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A Microprocessor-Based System for Monitoring Gas Turbines

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ABSTRACT

The development and testing of hardware and software for a microprocessor-based monitoring system for gas turbines is described in this paper. The operators of gas turbines can be trained to monitor running hours, slip between high and low pressure compressor spools and torque on the reduction gear-box under various conditions of operation. The system will replace the traditional method of monitoring these parameters which are more time consuming and error prone.

1. INTRODUCTION

The parameters monitored by a comprehensive microprocessor-based monitoring system are (a) running hours of the gas turbine logged under various power regimes; (b) slip between hpc and lpc spools and warning the operator in case it exceeds 200 revolutions per minute (rpm); and (c) torque on the reduction gear-box and warning the operator if it exceeds safe limits.

Very little work has been done in the area of digital control and monitoring of gas turbines in India so far. However, some work has been done elsewhere[1-5] in this area in shore-based installations. The development of such a system is discussed in this paper.

2. ENGINE HEALTH MONITORING

The training of the operator on this system enables him to take some corrective action before some abnormal condition escalates to the point of causing a trip or damage. The parameters whose abnormalities should cause a trip are usually monitored with a visual or audible alarm to alert the operator. The alarm values are set somewhat below the trip values. Engine monitoring is usually combined with monitoring of the

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propulsion plant. Propeller pitch, turbine speed, status of clutches, shaft brakes are parameters to be monitored and displayed. Parameters not directly connected with control of either engine or plant may also be monitored, for example, the pressure of reduction gear lubricating oil. Moreover, such a parameter may cause a trip via a stop order generated by the monitoring system.

The overall requirement for evaluating a health monitoring system in a warship exists at two levels.

2.1 Immediate Requirements

The immediate requirements of the ship which affect the day-to-day running of the engine and give the engineer officer of the ship confidence that

i) The full range of power of the engine can be achieved;
ii) The strength or material limits are not exceeded;
iii) Sufficient warning of a failure will be given to avoid a catastrophic failures;
iv) Deterioration and failure can be identified;
v) Maintenance schedules are realistic and effective; and
vi) The most important – ship's endurance is sufficient for the mission.

2.2 Long Term Requirements

The long term requirements which aid higher technical/administrative authorities to :

i) Extend the life of the engine and establish realistic time between overhauls;
ii) Make estimation of system reliability;
iii) Improve diagnostic capabilities; and
iv) Identify areas of possible design improvements.

Engine health monitoring (EHM) helps a great deal to satisfy these requirements. An EHM system will thus consider all or some of the parameters such as mechanical condition and behaviour; performance and gas path analysis; and oil and fuel systems.

When an engine is first installed the above aspects will be observed by means of pressure, temperature, speed, flow, vibration sensors and scavenge oil chip detectors. Throughout the engine's life these parameters are re-observed and compared with the initial values.

3. IMPORTANCE OF VARIOUS EHM TECHNIQUES

A chart showing relative importance and usefulness of various EHM techniques is shown in Fig. 1. It can be seen that the necessity of an integrated health monitoring system involving every aspect of the various techniques available is essential for having a good EHM system.

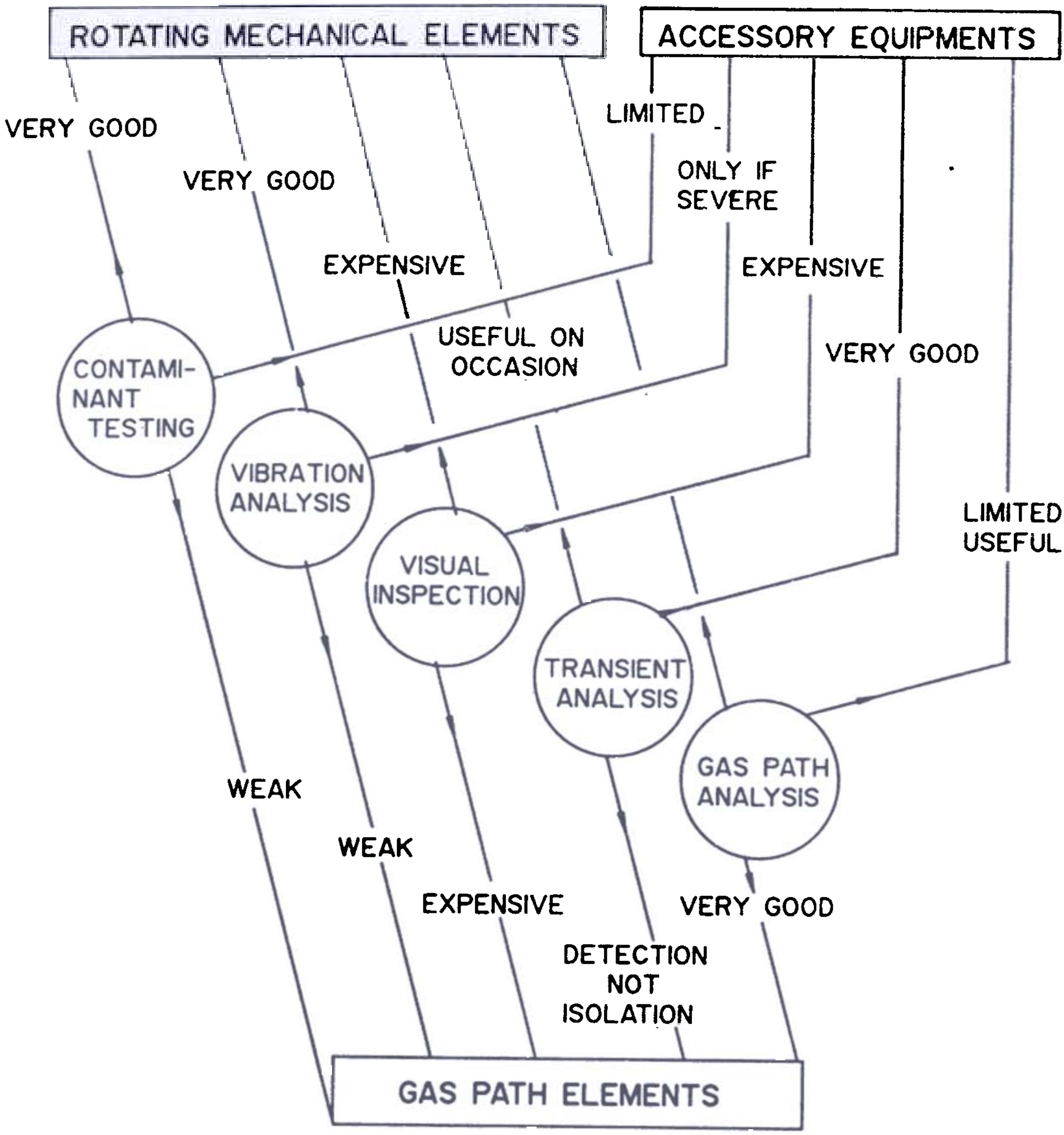

Figure 1. Relative importance of various EHM techniques.

3.1 Microprocessors in Control and Monitoring Systems

Microprocessors are already used in many industrial applications as their low cost, increased flexibility and reliability are obvious advantages.

On board ships, microprocessors make distributed control and monitoring systems a viable possibility by allowing power to be dispersed to on plant controllers. In addition communication between various microprocessor-based controllers can utilise serial data links. This results in a considerable reduction in the wiring required.

3.2 Automated Engine Monitoring Systems

Automated monitoring has not been widely accepted by the industry. The task of designing an automated monitoring system is primarily one of incorporating software and the collected wisdom of specialists in each major monitoring discipline.

In view of the very high cost of software development and questionable success of some EHM techniques, it would seem sensible for each operator to select, through field evaluation, those which are useful to his application and automate only for those which are both technically and economically feasible.

3.3 The Hardware

The 8085 microprocessor has been used for developing the monitoring system. This is an 8-bit microprocessor presently connected to a 3.57 MHz crystal. The mP-5 kit has been used to develop the target system. The functional block diagram alongwith various components is shown in Fig. 2. The RST 7.5 interrupt is connected to the 'timer-out' of 8155 which is a programmable input/output (I/O) port with 256 bytes. This is used as a scratch pad random access memory (RAM) by the software.

The 8279 programmable keyboard/display interface through an 8-digit, 7-segment display and a 22-key keyboard alongwith shift and control keys is the means of communication with the external world from the microprocessor.

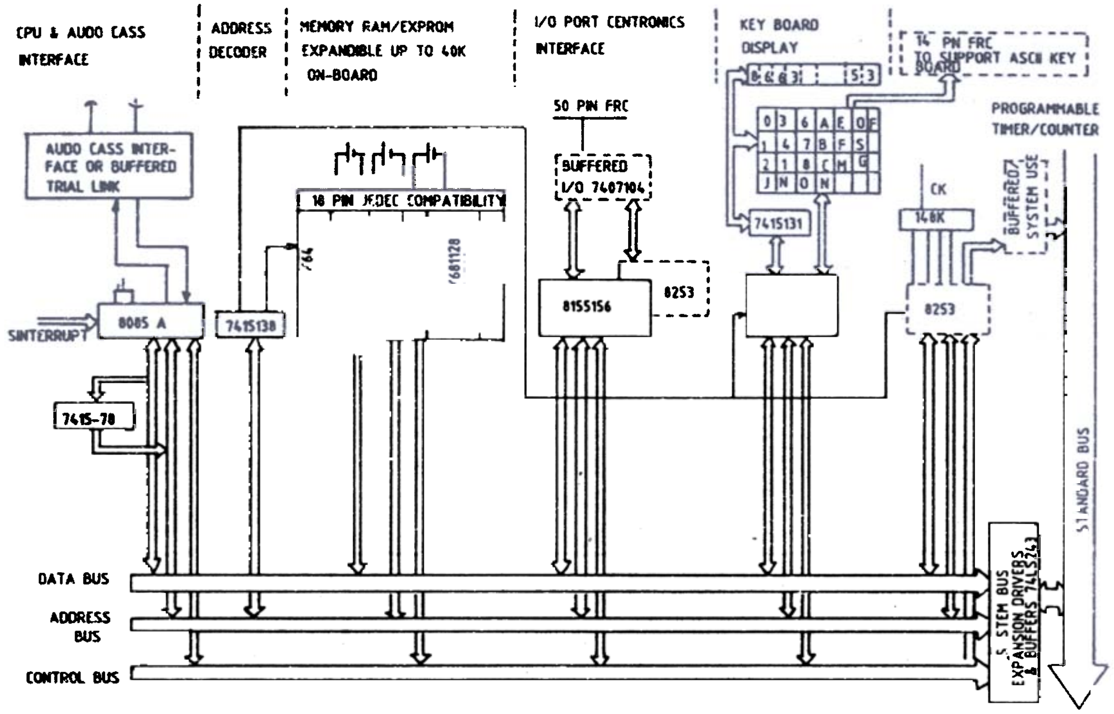

Figure 2. Functional block diagram of a monitoring system.

The 7109 ADC is a 12-bit analog-to-digital convertor with sign and overrange information is interfaced to the central processing unit via an analog multiplexer, instrumentation operational amplifier configuration and sample and hold amplifier. The 7109 employs the dual slope integrating principle to convert the analog data to digital form. This has an inherent advantage of filtering out noise from line frequency.

3.4 Generation of Real-Time Clock

The system clock is of 3.57 MHz. This is further divided by 16 and given to the 'timer-in' of the 8155. The 8155 timer is programmed to generate a 'timer-out' pulse after every 147 milli seconds. This is connected to RST 7.5. Every timer-out pulse thus vectors the microprocessor to a scratch pad RAM address by the program. It is then made to jump to the instrument landing system whose address is placed here for logging running hours according to the nominal power and the gas turbine in use.

3.5 Testing the System

The entire software has been tested by simulating the various voltages required by the use of multiturn helical potentiometers. This ensures testing the hardware/software under the worst possible conditions. A speaker is driven from PCo pin of 8155 I/O port to sound an audible alarm to the operator and bring his attention to the message being displayed, so that necessary corrective action can be taken by the operator.

3.6 Monitoring Running Hours

Gas turbines are designed to operate for fixed number of cycles and then carry out routine maintenance to bring the gas turbine back to the starting or new condition. This gives rise to the requirement of fixing the running hours at various speeds.

For the gas turbine under consideration, the running hours available under various power regimes are:

Below 0.7 nominal power	15,000 h
Between 0.7 and 0.8 nominal power	900 h
Above 0.8 nominal power	300 h

The power output of the gas turbine largely depends on ambient conditions of temperature and pressure. A graph (Fig. 3) is available on board the ship. This is for ambient temperature ($T(a)$) versus high pressure compressor speed (N(hpc)) from where the operator can find out the nominal power range in which the gas turbine is operating. Running hours are thus logged in the various power regimes.

At any given time the operator has to keep track of about 40 parameters when the ship is at sea. This does not allow the operator to effectively use this graph and

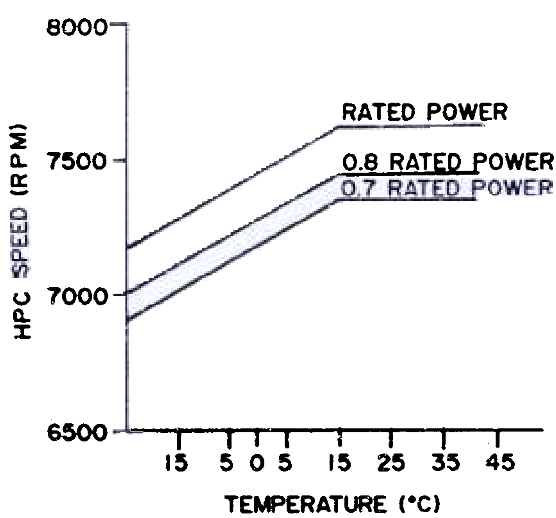

Figure 3. Relationship of speed of HPC and outside air temperature (for recording service life).

log running hours in the appropriate power range. This is a very serious disadvantage. The running hours may be logged under the 0.7 nominal power range inadvertently by the operator when the gas turbine is operating in the 0.8 nominal power range. It can be seen that the running hours allowed in the 0.8 nominal range are only 900 h whereas in the 0.7 nominal range it is 15,000 h. This may lead to inadvertent catastrophic failures. The failure will be due to incorrect logging of running hours in the lower power regimes.

The task of logging running hours in various power regimes is being done by the microprocessor by input of ambient temperature *T*(*a*) and *N*(hpc) and calculating the nominal power by the help of Fig. 3.

3.7 Measurement and Display of Slip

Air above the sea surface contains significant concentration of the salts of the sea. This may be in the form of gross drops of spray or in small droplets forming an aerosol. Figure 4 gives an idea of the concentration of aerosols to be expected. The most direct manifestation of the salt reaching an engine is loss of performance due to the salt coating compressor blades. The coating distorts the blade profile and narrows flow passages. The degradation is largely reversible by means of water washing of the compressor. This process is used with the present gas turbine.

Figure 5 shows a case of drastic performance loss followed by recovery after steam washing.

It is therefore essential that the gas generator compressors are kept as clean as possible from the build up of salt deposits. This helps to maintain performance and to minimise compressor and hot end corrosion. This is achieved by compressor blade cleaning at regular intervals. The procedure being followed to find degradation of performance of compressor on board the ship is explained below :

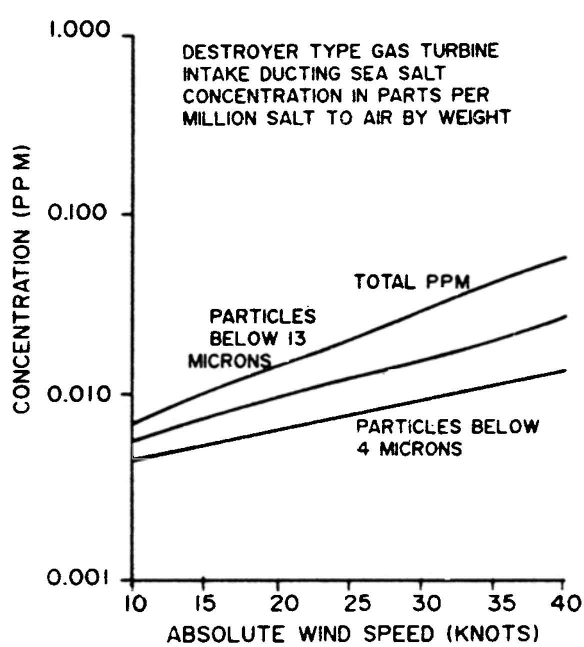

Figure 4. Sea-salt aerosol concentrations.

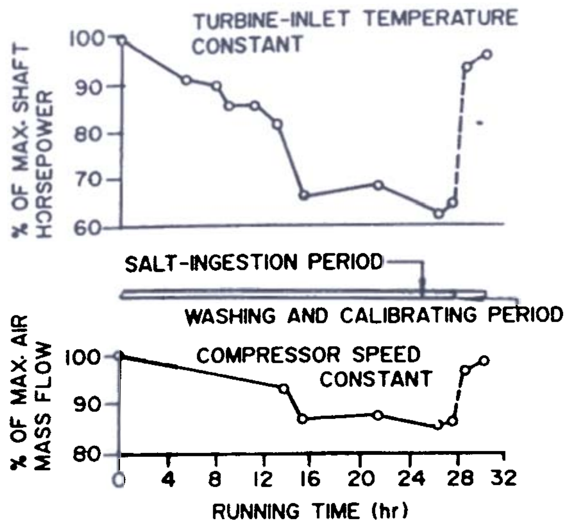

Figure 5. Performance degradation caused by salt ingestion

Figure 6 shows relationship between low pressure compressor speed (N(lpc)) and N(hpc) at various temperatures. With the knowledge of $T(a)$ and N(hpc), the operator is able to find the theoretical N(lpc). Having read the actual N(lpc) from the meters, the difference between the theoretical and actual N(lpc) is found out. If this exceeds 200 rpm, a slip condition exists. It implies that the compressor performance has gone below acceptable limits and immediate remedial action has to be taken to save the system from further damage.

The present system uses the microprocessor to do the calculations to find slip by using Fig. 6. In case of slip condition exists, a warning is issued to the operator and a message flashed so that necessary corrective action can be initiated.

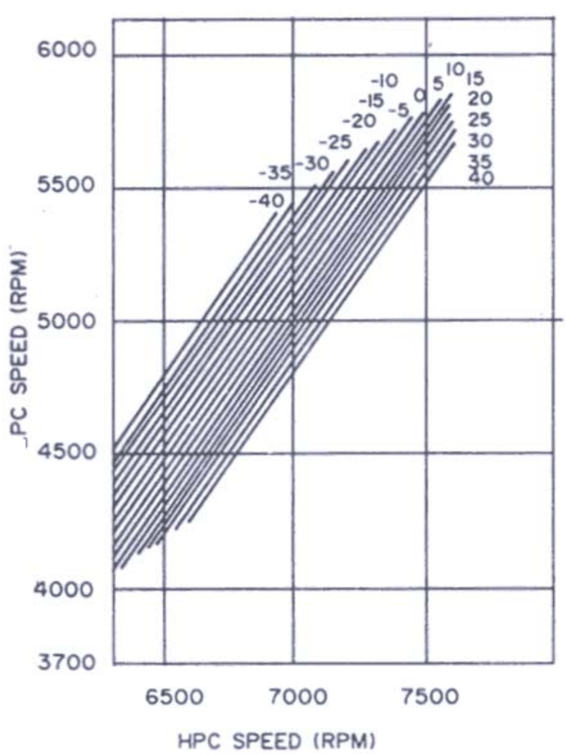

Figure 6. Relationship of speed of LPC and speed of HPC at different temperatures of outside air

4. MEASUREMENT AND DISPLAY OF SHAFT TORQUE CONDITIONS

Marine propulsion is affected by a device that converts the thermal energy obtained from consumption of a fuel (for example, in a gas turbine into a thrust). This conventionally requires the coordinated working of three distinct units.

i) *The engine,* which converts the thermal energy into mechanical energy. The mechanical energy is characterised by torque and rotational speed of an output shaft (in essence *fuel in, torque out*).

ii) *The transmission,* which transmits the mechanical energy to its point of use. This includes a speed reducing gear set and may include clutches, brakes and couplings of various types (in essence *torque in, torque out*).

iii) *The Propulsor,* which converts mechanical energy into the hydraulic energy of an accelerating fluid or the thrust horse power (in essence *torque in, thrust out*). This propulsor in our case is a screw propeller.

Once these units are matched, the engine and propeller should combine to produce an optimal fuel-to-thrust conversion under design operating conditions, while ensuring all operating conditions are acceptable to each other. Conservation of energy demands that the power produced by the engine (minus any loss in transmission) equal that absorbed by the propeller. Engine torque, multiplied by the reduction gear ratio, likewise must equal propeller torque and must do so at the common rpm.

This can be done for the design conditions. A gross change in resistance occurs if a tow is taken on. Hence the engine can be overloaded when towing, with consequent shortening of its time between overhauls. If hull resistance increases due to any cause, such as roughening of the surfaces by corrosion, a given power will require a higher propeller speed, i.e., the engine power would have to be increased. Under some conditions this may also lead to overloading of the engine if proper care is not taken.

It is known that gas turbines are very much susceptible to changes in power with changes in ambient conditions. Hence at the same *N*(hpc) there is a wide variation of power at different ambient conditions.

Figure 7 is a plot of *N*(hpc) versus *T(a)* to calculate the power produced by the gas turbine. Figure 8 is a plot of power developed versus shaft speed (*N*(s)) for safe/ unsafe loading. The operator of the gas turbine under consideration has to refer to both these graphs to check whether the reduction gear-box is safely loaded or not. The reading of these graphs for all gas turbines and checking safe loading apart from the routine work of monitoring the other parameters is not physically possible for the operator. This leaves a loop hole in the system where there is a chance of the failure of the system with time.

The task of monitoring the reduction gear-box torque is now to be done with the help of the microprocessor.

5. MAIN FEATURES OF THE SYSTEM

The entire software (about 12 k bytes) to monitor the parameters mentioned earlier has been written in Assembly language for the 8085 microprocessor. The software has been burnt in an EPROM (erasable programmable read-only memory)

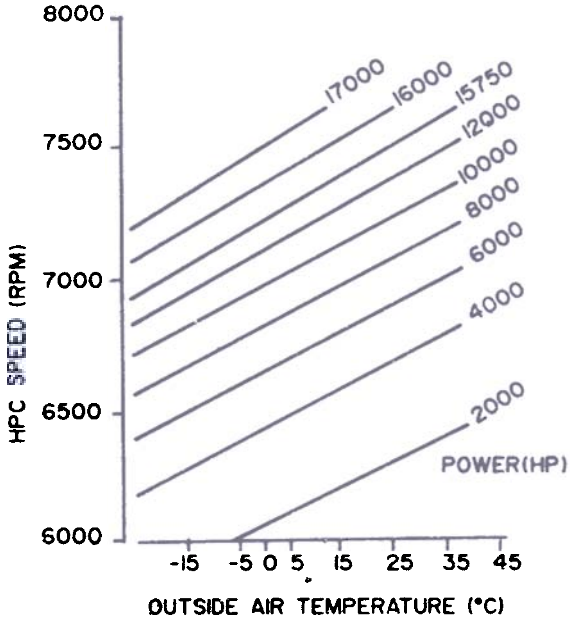

Figure 7. Relationship of speed of HP compressor and outside air temperature (for determination of power).

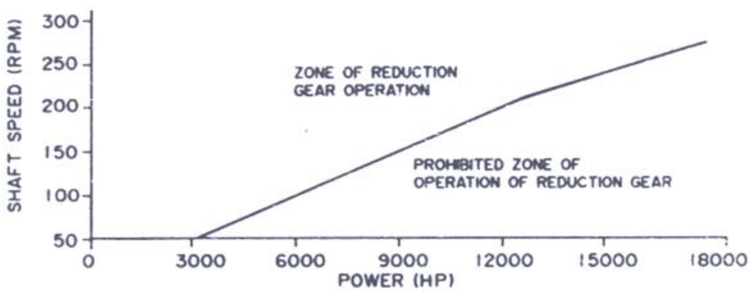

Figure 8. Chart for determination of reduction gear mode of operation.

and tested extensively under simulated conditions and proved satisfactory. The main features of the system developed are as follows :

i) It has built-in software to test fault conditions of input data and calculations performed.

ii) The system gives an option to the operator for running both or single gas turbine program.

iii) In case both gas turbines program is in operation, it gives option to the operator to stop this program and execute any of the individual gas turbines program.

iv) The system gives option to the operator to find out running hours consumed in the various nominal power ranges for both gas turbines.

v) It gives warning to the operator once allowable running hours exceed.

vi) It gives various other prompts/warnings depending on the fault conditions encountered during the execution of the program. The details are listed in Appendix A.

vii) When the gas turbines and their systems are operating satisfactorily, the operator need not bother about the system, except when desired.

It offloads the operator from monitoring the three parameters. This leaves more time for the operator to do other tasks of watchkeeping where his attention is essential.

ix) It will safeguard the gas turbines from maloperation. Hence allows the engineer officer of the ship to take action of steam washing/cleaning the compressor at an appropriate time.

x) The possibility of the reduction gear-box operating at higher torque levels will be avoided.

xi) The system is designed to operate independently. It will not interfere in any way with the operation of the existing monitoring and control system. It will be only an addition to the existing system as the present system does not cater for the monitoring of these parameters.

The system is very simple to operate and operators with very little knowledge about microprocessors and their peripherals can operate it with ease. The only training required to be given to the operator will be to switch on power supply and execute the program of a specified address.

xiii) In case both gas turbines are in operation and one has to be stopped, an option is available to the operator to run the respective gas turbine program. This will help in logging running hours correctly.

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APPENDIX 'A'

SYSTEM ERROR MESSAGES AND PROMPTS

INPUT VOLTAGE NEGATIVE PRESS Y TO CONTINUE E TO TRY AGAIN.

2. INPUT VOLTAGE OVERRANGE MAY DAMAGE ADC. PRESS Y TO CONTINUE E TO TRY AGAIN.
3. INPUT VOLTAGE NEGATIVE OVERRANGE MAY DAMAGE ADC PRESS Y TO CONTINUE E TO TRY AGAIN.
4. HOURS CONSUMED IN 0.7 NOMINAL POWER---HOURS AND---MINUTES ON DE 3109
5. HOURS CONSUMED IN 0.7 NOMINAL POWER---HOURS AND---MINUTES ON DE 3111
6. HOURS CONSUMED IN 0.8 NOMINAL POWER---HOURS AND---MINUTES ON DE 3109
7. HOURS CONSUMED IN 0.8 NOMINAL POWER---HOURS AND---MINUTES ON DE 3111
8. HOURS CONSUMED IN 1.0 NOMINAL POWER---HOURS AND---MINUTES ON DE 3109
9. HOURS CONSUMED IN 1.0 NOMINAL POWER---HOURS AND---MINUTES ON DE 3111
10. RUNNING HOURS ON GAS TURBINE DE 3109 OVER IN 0.7 N RANGE.
11. RUNNING HOURS ON GAS TURBINE DE 3111 OVER IN 0.7 N RANGE.
12. RUNNING HOURS ON GAS TURBINE DE 3109 OVER IN 0.8 N RANGE.
13. RUNNING HOURS ON GAS TURBINE DE 3111 OVER IN 0.8 N RANGE.
14. RUNNING HOURS ON GAS TURBINE DE 3109 OVER IN 1.0 N RANGE.
15. RUNNING HOURS ON GAS TURBINE DE 3111 OVER IN 1.0 N RANGE.
16. SLIP ON GAS TURBINE DE 3109 PRESS Y TO CONTINUE E TO TRY AGAIN.
17. SLIP ON GAS TURBINE DE 3111 PRESS Y TO CONTINUE E TO TRY AGAIN.
18. AM GETTING NEGATIVE SLIP ON DE 3109. NOT POSSIBLE. PRESS Y TO CONTINUE E TO TRY AGAIN.
19. AM GETTING NEGATIVE SLIP ON DE 3111. NOT POSSIBLE. PRESS Y TO CONTINUE E TO TRY AGAIN.
20. TORQUE ON REDUCTION GEAR-BOX EXCEEDED. TAKE NECESSARY ACTION. PRESS Y TO CONTINUE E TO TRY AGAIN.
21. IS POWER REALLY ABOVE 18000 ? PRESS Y TO CONTINUE E TO TRY AGAIN.
22. HOURS ?
23. PRESS A FOR DE 3109 B FOR DE 3111 AND 2 FOR BOTH GAS TURBINES.