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Statistical Correlation of Optimized Gas Turbine Fault Analysis

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ABSTRACT

Performance monitoring constitutes a key practice to ensure plant profitability, with considerable cost savings related to maintaining maximum fuel efficiency and availability. As shown in this article, gas turbine performance is strongly affected by "natural" parameters such as ambient environmental and load conditions. As such, only systems that use detailed thermodynamic models of the gas turbine and its components are capable of correctly separating these "natural" effects from actual equipment degradation. Since the performance of the gas turbines suffer greatly from the inefficiency of turbines and compressors due to insufficient boost pressure at successive stages of the compressor blade, it can lead to flow reversal at the later stage and then result in vibration which is detrimental to engine operating conditions. A step to correlate between boost pressure and vibration velocity amplitude at design stages led to the execution of this research. Also, a computer simulation technique is used to actualize this purpose with the operational data obtained from Delta IV unit of Ughelli power station GT 18 using VC++ programming language. Other results obtained show a linear relationship between the data using statistical z-test and data were accepted.The most striking result is that they should not be run above 9.5 boost pressure ratio which corresponds to 2.05mm/s vibration velocity amplitude to avoid catastrophic breakdown.

Keywords: *Computer simulation; Statistical correlation; Gas turbine; Fault analysis; Vibration amplitude; Boost pressure.*

NOMENCLATURE

x = Vibration velocity (mm/s)
$r_p = Y$ = Pressure ratio
X = Vibration velocity amplitude (mm/s)
r = Correlation coefficient
n = Number of sample
H_o = Null hypothesis
H_1 = Research hypothesis
Y = Pressure (bar)
T = Temperature (K)
Brg = Bearing
Cpd = Compressor discharge pressure

1. INTRODUCTION

The marine gas turbine (GT) in many respects is the most significant means of producing mechanical power among the other various means. The GT obtains its power by utilizing the energy of burnt gases and air which are at high temperature and pressure by expanding through several rings of fixed and moving blades [1]. It is increasingly being used all over the world for various applications; some of these applications include power generation, aero-propulsion, propulsion of ships, operation of pumps and compressors [2]. In Nigeria, gas turbines are used mainly for electricity generation, base-load operations, standby power generating plants including aircraft and ship propulsion. Most oil companies like Agip, Chevron, Elf and Shell also use GTs for electricity generation and other purposes [3].

In this paper, an approach is presented for estimating the risk associated with a mismatch in vibration amplitude and boost pressure. Use is made of VC++ programming language to determine the statistical correlation coefficient.

The word vibration can be defined as oscillation wherein the quantity is a parameter that defines the motion of mechanical system [4]. It occurs in very large ocean wave, rotating and stationary machinery structures such as buildings, ships, vehicles, industrial system (equipment). Vibration may be termed free (natural) or forced depending on the pressure of the external force acting on the system. According to Ogbonnaya (2004), vibration could be represented by Equation (1):

$$\text{Vibration amplitude response} = \frac{\textit{Dynamic force}}{\textit{Dynamic Resistance}} \qquad (1)$$

Equation 1 shows that a machine with acceptable vibration may have a marked higher level of a given insufficient support of foundation. Vibration has three quantities, which are of interest in vibration studies, the vibratory displacement, (amplitude), velocity (integration of acceleration signals or differentiation of displacement singals), acceleration (transducers are designed to measure vibratory acceleration and are called accelerometers that is acceleration sensors).

1.1 Factors Affecting Performance

GTs operate efficiently if the energy conversion process is operated at the following thermodynamically favorable conditions:

- high pressure and temperature at the turbine inlet;
- minimal losses during compression and expansion.

While conversion losses can be minimized through optimal aerodynamic design of the compressor and turbine expander, the high pressures (ratios of 20:1 or greater) and turbine inlet temperatures (1371.11°C and above) desirable for efficiency come at a price: reduced durability of the gas path components. Effectively, to achieve the thermal efficiencies delivered by modern gas turbines, they must work at process conditions that push the mechanical and thermal stress of the materials used in the machine's gas path components to their limits [5].

Ambient conditions affect a gas turbine at both the compressor inlet and the turbine outlet. At the compressor inlet, the higher the temperature and the lower the pressure, the less mass flow that can be generated through the turbine. Humidity also plays a role. Higher specific humidity increase the specific volume of the inlet air flow, so that the mass flow through the turbine is reduced resulting in less power output and increased heat rate. At the turbine outlet, ambient conditions also play a role. The higher the pressure the less energy that can be converted to shaft power [3].

1.2 Cause and Effect

The changes in power output and fuel consumption can have very 'natural' causes, and the effects can be as large as or larger than those arising from equipment degradation. To illustrate this, Figure 1 shows the typical impact on rated power and heat rate for a hypothetical 40 MW industrial gas turbine that would be caused by changes in inlet temperature, inlet pressure drop, part-load fraction, and steam injection flow [6].

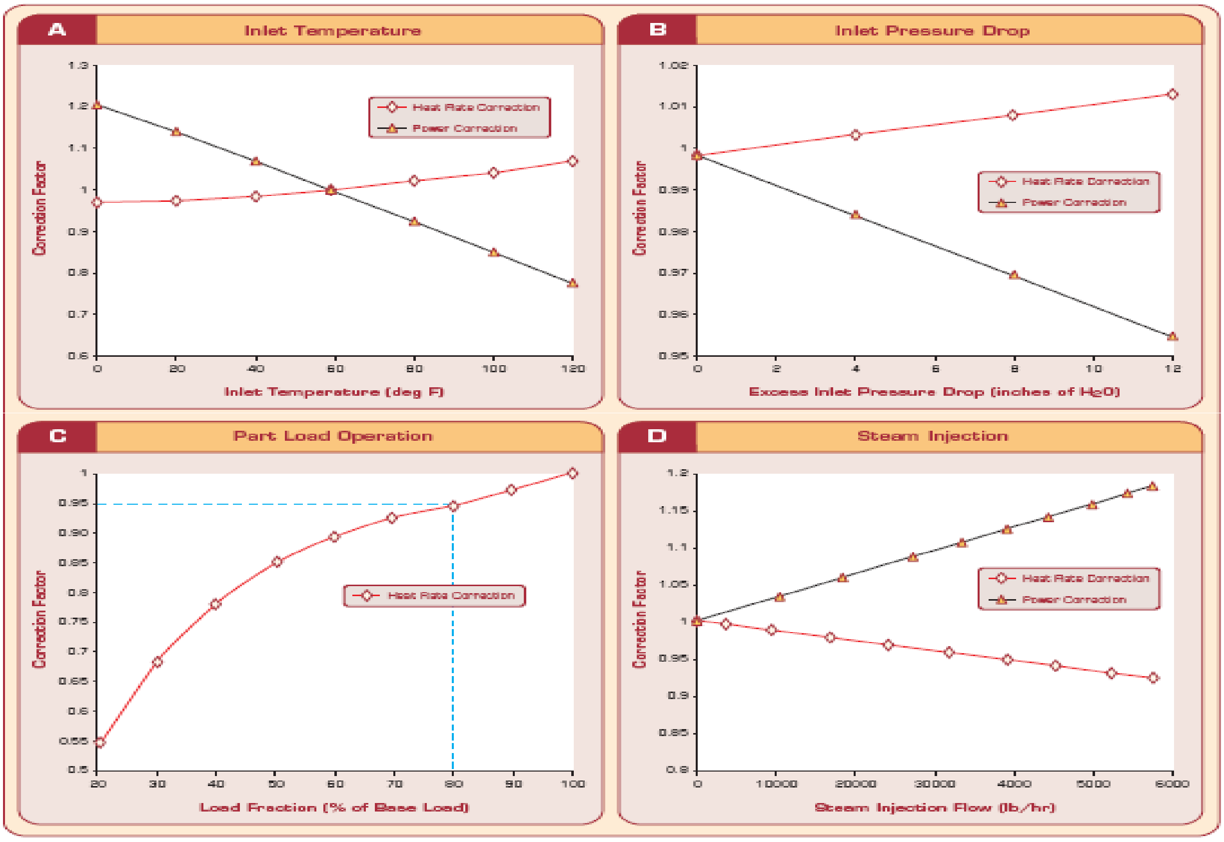

Figure 1. Changes in power output and heat rate for a 40 MW GT due to a) inlet temperature; (b) inlet pressure drop; c) partial loading; and, d) steam injection flow [1]

1.3 Pressure Measurement

The measurement of pressure is always relative to some particular datum, and the various methods of pressure measurement include the balancing of a column of liquid and the elastic deflection of various elements; the deadweight methods are exemplified by manometer and piston gauges while the elastic devices take many different forms [7].

2. MATERIALS AND METHODS

2.1 Vibrational Analysis

Vibrational analysis is the analysis on rotating machinery to enable the early detection of faults before breakdown, and the rotating components in a gas turbine is the compressor and turbine that is mounted on a common shaft. This research dwell on the effect of pressure ratio on vibration amplitude in an industrial GT through statistically correlation, however pressure ratio can be defined as the ratio of the absolute compressor pressure output to the absolute compressor pressure input. The purpose of vibrational analysis is to determine the mechanical condition of the engine and pinpoint any specific mechanical or operational defect. Data acquisition is the essential first step in vibration analysis and the right data must be acquired under appropriate condition [4].

2.2 Vibration Measurements

Some vibration measuring instruments are listed and explained below.

2.2.1 Vibrometer

A vibrometer is an instrument used in measuring the displacement of a vibrating body. Thus, a Vibrometer requires a heavy mass, which makes it bulky. On account of this, it is not commonly used for Vibration measurements. Also the angular frequency (ω) should be quite large. Therefore, it is a high frequency instrument.

2.2.2 Velometer

A velometer is an instrument used in measuring the velocity of a vibrating body. i.e. velocity vibration amplitude.

2.2.3 Accelerometer

It is an instrument used in measuring the acceleration of a vibrating body. A seismic accelerometer [4] is shown in Fig. 2.

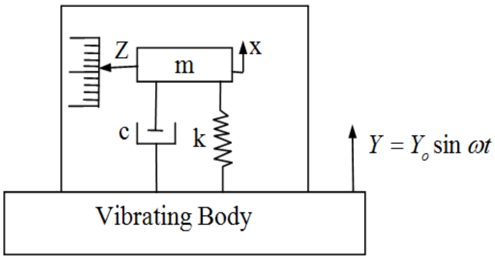

Figure. 2. Seismic accelerometer [1]

The seismic accelerometer is a low frequency instrument and various types of designs of accelerometers are available. The common types are of the seismic mass type and the semiconductor type accelerometers. The piezoelectric types are commonly used, and the accelerometer is most commonly used to measure vibration. The velocity and displacement are measured by converting acceleration into velocity and displacement by integrating circuits.

2.3 GT Vibration Monitoring Systems

Early detection of GT malfunctions gives the owners and operators an opportunity to prevent unexpected catastrophic failure. Vibration monitoring can quickly determine that a problem has occurred and the machine is in distress. For example, gas turbines generally trip offline due to high vibration from an event such as blade loss. Although blade failure is caused by another mechanism, adequate vibration monitoring and protection systems allow the operator to react to the failure, shut down the engine in a controlled manner and make necessary repairs [8].

2.4 Laplace Correction for Missing Data

Test data sets do not usually contain a complete representation of the confusion matrix. The low probability of the off diagonal elements occuring requries a very large data set to accurately capture the true distribuiton of the complete populaiton. Applying a Laplace correction to the mean cost matrix compensates for the missing data and improves the confidence interval on the resulting cost value [9].

In addition to improving the confidence interval on the average metric, we apply the Laplace correction to obtain improved confidence intervals on the entries in the confusion matrix, incluidng zero valuse entries that otherwise would not have a confidence interval [10].

The Laplace corrected matrix is produced with the equation below:

$$L = \frac{\mathrm{Pn} + \lambda}{\mathrm{n} + \mathrm{F}^2 \lambda} \qquad (2)$$

Where

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P = Confusion matrix as proportion of total diagnosis
n = Number of samples
λ = Laplace corrector
F = Number of fault types

Also, according to [11], without the knowledge of the relative frequency with which two or more phenomena occurs it would be impossible to predict accurately future events, i.e where correlation becomes involved.

2.5 Correlation

Correlation is one of the most common and most useful statistics. A correlation is a single number that describes the degree of relationship between two variables.

Linear correlation coefficient

Linear correlation coefficient is defined to be a measure of the linear relationship between two random variable x and Y and it is denoted by ρ [12]. It is used to correlate pressure ratio and vibration amplitude data obtained from an industrial gas turbine plant, since it is basically concerned with a measure of the relationship between two or more variable and it does not take into consideration the prediction of one variable from knowledge of an independent variables.

2.6 Correlation between Pressure Ratio and Vibration Amplitude Measurement

To estimate a linear correlation coefficient, we first choose a random sample of n pairs of measurements (X,Y). By constructing a scatter diagram for the (X,Y) value (see fig. 3(a). We are able to draw certain conclusions. Should the points follow closely a straight line of positive slope, we have a high positive correlation between the two variables.

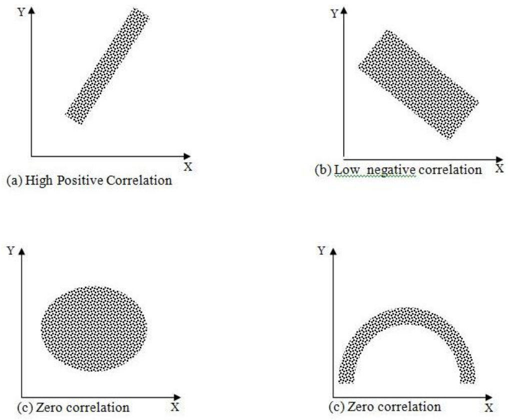

Figure. 3. Scatter diagrams showing various degrees of correlation [12]

On the other hand, if the points follows closely a straight line of negative slope. We have a high negative correlation between the two variables as in fig. 3(b). If the points follow a strictly random pattern as in fig. 3(c), we have zero correlation and conclude that there is no relationship between X and Y.

It is important to remember that the correlation coefficient between two variables is a measure of their linear relationship, and a value of $\rho = 0$ implies a lack of linearity and not a lack of association. Hence, if a strong quadratic relationship exists between X and Y as indicated in fig. 3(d). We will still obtain a zero correlation to indicate a nonlinear relationship.

The most commonly used measure of linear correlation between two variables is called the Pearson product-moment correlation coefficient, or simply the sample correlation coefficient.

Correlation Coefficient

The measure ρ of linear relationship between vibration amplitude and pressure ratio data's X and Y respectively is estimated by sample correlation coefficient r.

Where SSE = sum of squares of the errors.

$$\gamma = \frac{n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sqrt{\left[n\sum_{i=1}^{n} x_i^2 - \left(n\sum_{i=1}^{n} x_i\right)^2\right]\left[n\sum_{i=1}^{n} y_i^2 - \left(n\sum_{i=1}^{n} y_i\right)^2\right]}} = b\frac{S_x}{S_y} \quad (3)$$

Where

x = Vibration velocity amplitude (mm/s)
y = Pressure ratio

From the sum of squares of the errors;

$$SSE = (n-1)(S_y{}^2 - b^2 S_x{}^2) \quad (4)$$

Dividing both sides of this equation by $(n-1)S_y{}^2$

We obtain the relation

$$r^2 = 1 - \frac{SSE}{(n-1)S_y{}^2}$$

From which we conclude r^2 must be between zero and 1.

A test of the hypothesis

$$H_O: \rho = \rho_o \quad (5)$$
$$H_1: \rho \neq \rho_o \quad (6)$$

Is easily conducted from the sample information by using the quantity

$$\frac{1}{2}\ln\left(\frac{1+r}{1-r}\right)$$

Which is a value of a random variable that follows approximately the normal distribution with mean

$$(\tfrac{1}{2})\ln[(1+\rho)/(1-\rho)]$$

and variable $\frac{1}{(n-3)}$

Thus the test procedure is to compute

$$Z=\frac{\sqrt{n-3}}{2}\left[\ln\left(\frac{1+r}{1-r}\right)-\ln\left(\frac{1+\rho_o}{1-\rho_o}\right)\right] \qquad (7)$$

$$Z=\frac{\sqrt{n-3}}{2}\ln\left[\frac{(1+r)}{(1-r)}\frac{(1-\rho_o)}{(1+\rho_o)}\right] \qquad (8)$$

which compares to the critical point of the standard normal distribution.

The correlation will be use to advantage by indicating if the correlation is weak (i.e. if r is close to zero) or we can also say that a very good linear relationship exist if the values of P_r (Y) is accounted for by a linear relationship with vibration amplitude (X).

Figure 4 Shows the flow chart for obtaining correlation coefficient of the experimental data from GT 18 unit of Delta IV Power Station. The plant diagram and some of the characteristics of the test engine relevant to the research are shown in Appendix A.

From this flowchart, the program code in C++ was developed. The data for the program was used to produce the graphs shown in figs. 5 to 9.

3. RESULTS AND DISCUSSION

Hypothesis Testing of Detla IV GT Unit 18

Correlation coefficient (r) for

bearing 1 $=-3.9396e-007$

Null Hypothesis $H_0:\ \rho_0=0$

Research Hypothesis $H_1:\rho_1\neq 0$

Statistical Test: Since n is large, Z-test is appropriate.

Level of Significance $\alpha=0.05$ (95% confidence level)

Critical Region: $Z<-1.96$ and $Z>1.96$

Computations: Using equation (8)

$$Z_{C1}=\frac{\sqrt{n-3}}{2}\ln\left[\frac{(1+r)(1-\rho_0)}{(1-r)(1+\rho_0)}\right]$$

$$Z_{C1}=\frac{\sqrt{12-3}}{2}\ln\left(\frac{0.9964}{1.0036}\right)$$

$$=\frac{\sqrt{9}}{2}\ln(0.9928)$$

$$Z_{C1}=-0.11$$

Decision: $Z_{C1}<-1.96$ Accept H_0

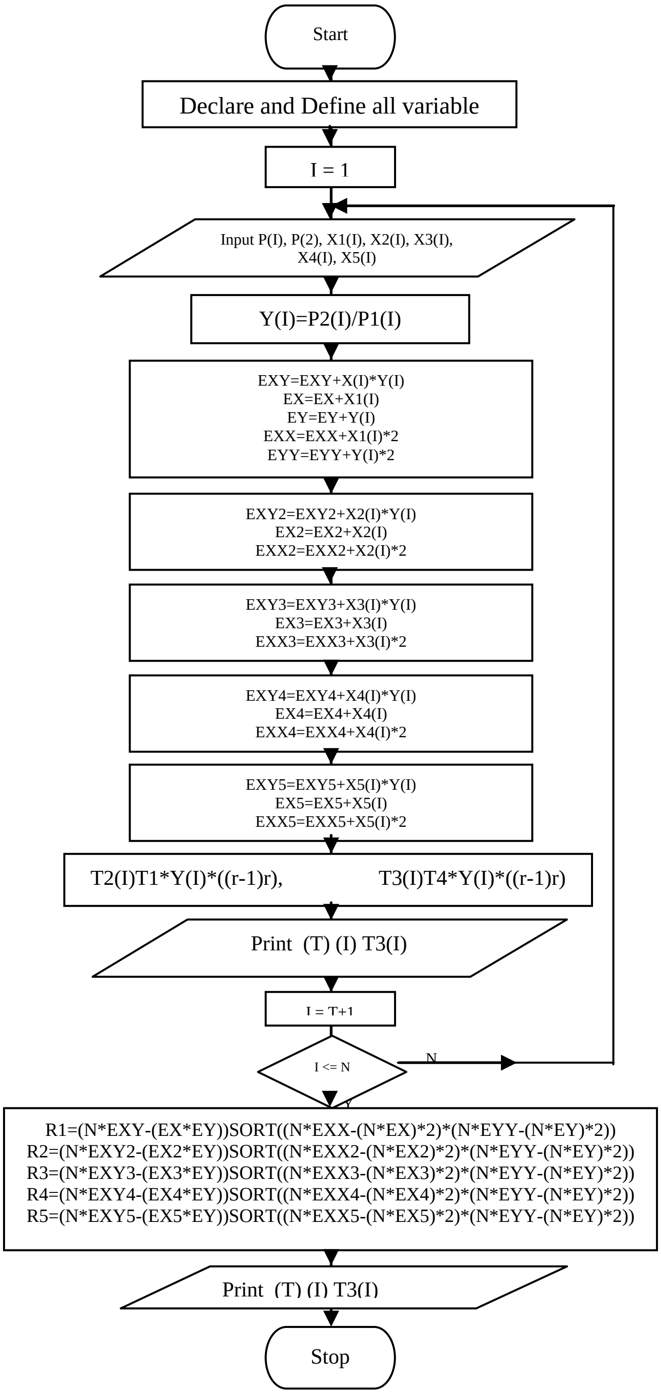

Fig. 4: Program Flow chart for correlation coefficient of the experimental data from GT 18 unit of the Delta IV Power Station

Correlation coefficient (r) for

Bearing 2 $= 2.1142e-007$

$Z_{C2} = 0.006$

Decision: $Z_{C2} < 1.96$ Accept H_0

Correlation coefficient (r) for

Bearing 4 $= 2.66108e-005$

$Z_{C4} = 0.054$

Decision: $Z_{C4} < 1.96$ Accept H_0

Correlation coefficient (r) for

Bearing 5 $= -1.53368e-005$

$Z_{C5} = -0.031$

Decision: $Z_{C5} < -1.96$ Accept H_0

Theoretically;

$$r_p = \frac{p_2}{p_1} = \frac{p_3}{p_4}$$

But practically;

$$r_{p_c} = \left(\frac{T_2}{T_1}\right)^{\frac{r}{r-1}} \qquad r_{p_c} = \left(\frac{60.8367}{30}\right)^{\frac{1.4}{1.4-1}}$$

$$r_{p_c} = (2.0279)^{3.5} \qquad r_{p_c} = 11.88$$

$$r_{p_t} = \left(\frac{T_3}{T_4}\right)^{\frac{r}{r-1}} \qquad r_{p_t} = \left(\frac{1020.92}{537}\right)^{\frac{1.4}{1.4-1}}$$

$$\mathbf{r_{p_t} = (1.9012)^{3.5} = 9.47}$$

i.e. $r_{p_c} \neq r_{p_t}$ (practically)

From the output of the sub-routine program, it is observed that the pressure ratio of the compressor is not equal to the pressure ratio of the turbine and this can be accounted for by the decrease in boost pressure.From the graph, it is observed that an increase in pressure ratio results to a corresponding increase in vibration velocity amplitude to some extent. But maximum vibration occurs at a pressure ratio of about 9.5 with a corresponding vibration velocity amplitude of about 4.1mm/s which is not advisable to run an engine at such readings so as to avoid eccentricity and imbalance of the engine.

However, it is observed from both graphs that the pressure ratio increases with a corresponding increase in vibration velocity amplitude to some extent. But the maximum vibration for fig. 4.3 occurs at a pressure ratio of about 9.5 with corresponding vibration velocity amplitude of about 1.2mm/s and for fig. 4.4, it takes place at the same pressure ratio with maximum vibration of about 0.28mm/s which is not detrimental to engine operating condition.

Table 1. Readings taken from GT 18 Unit of Delta IV Power Station

May time	Load (MW)	Brg 1 (mm/s)	Brg 2 (mm/s)	Brg 4 (mm/s)	Brg 5 (mm/s)	Speed (rpm)	Cpd Pressure	Pressure Ratio
1:00	50	3.2	1.6	0.5	0.1	3090	8.3	8.04
2:00	51	3.3	1.65	0.58	0.12	3060	8.7	8.43
3:00	52	3.4	1.7	0.66	0.14	3030	9.1	8.81
4:00	53	3.5	1.75	0.74	0.16	3000	9.5	9.2
5:00	54	3.6	1.8	0.82	0.18	2970	9.1	8.81
6:00	55	3.7	1.85	0.9	0.2	2940	8.7	8.43
7:00	56	3.8	1.9	0.98	0.22	2910	8.3	8.04
8:00	57	3.9	1.95	1.06	0.24	2880	8.8	8.53
9:00	58	4	2	1.14	0.26	2850	9.3	9.01
10:00	59	4.1	2.05	1.22	0.28	2820	9.8	9.5
11:00	60	4.2	2.1	1.3	0.3	2790	9.4	9.1

12:00	61	4.3	2.15	1.38	0.32	2760	9	8.72

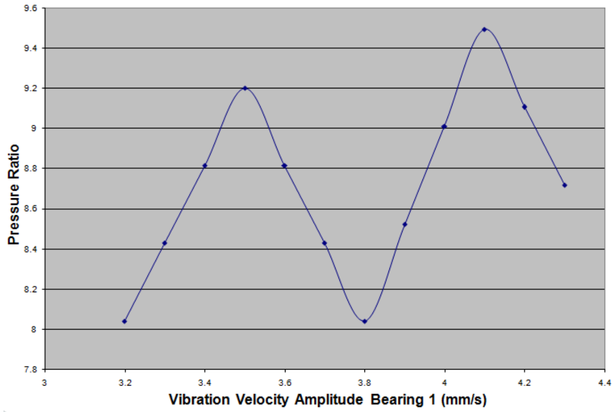

Figure 5. Pressure ratio against vibration velocity amplitude of Bearing 1.

From the graph, it is also observed that increase in pressure ratio results to a corresponding increase in vibration velocity amplitude to some extent. But maximum vibration takes places at a pressure ratio of about 9.5 with a corresponding vibration velocity amplitude of about 2.05mm/s which is not advisable to run an engine for a long time so as not to result in bearing 2 damage.

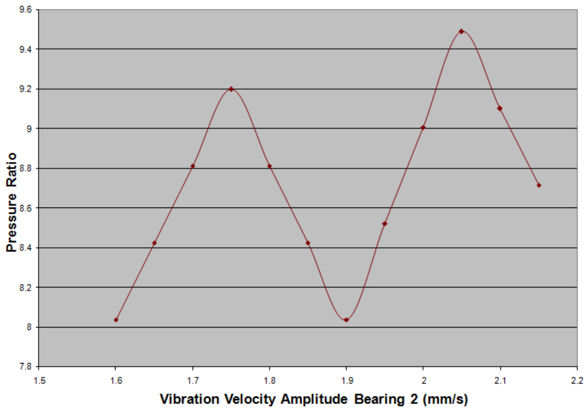

Figure.6. Pressure ratio against vibration velocity amplitude of Bearing 2

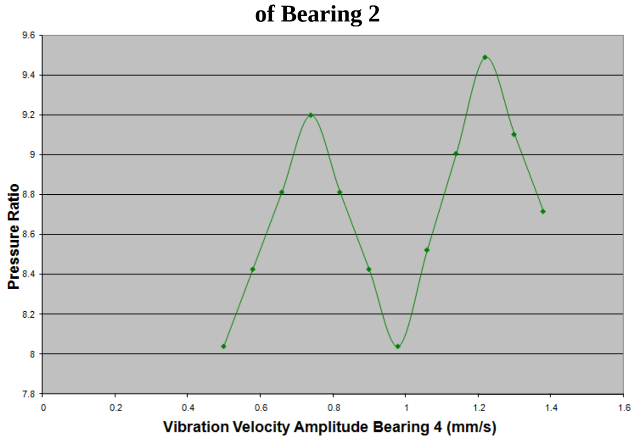

Figure 7. Pressure ratio against vibration velocity amplitude of Bearing 4

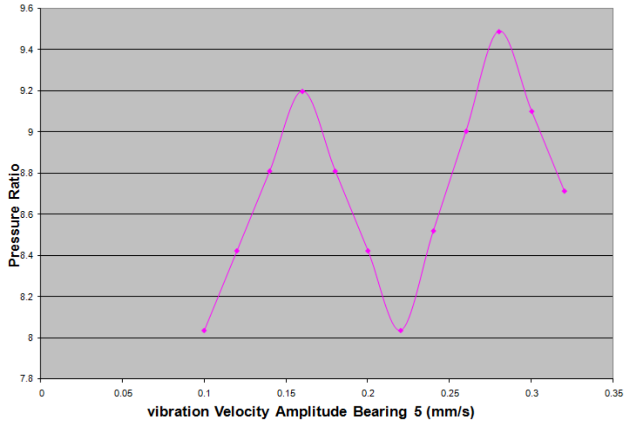

Figure 8. Pressure ratio against vibration velocity amplitude of Bearing 5

From the graphs in figs. 10-13, it is observed that there is a linear relationship between the load and the vibration velocity amplitude such that the load is directly proportional to the vibration velocity amplitude of the bearings.

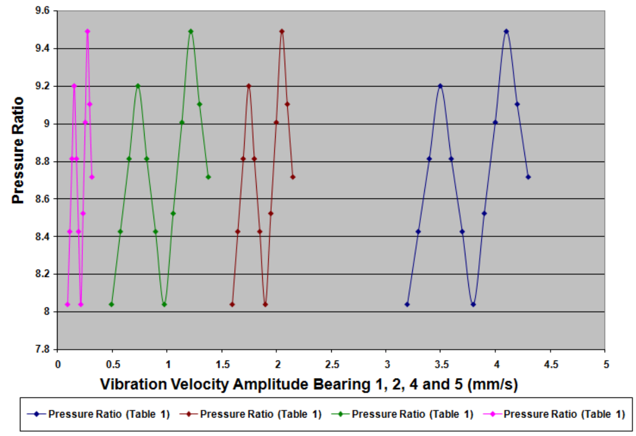

Figure 9. Pressure ratio versus vibration velocity amplitude of Bearing 1, 2, 4, & 5

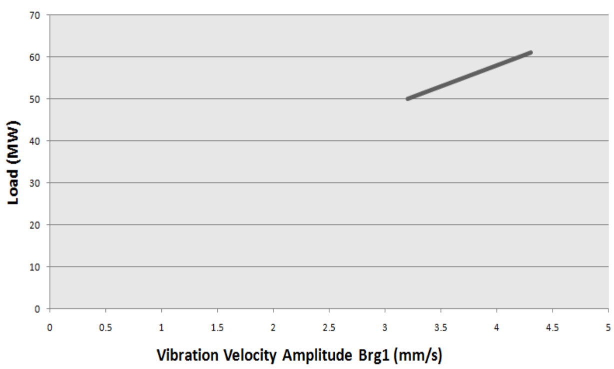

Figure 10. Load against vibration velocity amplitude of Bearing 1

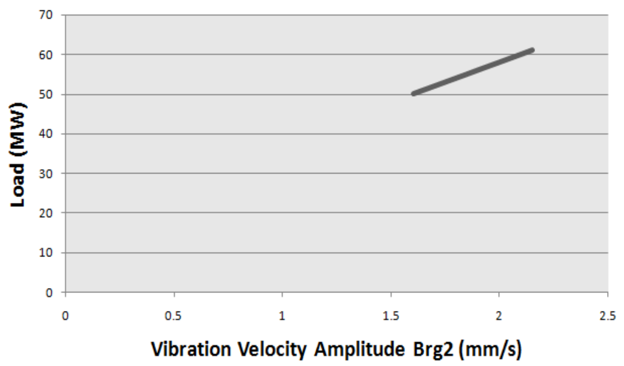

Figure 11. Load against vibration velocity amplitude of Bearing 2

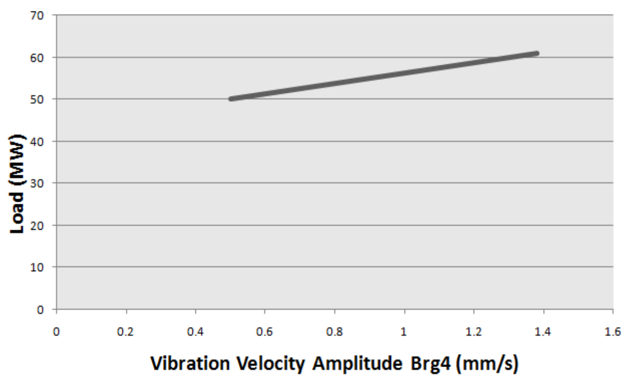

Figure 12. Load against vibration velocity amplitude of Bearing 4

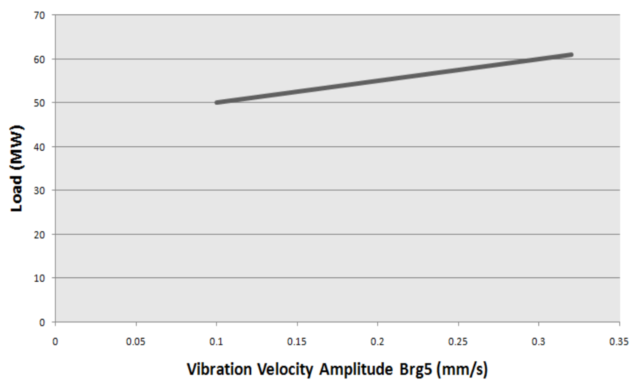

Figure 13. Load against vibration velocity amplitude of Bearing 5

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

A research work has been carried out on correlation between boost pressure and vibration amplitude of a marine GT. It is observed that the pressure ratio is a function of compressor discharge pressure and turbine inlet pressure. This is to complement the constant pressure process for which the design operation is based.

A step-by-step analysis of the plant parameters obtained is used to run a computer simulation in VC++ programming language to determine the statistical correlation coefficient of the plant parameters as shown and the turbine side bearing of the gas turbine plant carried much load, thus has high vibration amplitude. Results obtained show that appropriately matching boost pressure and vibration amplitude in GTs would lead to more trouble-free operation of the plant.

4.2 Recommendations

At the end of this research, the following are recommended:

- The plant should be incorporated with a mass flow rate monitoring device.
- A theory to suggest weather the relationship between two variables would either positive or negative should be developed.

ACKNOWLEDGMENTS

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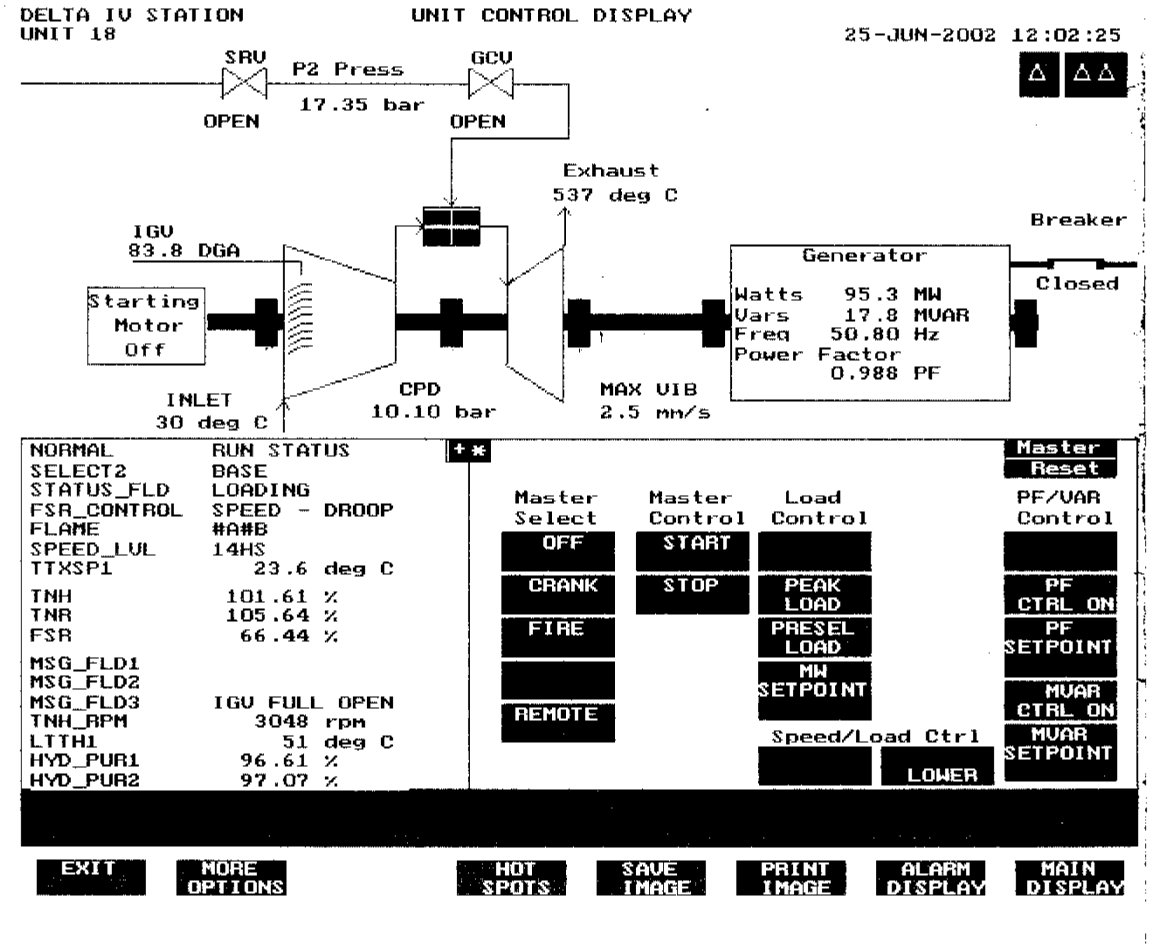
Appendix A

The Plant Diagram of GT18 Unit of Delta IV Power Station (Ughelli PHCN)



Some Characteristics of Ughelli Gas Turbine GT18 Unit:

1.	Name of Engine:	Gas Turbine
2.	Name of Manufacturer:	General Electric
3.	Type of Engine:	G. E. Frame 9
4.	Year of Manufacture:	1990

5.	Direction of Rotation:	Counter Clockwise (from generator end)
6.	Types of Bearing:	Journal Thrust Bearing
7.	Number of Turbine Blades:	92/stage
8.	Number of Turbine Stages:	3
9.	Compressor Inlet Temperature and Pressure:	
	(a) Temperature:	32^0C
	(b) Inlet or Atmospheric Pressure	760mmHg or $1.01325 \times 10^5 N/m^2$
10.	Mass of Rotor Shaft:	2852.9kg
11.	Stiffness Constant of Shaft:	20
12.	Critical Damping Coefficient:	3502Ns/m
13.	Area of Shaft:	$36.08m^2$

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