rolling frictional losses decrease with increased load. Windage losses are only significant for gears running at very high speeds (greater than 3000 rpm). The results also showed that the overall efficiency varies over the path of contact of the gear meshes ranging between 94% to 99.5%. Figure 2.5 shows the windage power lose for speed and from this graph the windage loses can be neglected in case of naval ship.

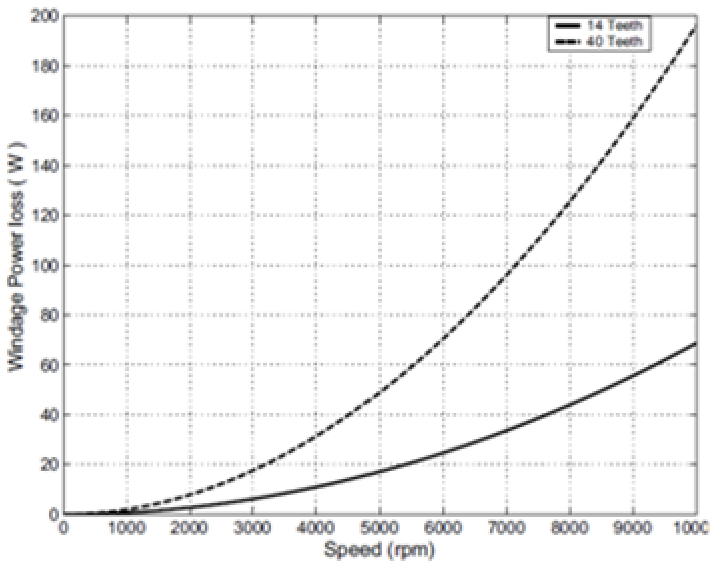


Figure 2.5: Windage power lose Vs Speed [8]

Here, the model incorporated a gear load distribution model, a friction model and a mechanical efficiency formulation to predict the mechanical efficiency of a gear pair under typical operating, surface and lubricating conditions. The rolling friction is periodic at the mesh period and reduces with increased load. This is due to the decreased film thickness with increased load. Instantaneous sliding lose is the function of instantaneous sliding velocity and the friction force which is a function of the instantaneous normal load and the instantaneous coefficient of friction.

Patel [9] has described these load dependent (or mechanical) losses are all induced by friction at contacting interfaces of the transmission. Gear meshes and the rolling element bearings provide multiple contacts, contributing significantly to the mechanical losses of the transmission. The other group of power losses is associated mostly with the interactions between the surrounding medium (oil, air or a mixture of the two) with the rotating components such as gears and bearings. These spin power losses are independent of load transmitted and are dictated mostly by factors such as effective oil levels, rotational speeds, transmission temperature and the geometry of the transmission housing.

Hohn et al [9] has pointed out the loses occur in bearing. No load bearing losses depend on bearing type and size, bearing arrangement, lubricant viscosity and supply. Load dependent bearing losses depend on bearing type and size, load and sliding conditions in the bearing and on lubricant type.

Vaidyanathan [10] has calculated the bearing loses as below. This bearing loses can be consider in calculating GB loses.

$$F_M = z(\frac{F_S}{C_S})^y \times F_\beta \times D_M \tag{2.7}$$

Where $\alpha$ is the contact ratio. It is $0^0$ for DGBB and $40^0$ for four point angular bearing and $F_\beta = Max((0.9F_a \cot\alpha - 0.1F_R), F_R$ Bearing mechanical lose,

$$P_B = F_M \times \omega \tag{2.8}$$

## 2.5 Propeller Parameter

Smogeli [11] has presented a comparison study and analysis of thruster shaft speed, torque, and power controllers, and shows that significant reductions in thrust, torque, and power fluctuations can be achieved. This paper is focused on modeling and control of electrically driven fixed pitch propellers (FPP). The main contributions are the analysis of torque and power control for electrically driven thrusters on ships, and the presentation of steady- state sensitivity functions used to analyze the robustness of the various low-level thruster controllers when the propeller is subject to losses. The actual propeller thrust Ta and torque $Q_a$ are influenced by many parameters, the most important being propeller geometry, submergence, and propeller loading-which depends on the propeller pitch ratio and shaft speed. $T_a$ and $Q_a$ can in general be formulated as functions of fixed thruster parameters p (i.e. propeller diameter, geometry, position, etc.), the shaft speed n, and variables $X_P$ (i.e. pitch ratio, advance velocity, submergence, etc.)

The pitch ratio in case of FPP will be fixed parameters but in case of CPP it will be varying parameters. The relationships between the propeller thrust Ta, torque $Q_a$, shaft speed $n$ (in revolutions-per-second-rps), diameter D, and density of water $\rho$ are commonly given by

$$T_a = sign(n) K_T \rho D^4 n^2 \tag{2.9}$$

$$T_a = sign(n) K_Q \rho D^5 n^2 \tag{2.10}$$

$K_T$ and $K_Q$ are strictly positive thrust and torque coefficients, where the effects of thrust and torque losses have been accounted for. The inclusion of loss effects in $K_T$ and $K_Q$ is not conventional, but is convenient for consistency in the description of the propeller characteristics. The expressions for $K_T$ and $K_Q$ for deeply submerged propellers are found by so-called open-water tests, usually performed in a cavitations tunnel or a towing tank. The corresponding open- water efficiency is defined as the ratio of produced to consumed power for the propeller.

$$n_o = \frac{V_a T_a}{2\Pi n Q_a} \tag{2.11}$$

Smogeli and Hansen [12] has introduced thrust and torque reduction coefficients and which express the ratio of actual to nominal thrust and torque.

Beek [13] has mentioned that the largest propeller diameter gives the highest propulsive efficiency. However, the diameter behind the ship is normally limited by the draught of the vessel and the tip clearance.

## 2.6 Ship Resistance

Harvald [14] has described the ship resistances. A ship's resistance is particularly influenced by its speed, displacement, and hull form. The total resistance consists of many source-resistances R which can be divided into three main groups, viz.:

a. Frictional resistance

b. Residual resistance

c. Air resistance

The influence of frictional and residual resistances depends on how much of the hull is below the waterline, while the influence of air resistance depends on how much of the ship is above the waterline. Thus, if water is being completely stopped by a body, the water will react on the surface of the body with the dynamic pressure, resulting in a dynamic force on the body. This relationship is used as a basis when calculating or measuring the source-resistances R of a ship's hull, by means of dimensionless resistance coefficients C. Thus C are related to the reference force K, defined as the force which the dynamic pressure of water with the ship's speed V exerts on a surface, which is equal to the hull's wetted area AS. The rudder's surface is also included in the wetted area. The general data for resistance calculations is thus:

Reference force,

$$K = 0.5 \times \rho \times V^2 \times A_s \tag{2.12}$$

And Source resistance,

$$R = C \times K \tag{2.13}$$

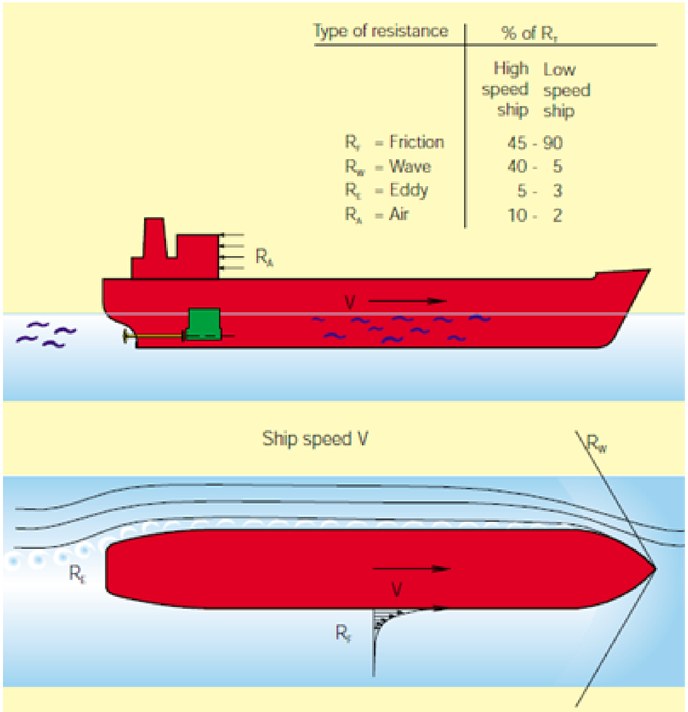


Figure 2.6: Ship Resistances [17]

The frictional resistance of the hull depends on the size of the hull's wetted area As, and on the specific frictional resistance coefficient $C_F$. The friction increases with fouling of the hull. An attempt to avoid fouling is made by the use of anti-fouling hull paints to prevent the hull from becoming "long-haired". When the ship is propelled through the water, the frictional resistance increases at a rate that is virtually equal to the square of the vessel's speed.

Frictional resistance represents a considerable part of the ship's resistance, often some 70-90 % of the ship's total resistance for low-speed ships (bulk carriers and tankers), and sometimes less than 40% for high-speed ships (cruise liners and passenger ships). The frictional resistance is found as follows:

$$R_F = C_F \times K \tag{2.14}$$

Residual resistance $R_R$ comprises wave resistance and eddy resistance. Wave resistance refers to the energy loss caused by waves created by the vessel during its propulsion through the water, while eddy resistance refers to the loss caused by flow separation which creates eddies, particularly at the aft end of the ship. Wave resistance at low speeds is proportional to the square of the speed, but increases much faster at higher speeds. In principle, this means that a speed barrier is imposed, so that a further increase of the ship's propulsion power will not result in a higher speed as all the power will be converted into wave energy. The residual resistance normally represents 8-25% of the total resistance for low-speed ships, and up to 40-60% for high-speed ships. The residual resistance is found as follows:

$$R_R = C_R \times K \tag{2.15}$$

In calm weather, air resistance is, in principle, proportional to the square of the ship's speed, and proportional to the cross-sectional area of the ship above the waterline. Air resistance normally represents about 2% of the total resistance. For container ships in head wind, the air resistance can be as much as 10%. The air resistance can, similar to the foregoing resistances, be expressed as $R_A = C_A \times K$, but is sometimes based on 90% of the dynamic pressure of air with a speed of V, i.e.

$$R_A = 0.9 \times \frac{1}{2} \times \rho_{air} \times V^2 \times A_{air} \tag{2.16}$$

where $\rho_{air}$ is the density of the air, and $A_{air}$ is the cross-sectional area of the vessel above the water.

The ship's total towing resistance $R_T$ is thus found as:

$$R_T = R_F + R_R + R_A \tag{2.17}$$

The corresponding effective (towing) power, $P_E$, necessary to move the ship through the water, i.e. to tow the ship at the speed V, is then:

$$P_E = V \times R_T \tag{2.18}$$

The power delivered to the propeller, $P_D$, in order to move the ship at speed V is, however, somewhat larger. This is due, in particular, to the flow conditions around the propeller and the propeller efficiency itself.

# Chapter 3

# Mathematical Model for EHM System

Experimental and actual trial data is given by manufacturer. The objective was to develop EHM system using these data. EHM system predicts the expected value of the parameter. The numerical analysis of given data is done to compute the equation which will predict the parameter value.

## 3.1 Manufacturer Data Analysis

Manufacture has given the data of various input parameters. This data is divided into two category.

a. Input Variable

b. Output Variable

Input variables can be changed by the operator. As per data, power and speed are the two input variables. Power can be changed by increasing or decreasing the fuel supply to the engine. It is possible with the help of throttling. Speed can be changed with the help of gearbox.

Table I: Engine fuel system experimental data

| Power in KW (X) | Speed in RPM(Y) | Hourly fuel consumption in Kg/Hr | Pressure After Filter in Bar | Fuel inlet temp in c |
|---|---|---|---|---|
| 0 | 0 | 0 | 2.28 | 24.87 |
| 253.125 | 83 | 123.54 | 2.29 | 21.25 |
| 506.25 | 165 | 210.11 | 2.3 | 22.2 |
| 1012.5 | 330 | 385.23 | 3.2 | 20.12 |
| 2025 | 660 | 415.46 | 3.49 | 21.79 |
| 4050 | 834 | 773.2 | 3.33 | 27.95 |
| 6075 | 955 | 1212.12 | 3.4 | 22.8 |
| 7290 | 1013 | 1441.87 | 3.94 | 22.82 |
| 8100 | 1050 | 1656.89 | 3.3 | 25.9 |
| 8910 | 1080 | 1759.32 | 3.4 | 23.85 |

Output variables are depend on input variables. As per data various performance parameters are output variables. These output variables changes when operator changes the speed or power.

Manufacturer has given the data in the format power-speed-parameter ie for particular value of power and speed, parameter value is given.

For example, table I shows manufacturer testing data for following parameters related to fuel supply system.

a. Fuel consumption

b. Fuel pressure

c. Fuel inlet temperature

The data shown in table I can be map in a equation. The dependent variable of this equation will be performance parameter and independent variables will be power and speed. Least square method is used to find out the governing equation. LSM uses the given data points and generate the curve equation. This curve will try to pass through the given data points ie the equation will define the behavior of the parameter with respect to power and speed.

Formulation of the data is done as follow

Independent Variable,

X= Power

Y= Speed

Dependent Variable is Z. Following are the dependent variables for components of propulsion system.

**A.For Engine**

a. Torque

b. Fuel Consumption

c. Fuel pressure after filter

d. Fuel inlet temperature

e. Air temperature before and after CAC

f. Starting air pressure

g. Average exhaust gas temperature

h. Average bearing temperature

i. Average connecting road bearing temperature

j. Lub oil inlet temperature

k. Lub oil cooler inlet and outlet temperature

l. Lub oil pressure after filter

m. Turbocharger temperature before and after cooler

n. Turbocharger pressure before and after cooler

o. High temperature water engine inlet and outlet temperature

p. High temperature water pump outlet pressure

**B.For Gearbox**

a. Shaft speed after gearbox

b. Clutch Oil Pressure (Primary)

c. Control Oil Pressure

d. Sea Water Pressure

e. Thrust Bearing Temperature Ahead

f. LO Temperature before and after LO cooler

g. SW Temperature before and after LO cooler

h. Gearbox Lube Oil Pressure (Primary)

i. Torsion meter Shaft Speed

j. Torsion meter Torque

**C.For Propeller**

a. Stern Tube SW Cooling flow meter

b. CPP Hydraulic Oil Pressure (Primary)

c. Actual Pitch for Indication (Primary)

### 3.1.1 Selection of Primary Function

The primary function selection makes great influence to the fitting precise and computing efficiency, and become a key point in curve fitting. Many researchers prefer to determine the primary function according to the source data. General primary function should be used for curve fitting procedure. Polynomial is a common general primary function.

$$Y = f(X) = a_0 + a_1X + ....... + a_nX^n \tag{3.1}$$

To decide the primary function of each parameter, a graph is plotted from manufacturer data. This graph give a initial idea about the trend of the parameter with respect to power and speed. If the graph is linear then the degree of polynomial is 1. if the graph is non linear in nature then degree of polynomial can be increased accordingly.

### 3.1.2 Selection of Degree of Polynomial Equation

The linear least square is the simplest method that map the given data by line. For 2 independent variable and 1 dependend variable following primary equation is selected.

$$Z = P_1 + P_2X + P_3Y \tag{3.2}$$

Where $P_1$, $P_2$ and $P_3$ are constant to be determined from given data points.

Following matrix equation is used to calculate these constants

$$\begin{bmatrix} n & \sum x & \sum y \\ \sum x & \sum x^2 & \sum xy \\ \sum y & \sum xy & \sum y^2 \end{bmatrix} \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \end{Bmatrix} = \begin{Bmatrix} \sum z \\ \sum xz \\ \sum yz \end{Bmatrix}$$

Using linear least square method mapping of air temperature after charge air cooler can be done. Table II is showing the comparison between experimental value and calculated value. It can be observed that for some data point the error occurred in the calculated value is more than 10% which is not acceptable. This error can be reduce by increasing the degree of polynomial equation. In section 3.1.3 quadratic equation is considered.

Table II: Comparisons between actual and calculated air temperature values using linear LSM

| Power in KW (X) | Speed in RPM(Y) | Air temp (Z) after CAC in ∘C | Air temp after CAC by LSM | % Error |
|---|---|---|---|---|
| 0 | 0 | 42.4 | 50.34 | -18.7 |
| 253.125 | 52 | 46.25 | 51.25 | -10.8 |
| 506.25 | 104 | 53.15 | 52.17 | 1.9 |
| 1012.5 | 209 | 62.14 | 53.99 | 13.1 |
| 1113.75 | 230 | 62.14 | 54.35 | 12.5 |
| 4050 | 834 | 61.1 | 64.93 | -6.3 |
| 6075 | 955 | 62 | 61.79 | 0.3 |
| 7290 | 1013 | 59 | 59.39 | -0.7 |
| 8100 | 1050 | 57 | 57.73 | -1.3 |
| 8910 | 1080 | 56.6 | 5.83 | 1.4 |

### 3.1.3 Quadratic Least Square Regression

The degree of polynomial is increase to 2. The multivariate quadratic equation is considered for the further analysis.

$$Z = P_1 + P_2X + P_3Y + P_4X^2 + P_5XY + P_6Y^2 \tag{3.3}$$

Where constants $P_1$, $P_2$, $P_3$, $P_4$, $P_5$ and $P_6$ can be found out with LCM. For mulivariate quadratic equation matrix equation is used to find out the constants.

Using quadratic least square method mapping of air temperature after charge air cooler can be done. Table III is showing the comparison between experimental value and calculated value for quadratic LSM. The error computed by quadratic LSM is reduced considerably. This quadratic equation establish a relation between the parameter and input variable power and speed. This equation can be used in trial data analysis.

The accuracy of this equation can be improved by increasing the order of the

$$\begin{bmatrix} n & \sum x & \sum y & \sum x^2 & \sum xy & \sum y^2 \\ \sum x & \sum x^2 & \sum xy & \sum x^3 & \sum x^2 y & \sum xy^2 \\ \sum y & \sum xy & \sum y^2 & \sum x^2 y & \sum xy^2 & \sum y^3 \\ \sum x^2 & \sum x^3 & \sum x^2 y & \sum x^4 & \sum x^3 y & \sum x^2 y^2 \\ \sum xy & \sum x^2 y & \sum xy^2 & \sum x^3 y & \sum x^2 y^2 & \sum xy^3 \\ \sum y^2 & \sum xy^2 & \sum y^3 & \sum x^2 y^2 & \sum xy^3 & \sum y^4 \end{bmatrix} \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{Bmatrix} = \begin{Bmatrix} \sum z \\ \sum xz \\ \sum yz \\ \sum x^2 z \\ \sum xyz \\ \sum y^2 z \end{Bmatrix}$$

primary equation. But increase in order will also increase the mathematical complexities. After some order the improvement in the result is very less. Hence optimum order of the equation can be taken.

Table III: Comparisons between actual and calculated air temperature values using Quadratic LSM

| Power in KW (X) | Speed in RPM(Y) | Air temp Before CAC in $\circ$C (Z) | Air temp before CAC by LSM | % Error |
|---|---|---|---|---|
| 0 | 0 | 42.4 | 41.42 | 2.3 |
| 253.125 | 52 | 46.25 | 47.71 | -3.2 |
| 506.25 | 104 | 53.15 | 53.16 | 0.0 |
| 1012.5 | 209 | 62.14 | 61.53 | 1.0 |
| 1113.75 | 230 | 62.14 | 68.17 | 0.2 |
| 4050 | 834 | 61.1 | 62.02 | -1.5 |
| 6075 | 955 | 62 | 60.44 | 2.5 |
| 7290 | 1013 | 59 | 59.26 | -0.4 |
| 8100 | 1050 | 57 | 58.39 | -2.4 |
| 8910 | 1080 | 56.6 | 55.83 | 1.4 |

Figure 3.1 shows the comparison between actual parameter value, linear LSM and quadratic LSM. The result obtained by increasing the degree of equation ie using quadratic equation, error ocuured is reduced considerably. Hence the equation obtained by quadratic LCM gives more fine result.

For different parameters the primary function used can be different. Increasing the order of polynomial further, more close data mapping is possible with LSM. But

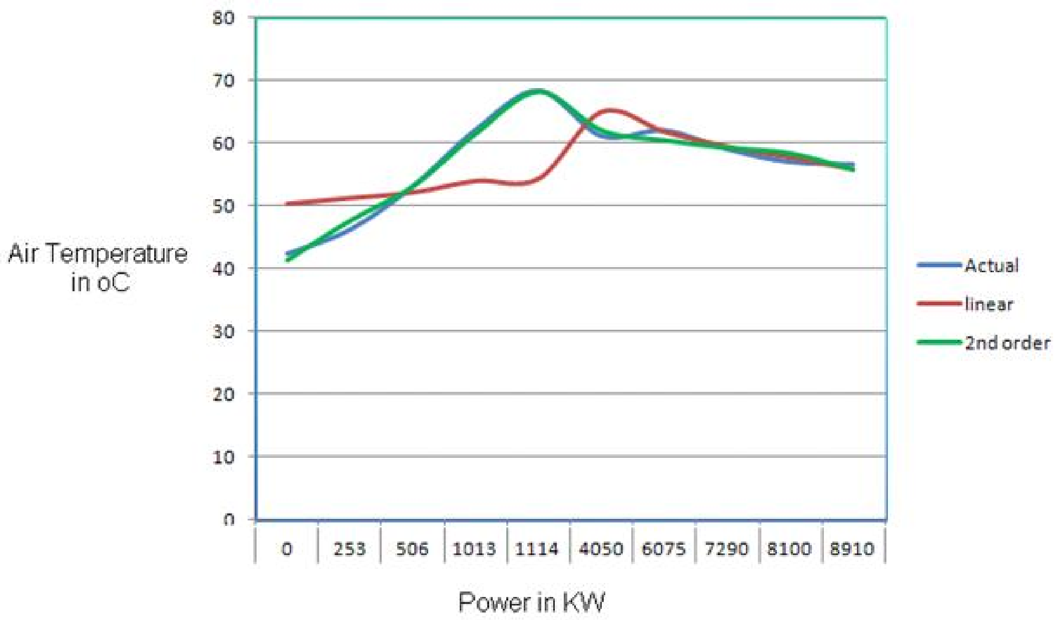


Figure 3.1: Air Temperature before CAC Vs Power and Speed

results of quadratic and cubic equation are nearly similar. Henceforth the quadratic LSM is used for mapping of air temperature.

This analysis is done for the various component parameters listed in section 3.1. Equations for some parameters are explained below

**1.Exhaust gas temperature**

Equation obtains for exhaust gas temperature (Z) in terms of power (X) and speed (Y) by using experimental data. Quadratic LSM is used for the computing this equation.

$$Z = 120.2917 + 0.402048X - 0.8309Y + 0.000026X^2 - 0.000678XY + 0.001825Y^2 \tag{3.4}$$

Figure 3.2 shows the graph plotted between experimental values and computed values for engine exhaust gas temperature. This graph signifies that for engine exhaust gas temperature, quadratic equation can be used.

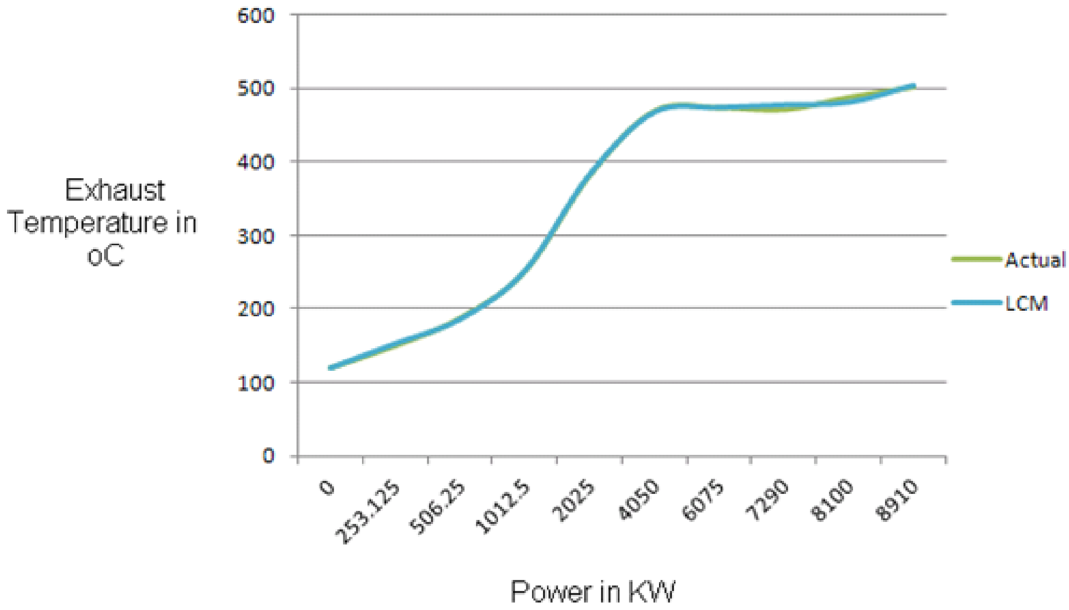


Figure 3.2: Engine Exhaust Temperature Vs Power and Speed

**2.GB lub oil pressure**

Equation can be obtained for GB Lube Oil Pressure (Z) in terms of power (X) and speed (Y) by using experimental data. Quadratic LSM is used for the computing this equation.

$$Z = 273.3176 - 0.2294X - 0.63719Y + 0.000002723X^2 + 0.0001565XY + 0.001009Y^2 \quad (3.5)$$

Figure 3.3 shows the graph plotted between experimental values and computed values for GB LO pressure. This graph signifies that for GB LO pressure, quadratic equation can be used.

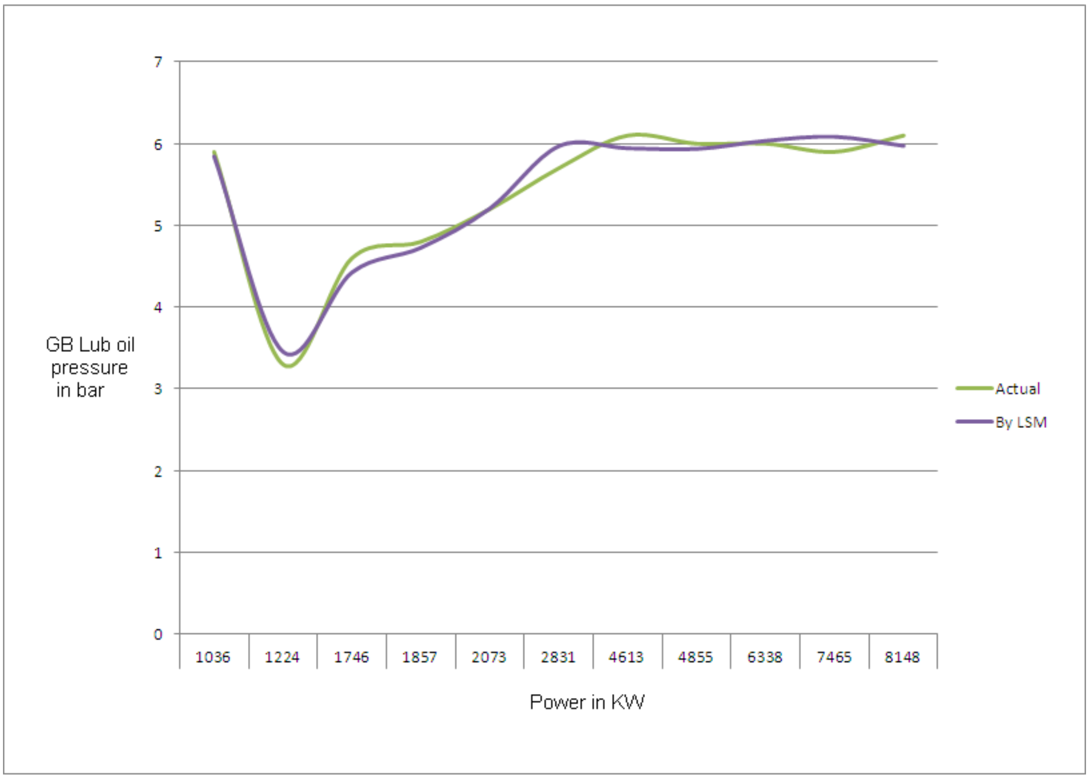


Figure 3.3: GB Lub Oil pressure Vs Power and Speed

**3.Stern tube SW cooling Flow**

Equation can be obtained for Stern tube SW cooling Flow (Z) in terms of power (X) and speed (Y) by using experimental data. Quadratic LSM is used for the computing this equation.

$$Z = 4784.715569 - 4.002X - 11.11601542Y - 0.00005136X^2 + 0.002792314XY + 0.0173355Y^2 \tag{3.6}$$

Figure 3.4 shows the graph plotted between experimental values and computed values for Stern tube SW cooling Flow. This graph signifies that for Stern tube SW cooling flow, quadratic equation can be used.

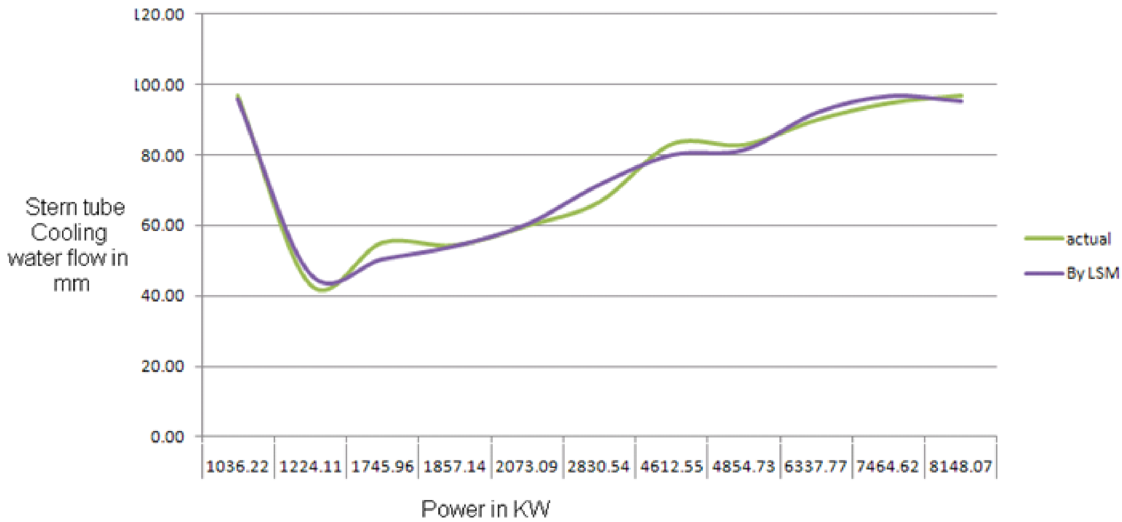


Figure 3.4: CPP Stern Tube Cooling Water Flow Vs Power and Speed

## 3.2 Constraints

The input data is given in the form of power, speed and parameter that means for a particular value of power and speed, the value of parameter is measured. Hence there is a relation between power and speed, which should be followed while taking measurement of parameter. So in order to work the above analysis, it is necessary to follow the below relation.

### 3.2.1 Relation between Power and Speed

Following power equation gives the relation between power, speed and torque

$$P = \frac{2\Pi NT}{60000} \tag{3.7}$$

Where, P= Power in KW N= Speed in RPM T= Torque in Nm This equation signifies that Power is directly proportional to product of speed and torque. If we increase the speed, keeping power constant then torque will reduce and wise versa.

### 3.2.2 Necessity of the Power Equation

The manufacture has given the toque for particular speed and power. For same speed and power, torque is calculated using the equation. Table IV shows that engine follows the torque equation.

Table IV: Comparisons between experimental and calculated values of torque

| Power in KW (X) | Speed in RPM(Y) | Torque in KNm(Z) | Torque calculated by formula | % Error |
|---|---|---|---|---|
| 0 | 0 | 0 | 0.00 | 0.00 |
| 2025 | 660 | 29.64 | 29.30 | 1.15 |
| 4050 | 834 | 46.47 | 46.37 | 0.21 |
| 6075 | 955 | 60.78 | 60.75 | 0.06 |
| 7290 | 1013 | 68.69 | 68.72 | -0.05 |
| 8100 | 1050 | 73.64 | 73.67 | -0.04 |
| 8910 | 1080 | 75.6 | 78.78 | -4.21 |

Trial data has given torque, which is measured by torsion meter. This torque is also checked with the formula in table V. It is satisfying the power equation.

Table V: Comparisons between actual and calculated values of torque

| Power in KW (X) | Speed in RPM(Y) | Torque measured by Torsion meter (Z) | Torque calculated by formula | % Error |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 1654 | 135.8 | 117 | 116.3 | 0.6 |
| 1657 | 135.9 | 115 | 116.4 | -1.2 |
| 6911 | 215 | 303 | 307.0 | -1.3 |
| 7981 | 231.2 | 325 | 329.6 | -1.4 |
| 8206 | 230 | 336 | 340.7 | -1.4 |
| 1437 | 134.4 | 99 | 102.1 | -3.1 |
| 1297 | 134.5 | 92 | 92.1 | -0.1 |

Table IV and V signifies that the analysis which is done here will be valid only when the input data like speed and power should follow the power equation. The parameter values obtain from the above equations will predict the validate result if inputs like power, speed follows power equation.

## 3.3 Validation and Modification

Trial data is the values of various output variables at different speed and power taken during actual sailing of ship. This data replicate the actual working condition of the ship. This data differs from the experimental data provided by the manufacturer because experimentation is done under control condition. But while sailing some unpredictable loses occurs which cause the variation from experimental values.

If we use the computed equation for the analysis, it will not replicate the actual working condition. Modification of the constants of the equation is required so that the equation will also consider the effect of actual working condition. Using least square regression the constants are calculated from trial data and then the actual constants as per experimental data analysis are modified, so that the equation will satisfy the trial data.

This final equation will return the values of output variable, considering actual working condition. The example of trial data analysis carried out on starting air pressure of engine is explained in below sections.

### 3.3.1 Equation obtain from Experimental Data

The equation is obtained from experimental data. The quadratic LSM is used for computing this equation.

$$Z = 25.835 - 0.001656X - 0.0125Y + 0.0000001X^2 - 0.000003XY + 0.000027Y^2 \quad (3.8)$$

Table VI shows the comparison between experimental data value and computed values of air pressure. This comparison shows that the error between trial data value and computed data value for same power and speed is less than 10%. This much error in predicted values are acceptable and we can use this equation for further analysis.

Table VI: Comparisons between calculated air pressure values using Quadratic LSM and trial data

| Power in KW (X) | Speed in RPM(Y) | Starting air pressure in bar(Z) | Starting air pressure calculated by LSM | % Error |
|---|---|---|---|---|
| 0 | 0 | 25.8 | 25.8 | 0 |
| 253.125 | 83 | 24.3 | 24.5 | -1 |
| 506.25 | 165 | 23.85 | 23.5 | 2 |
| 1012.5 | 330 | 22.12 | 22.3 | -1 |
| 2025 | 660 | 23.2 | 23.5 | -1 |
| 4050 | 834 | 24 | 23.2 | 3 |
| 6075 | 955 | 23.3 | 24.1 | -3 |
| 7290 | 1013 | 24.5 | 25.3 | -3 |
| 8100 | 1050 | 28.3 | 26.5 | 6 |
| 8910 | 1080 | 27.1 | 27.8 | -3 |

### 3.3.2 Checking of Equation with Trial Data

Trial data represent the actual working condition. Hence the equation obtained from experiential data should be satisfied by trial. Table VII shows the comparison between parameter value computed by equation and values from trial data. This comparison decides the compatibility of the equation obtain from experimental data. If the error occurred is more than 10% then we can not used the equation obtained from experimental data. Modification of the equation is necessary to reduce the error below tolerable limits. Trial data can be used to modify the constants of the equation.

### 3.3.3 Determination of Constants as per Trial Data

The error occurred for air temperature is above 10% hence the equation need to modify as per trial data. The values of constants are recalculated by using LSM. The new constants are shown in table VIII

Table VII: Comparisons between air pressure as per equation and trial data

| Power in KW(X) | Speed in rpm(Y) | Starting Air Press in bar | As per Equation | %Error |
|---|---|---|---|---|
| 0 | 0 | 29.6 | 25.9 | 12 |
| 1036 | 405 | 24.0 | 22.5 | 6 |
| 1302 | 496 | 21.0 | 22.7 | -8 |
| 1409 | 524 | 33.2 | 22.8 | 31 |
| 1613 | 569 | 21.7 | 22.9 | -6 |
| 1803 | 604 | 25.6 | 23.0 | 10 |
| 2174 | 660 | 31.7 | 23.1 | 27 |
| 2470 | 697 | 28.0 | 23.2 | 17 |
| 2704 | 723 | 33.8 | 23.2 | 31 |
| 3224 | 773 | 20.4 | 23.2 | -14 |
| 4381 | 861 | 32.0 | 23.4 | 27 |
| 6014 | 955 | 28.3 | 24.1 | 15 |
| 6421 | 975 | 33.3 | 24.5 | 26 |
| 7418 | 1020 | 32.3 | 25.5 | 21 |
| 8148 | 1050 | 33.8 | 26.5 | 22 |

### 3.3.4 Final Modified Equation

The difference between constants is added to constants computed by experimental data. The equation is checked with trial data. If it satisfies the equation, the modified equation can be used for analysis. Otherwise the equation is modified so that the error occurred should be less than 10%.

For air pressure the error occurred for trial data is less than 10%. Hence this

Table VIII: Constants calculated by LSM using trial data

| | |
|---|---|
| P1 | 28.761081 |
| P2 | -0.021191 |
| P3 | 0.007025 |
| P4 | 0.00000 |
| P5 | 0.000011 |
| P6 | 0.000056 |

modified equation is the final equation for air pressure. Table IX shows the % error occurred after putting trial data in final equation.

$$Z = 29.56162 - 0.0007212X - 0.041102Y + 0.000001X^2 - 0.000001602XY + 0.00010628Y^2 \quad (3.9)$$

Table IX: Validation of final equation using trial data

| Power in KW(X) | Speed in rpm(Y) | Starting Air Press in bar | As per Equation | %Error |
|---|---|---|---|---|
| 1309 | 498 | 25.3 | 25.9 | -3 |
| 1707 | 587 | 27.3 | 28.0 | -2 |
| 2080 | 647 | 29.0 | 29.2 | -1 |
| 2648 | 717 | 28.5 | 30.1 | -6 |
| 3556 | 801 | 29.5 | 30.5 | -4 |
| 6358 | 972 | 28.8 | 30.9 | -7 |
| 6872 | 996 | 32.4 | 31.4 | 3 |

### 3.3.5 Final Equation for EHM System

The final equation can be used for predicting the value of output variable for a set of power and speed. The output variables actual value obtain from channel is compared with predicted value. If the actual value is beyond permissible limit the alarm will generate and feedback system will get activate to take precautionary measures and control the parameter.

## 3.4 Calculation of Efficiencies

This efficiency model is proposed in addition to numerical analysis done in earlier section.

Efficiency is the measure of the performance of any system. Based on the literature reviewed, mathematical model is developed which will calculate the efficiencies of the components like diesel engine, gear box and propeller. Addition of this model to EHM system will allow to replicate the overall performance of the each equipment.

The ship resistance is also calculated in 3.4.4 in order to know how much power is required to propel the ship at required speed.

Addition of this model to EHM will improve the effectiveness of the system.

### 3.4.1 Diesel Engine Efficiency Calculation

Formulation shown in table X will calculate thermal efficiency, mechanical efficiency and specific fuel consumption of diesel engine.

The input variables and constants listed in table should be taken as per the specification of engine or it should be provided by the manufacturer of the engine. A mathematical formulation is developed in computer application to calculate the output variables.

Table X: Diesel engine efficiency calculation

| **Parameter** | **Symbol /Formula** | **Value** |
|---|---|---|
| **Input Variables** | | |
| Speed of the engine(RPM) | N | 1050 |
| Fuel consumed in kg/sec | $\dot{m}_f$ | 0.46 |
| Indicated mean effective pressure(bar) | IMEP | 20 |
| Brake Power(KW)/Power output | B.P. | 8100.00 |
| **Constants** | | |
| Stroke Length(m) | [L] | 0.5 |
| Area of Piston (sq m) | [A] | 0.13 |
| Number of cylinder | [n] | 14 |
| K(4 Stroke) | | 0.5 |
| **Output Variables** | | |
| Torque(Nm) | $\tau = \frac{B.P. \times 1000 \times 60}{2 \times \Pi \times N}$ | 73666.0 |
| Indicated Power(KW) | $I.P. = \frac{n \times IMEP \times L \times A \times N \times K \times 10}{6}$ | 15925.00 |
| Bmep (bar) | $BMEP = \frac{B.P. \times 6}{L \times A \times N \times K \times n \times 10}$ | 5.09 |
| Frictional power(KW) | $F.P = I.P - B.P$ | 7825.00 |
| Heat supplied(KW) | $Q = m_f \times \rho_f \times C_V$ | 20 |
| Indicated Thermal Efficiency (%) | $\frac{I.P.}{Q}$ | 40 |
| Brake Thermal Efficiency(%) | $\frac{B.P.}{Q}$ | 1050 |
| Mechanical Efficiency(%) | $\frac{B.P.}{I.P.}$ | 0.46 |
| Specific Fuel Consumption (kg/KWh) | $\frac{\dot{m}_f}{B.P.}$ | 20 |

### 3.4.2 Gearbox Efficiency Calculation

Formulation shown in table XI is done to calculate efficiency of gearbox and gearbox loses.

The input variables and constants listed in table should be taken as per the specification of gearbox or it should be provided by the manufacturer of the gearbox. A mathematical formulation is developed in computer application to calculate the output variables of gearbox.

Table XI: Gearbox efficiency calculation

| **Parameter** | **Symbol /Formula** | **Value** |
|---|---|---|
| **Input Variables** | | |
| Number of teeth on pinion | $Z_1$ | 18 |
| Number of teeth on gear | $Z_2$ | 72 |
| Gear ratio | $\mu$ | 04 |
| helix angle | $\beta$ | 20 |
| Profile contact ratio | $\varepsilon_\alpha$ | 2 |
| Tip contact ratio 1 | $\varepsilon_1$ | 2 |
| Tip contact ratio 2 | $\varepsilon_2$ | 2 |
| Mean coefficient of gear friction | $\mu_{mz}$ | 0.1 |
| **Output Variables** | | |
| Gear Lose factor | $H_V = \frac{\Pi(\mu+1)}{Z_1\mu\cos(\beta)} \times (1 - \varepsilon_\alpha + \varepsilon_1^2 + \varepsilon_2^2)$ | 1.625 |
| Gear Loses(KW) | $P_L = H_V \times \mu_{mz} \times P_i$ | 1316.39 |
| Gear Box Efficiency (%) | $\eta_G$ | 83.748 |

### 3.4.3 Propeller Efficiency Calculation

Formulation done in table XIIis done to calculate efficiency of propeller. The input variables and constants listed in table should be taken as per the specification of propeller or it should be provided by the manufacturer of the propeller.

A mathematical formulation is developed in computer application to calculate the output variables. Power developed by propeller is calculated. In order to propel the ship at required speed, the power develop by propeller should be more than resistance of ship.

Table XII: Propeller efficiency calculation

| **Parameter** | **Symbol /Formula** | **Value** |
|---|---|---|
| **Input Variables** | | |
| Propeller speed(RPS) | n | 3.3 |
| Propeller advance(inflow) velocity (m/s) | $V_a$ | 10 |
| **Constants** | | |
| Thrust Coefficient | $K_T$ | 0.9 |
| Torque Coefficient | $K_Q$ | 0.5 |
| Diameter of the propeller (m) | D | 1.1 |
| **Output Variables** | | |
| Advance Coefficient | $J = \frac{V_a}{nD}$ | 2.8 |
| Propeller Thrust(KN) | $T_a = sign(n) \times K_T \times \rho \times D^4 \times n^2$ | 563.20 |
| Propeller Torque | $Q_a = sign(n) \times K_Q \times \rho \times D^5 \times n^2$ | 344.18 |
| Propeller Power consumption(KW) | $P_P = 2 \times \Pi \times n \times Q_a$ | 7028.25 |
| Open water efficiency (%) | $n_0 = \frac{V_a T_a}{P_P}$ | 80.13 |

### 3.4.4 Ship Resistance Calculation

Table XIII shows ship resistance calculation. The input variables and constants listed in table are taken from the literature reviewed. A mathematical formulation is developed in excel to calculate the total resistance offered by the external agencies like wind and water on the ship. Calculation of ship resistances signifies the overall power required to propel the ship at particular velocity.

This model can be added to EHM system so that it will calculate the resistance at particular speed. It will allow operator to understand how much power should be generated by the propulsion system and the input parameters can be changed accordingly.

Table XIII: Resistance on ship

| **Parameter** | **Symbol /Formula** | **Value** |
|---|---|---|
| **Input Variables** | | |
| Ship Velocity(m/s) | V | 10 |
| Water Velocity(m/s) | $V_W$ | 0.1 |
| Air Velocity(m/s) | $V_a$ | 1 |
| Hull's wetted area ($m^2$) | $A_S$ | 574 |
| Hull air exposed area ($m^2$) | $A_a$ | 320 |
| Specific frictional resistance | $C_f$ | 0.9 |
| Specific Residual Resistance | $C_R$ | 0.8 |
| **Output Variables** | | |
| Frictional Resistance | $R_f = C_f \times \frac{1}{2} \times \rho \times V^2 \times A_S$ | 265 |
| Residual Resistance | $R_R = C_R \times \frac{1}{2} \times \rho \times V_{rs}^2 \times A_S$ | 231 |
| Air Resistances | $R_a = 0.9 \times \frac{1}{2} \times \rho \times V_{ra}^2 \times A_a$ | 0.140 |
| Total resistance | $R_T = R_f + R_R + R_a$ | 495.6 |
| Power Require to Move the ship(KW) | $P_T$ | 4956 |

# Chapter 4

# Feedback System

The parameter value can cross the upper or lower limits. In such a situation alarm signal is generated to intimate the operator and then he will take the precautionary measures. In this chapter a feedback system is proposed for the temperature and pressure parameter for automatic control ie this feedback system will keep the parameter within permissible limit automatically.

## 4.1 Feedback system for Temperature

There is a continuous need to keep the temperature under a certain critical value. This can be achieved through lubrication. A continuous supply of lubricant is not a cost-effective solution. Hence the automatic control is achieved by controlling the supply of the lubricant. The temperature is also sensed and sent to a monitoring terminal using wireless technology.

Temperature is considered as one important indicator about bearing life. Friction is one causes of temperature rise. Rise in temperature can cause fatigue damage as well. There are different products available in the market to lubricate shaft bearing.

Different products incorporate automatic lubrication by controlling the amount of lubricant as well as the frequency. Most of the proposed automatic lubrication control focuses on the amount of the required volume of lubricant besides the frequency at which the lubricant must be supplied.

A system is proposed by Hassan, [18] to control the bearing temperature. In this work, the lubricant will only be applied when the bearing temperature reaches a pre-set value. A different approach is adopted where the control action is based on the measured bearing temperature. In other words, the lubricant will only be applied when the bearing temperature reaches a pre-set value. The control mode is programmed on-off type. Following flowchart will show the feedback loop for bearing temperature.

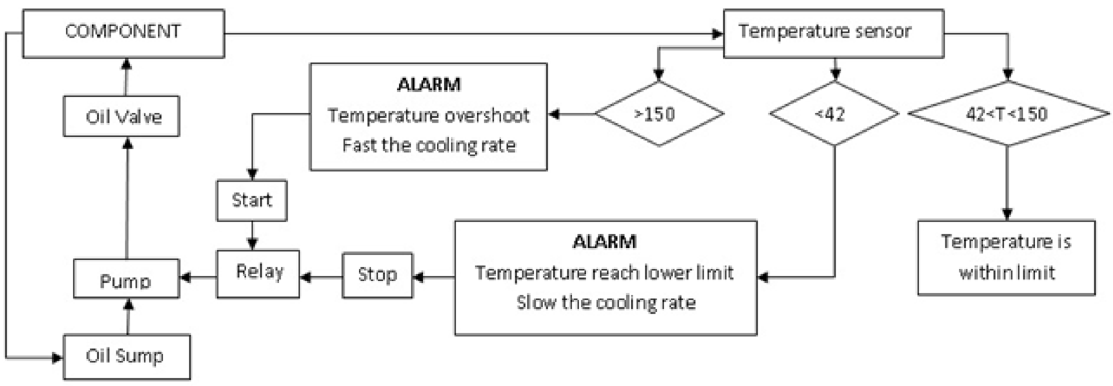


Figure 4.1: Feedback loop for temperature

## 4.2 Feedback System for Pressure

Pressure of the fluid should be within the tolerable limit for good performance of the equipment. High pressure can cause,

a. Dis-functioning of the equipment

b. Damage to the equipment

c. Increase in temperature

Low pressure can cause,

a. Low efficiency

b. Improper working of the equipment

Hence Necessary precaution should be taken to keep the pressure in tolerable limit.

Following close loop system can be used to keep the temperature within tolerable limit.

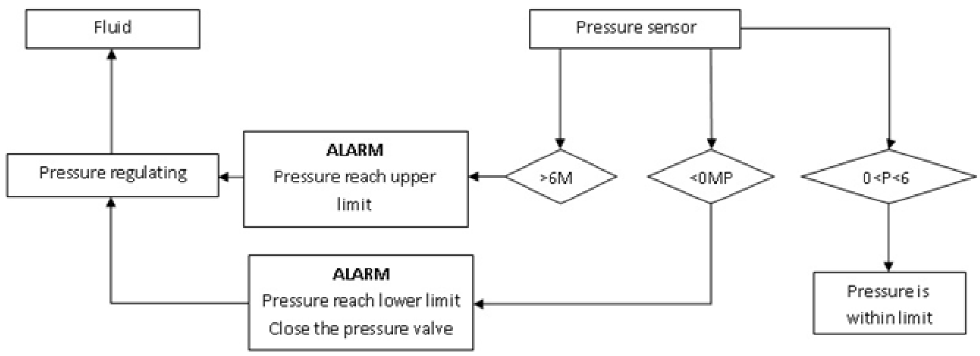


Figure 4.2: Feedback loop for pressure

# Chapter 5

# Flowchart for Development of EHM System

The numerical analysis done in this project is helpful to devlope a software for EHM system. In order to implement the EHM system for various naval ship propulsion, a generalized methodology should be adopted. The flowchart is proposed to develop the software for EHM system of any naval ship.

Flowchart shown in figure 5.1 gives the methodology to do the analysis for any naval ship. This flowchart summaries the work done in this project. It gives the information about the input data required for the analysis so that data can be arranged in priority to save the time.

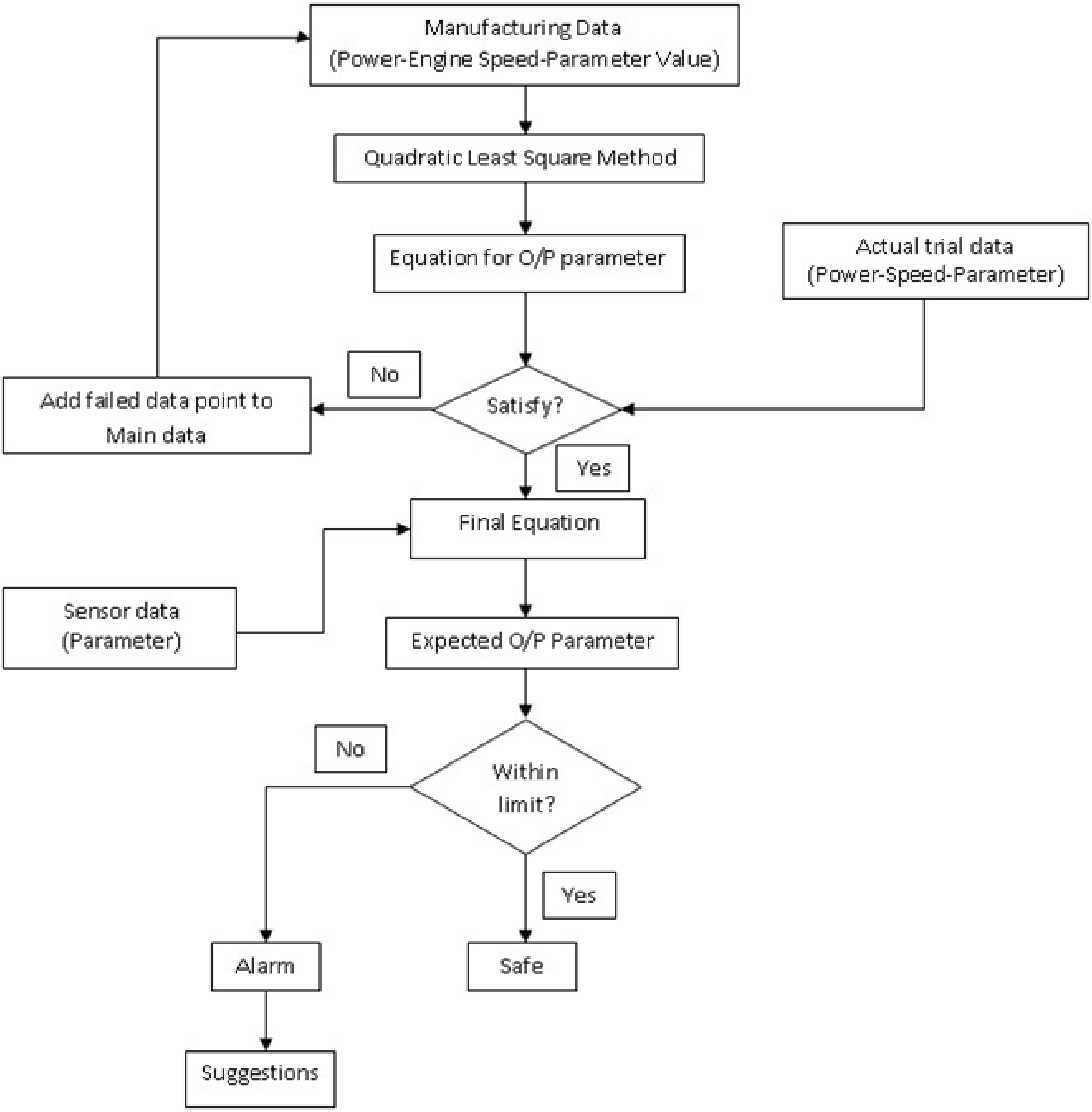


Figure 5.1: Flowchart for development of EHM

# Chapter 6

# Conclusion And Future Scope

## 6.1 Conclusion

The mathematical model has been developed for the EHM system of the equipments of propulsion system of ship. The main input data required for carry out this analysis are experimental data obtained from manufacturer of the equipments and trial data obtain at the time of sailing of the ship. The proposed mathematical model helped to decide the methodology for development of EHM system. The implementation of this model is easy because the input data required is minimum and it uses the data which is available easily. The predicted values calculated by the model are within the tolerable limits.

Another model is proposed which will calculate the efficiencies of the main component of the propulsion system. This model monitors the overall performance of the equipments. Adding this model to EHM system improve the effectiveness of the EHM system.

## 6.2 Future Scope

In this project, the objective was to develop the methodology for EHM system. The effectiveness and accuracy of the mathematical model can be improved. Following points discuss the farther scope.

a. Advance curve fitting techniques can be used.

b. Primary function can be exponential/trignomentric/logarethmic instead of polynomial for best data mapping.

c. Interfacing of the EHM with equipments to control parameters automatically.

d. development of software based on mathematical model

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