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Software for Fuel Schedule Selection and Transient Behaviour of Marine Gas Turbine

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ABSTRACT

A software package has been developed to predict the transient behaviour of marine gas turbines accurately and methodically to provide suitable data for design of fuel controller. Limits of fuel scheduling were established initially. This was done with the help of an independent module made to provide a graphical tool for fuel path selection which is an iterative process and has direct effect on dynamic behaviour of the plant. After independent trials a set of four fuel paths were selected. Transient behaviour of the gas turbine was studied based on these four fuel paths.

It is found that this package provides accurate and adequate information for design of analog or linear fuel controller. It is also noted that if an error of about 10 per cent is tolerated, then data obtained from this package is equally suitable for digital fuel controller design.

NOMENCLATURE

ω	angular speed of the gas generator shaft
η_m	mechanical efficiency
C_{pa}	specific heat at constant pressure for air
C_{pg}	specific heat at constant pressure for gas

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H_1	enthalpy at compressor inlet
H_2	enthalpy at compressor outlet
H_3	enthalpy at gas generator turbine inlet
H_4	enthalpy at gas generator turbine outlet
I_{gg}	polar moment of inertia of gas generator shaft
m_1	mass flow of air through the compressor
m_3	mass flow of gas through gas generator turbine
N_{gg}	gas generator speed (rpm)
N_{pt}	power turbine speed (rpm)
Q_{net}	gas generator net torque
Q_{pt}	power turbine net torque
T_{01}	stagnation temperature at compressor inlet
T_{02}	stagnation temperature at compressor outlet
T_{03}	stagnation temperature at gas generator turbine inlet
T_{04}	stagnation temperature at gas generator turbine outlet
W_c	gas generator compressor power
W_{net}	gas generator net power
W_{pt}	power turbine net power
W_t	gas generator turbine power

1. INTRODUCTION

With increasing costs and the complexity of the propulsion plant of the ship, detailed knowledge of transient behaviour of components of the plant at early stages of design has become essential. In the case of gas turbines, a popular prime mover for naval ships, the transients of the engine is directly affected by the design of fuel controller.

Reduction in cost and improvements in the design of microprocessors have made the control systems an integral part of any modern engineering plant design. This would facilitate application of simulation techniques as a powerful tool for prediction of system or component behaviour. This paper describes the generation of software to simulate transient behaviour of a single spool marine gas turbine, with the objectives of (i) accurate and methodical prediction of transient behaviour, and (ii) providing suitable data for design of fuel controller. The work started following a detailed survey[1,2] of the available literature and existing work on steady state behaviour of a gas turbine engine.

2. MATHEMATICAL REPRESENTATION

A single spool free power turbine (Fig.1) was selected as the model for study. Compressor and gas generator characteristics were represented in the familiar form of non-dimensional values of mass flow, pressure and temperature ratio versus non-dimensional speed of gas generator.

Combustion chamber characteristics were simulated using empirical relationships given in the tables of gas thermodynamic properties. It was assumed that combustion chamber efficiency is 100 per cent and that there is no combustion lag. These assumptions would be quite justifiable for marine applications. However, the modular nature of the package makes any further improvement in combustion chamber to be easily implemented without major changes in the structure of the package.

Free power turbine characteristics were generated using established nozzle relations because the data available for compressor and gas generator turbine were that of an aeroengine. It is well established that nozzle and free power turbines exert the same kind of restrictions on operating zone when operated in series with a gas generator for stationary plants. Hence using the above obtained map for free power turbine does not introduce any error in the study of steady state or transient behaviour of marine gas turbine which is as good as a stationary plant[3] (Fig. 2).

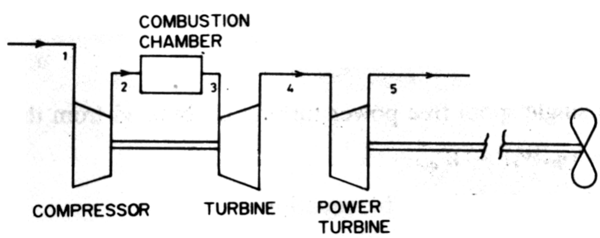


Figure 1. Single spool marine gas turbine.

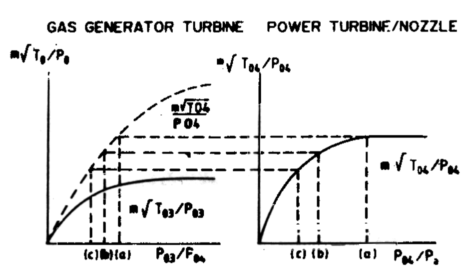


Figure 2. Operation of turbines in series.

2.1 Steady State

It is assumed that the engine satisfies the compatibility of flow both in steady state and transient operation. In steady state, the net power developed by the turbine equals that used by the compressor plus the mechanical losses. In other words, in steady state equilibrium operation the plant satisfies the compatibility of work as well as flow. Steady state running line values have been taken from an earlier study on the experimental engine. In this work the equilibrium running line was found assuming constant values for air and gas properties. Taking the values of temperature at the equilibrium points, the final equilibrium line was found for the calculations of temperature dependent properties of air and gas.

2.2 Transient Calculation

Assuming that the plant satisfies the compatibility of flow and not that of work during any acceleration or deceleration, it can be concluded that any net torque due to this imbalance of work is used to accelerate or decelerate the gas generator. Hence using the laws of motion, one could get a measure of engine transients. It is to be noted that by transient it is meant that the manner in which the plant moves from one steady state point to the next, the time it makes for the move and whether or not the plant exceeds the limits imposed on the engine are areas of concern for designers and performance engineers.

2.2.1 Calculation of Net Torque

From Newton's second law of motion we have

$$Q_{net} = I_{gg}\, d\omega/dt \tag{1}$$

Net power for a single spool free power turbine is obtained from the equation,

$$W_{net} = (\eta_m W_t) - W_c \tag{2}$$

Net torque Q_{net} is obtained from the equation

$$W_{net} = Q_{net}\omega = 2\pi N_{gg} Q_{net} \tag{3}$$

or $$Q_{net} = W_{net}/(2\pi N_{gg}) \tag{4}$$

also $$d\omega/dt = 2\pi\, dN_{gg}/dt \tag{5}$$

Hence $$dN_{gg}/dt = W_{net}/(4\pi^2 I_{gg} N_{gg}) \tag{6}$$

Net power for gas generator can be calculated using the engine parameters

$$W_t = m_3 C_{pg}(T_{03} - T_{04}) = m_3(H_3 - H_4) \tag{7}$$

$$W_c = m_1 C_{pa}(T_{02} - T_{01}) = m_1(H_2 - H_1) \tag{8}$$

Survey of the available literature reveals that mainly three approaches have been employed by different researchers to get the transient behaviour of gas turbines, which is mainly the solution of Eqn. (6) using numerical techniques. One method suggests, acceleration to remain constant as the plant moves from one steady state point to the next for which data is available. Then having the acceleration, which is the rate of change of speed of the gas generator, the time taken for any two consecutive points can be calculated and the summation of these values would yield a value of transient time.

The other two methods are similar in nature but depending on the type of data available, each would take a different form. In the first, the Eqn. (6) can be changed to

$$(Q_{net}/I_{gg}N_{gg})\, dt = 4\pi^2\, dN_{gg}/N_{gg} \tag{9}$$

$$\ln N_{gg_2} - \ln N_{gg_1} = Q_{net}\, dt/(4\pi^2 I_{gg} N_{gg}) \tag{10}$$

Knowing the values of N_{gg2} and N_{gg1} and engine parameters during the transient, the above equations could be solved using numerical integration techniques.

The other method which was used in present work, rearranges Eqn. (6) in the form

$$dN_{gg} = [W_{net}/(4\pi^2 I_{gg} N_{gg})]\, dt \tag{11}$$

$$N_{gg_2} = N_{gg_1} + [W_{net}/(4\pi^2 I_{gg} N_{gg})]\, dt \tag{12}$$

Equation (12) can be solved assuming a short interval of time during which the properties of working gases remain unchanged, and gas generator speed after this time increment is N_{gg2}. Repeating this process and recording engine parameters against time till the final desired speed is reached, a tabular pattern for transient behaviour of the engine is obtained[4].

3. SOFTWARE DEVELOPMENT

During acceleration, the transient of gas turbine is generally limited by the proximity of acceleration trajectory to surge line in the lower speed range and thereafter it becomes limited by the maximum temperature which the turbine blades could stand for a short interval of time (Fig. 3). This indicates that on compressor map one has to establish the surge line values and locus of maximum turbine entry temperature. Major steps involved in for the prediction of gas turbine transients are listed below.

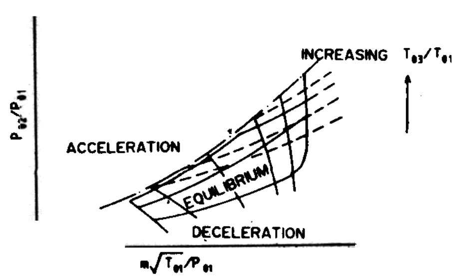


Figure 3. Transient trajectories in compressor characteristics.

(a) Establishing surge line parameters of plant using compatibility of flow;

(b) Establishing locus of maximum turbine entry temperature using compatibility of flow only;

(c) Deciding a safety margin and selecting a fueling path;

(d) Checking engine limits for the selected fuel path for acceleration; and

(e) Calculating transient pattern for the engine.

In addition, suitable plotting programs had to be made to facilitate graphical selection of acceleration fueling and plotting of final results. The above steps are briefly dealt in the following paragraphs.

3.1 Surge Line Values

In most of the gas turbines, acceleration is limited by surge line at the lower ranges of speed. Hence the first module was programmed for determination of surge line values assuming that (i) the plant has to satisfy compatibility of flow, (ii) multiple speed line performance characteristics for gas generator turbine, and (iii) there is no combustion time lag.

Steady state running line was used as the starting value for iteration and the window for turbine entry temperature (TET). Thus, set between steady state and maximum TET, the program had to carry out an internested iteration, that is for a guessed value of T_{03}/T_{01} corresponding to P_{03}/P_{01} had to be found and then P_{03}/P_{04} had to be checked against the guessed value.

The program made for this purpose uses only the component characteristics as input without using any results from previous programs. This independent module assumes single line characteristics for turbine, and the plant to satisfy compatibility of flow only. The surge line values using component maps were prepared systematically as look up tables. The range of values obtained from this program was 2500 > TET > 1650 K.

A detail investigation and manual computation was carried out at this stage. It was verified that the expected limit imposed on transient as being the surge line did not hold true for this particular gas turbine. Accordingly, the window for iteration in the previous two programs were altered to include high values up to 3500 K and the end results of all the three programs matched excellently, i.e., the values of TET for surge line from each program were obtained as follows :

3000 > TET > 1700 K

2500 > TET > 1600 K

2500 > TET > 1650 K

Based on the results obtained, it was concluded that surge line in the case of this plant does not impose any limitation on acceleration and the only limitation for acceleration would then be the locus of maximum TET over the whole operating range of the gas generator. Another valid observation was the fact that this engine with present physical configuration has a good potential for power improvement provided maximum TET could be improved.

3.2 Locus of Maximum Turbine Entry Temperature

If the engine was to operate along a given TET, a module was made to provide the engine parameters. To obtain the locus of maximum turbine entry temperature, a value of 1400 K was selected and the corresponding engine parameters were shown in tabular form. This module assumes single line map for the turbine, and uses steady state values as the starting point for iteration.

The engine parameters thus obtained would constitute the upper limit for acceleration and the lower limit was already available as steady state.

3.3 Choice of Fuel Path

The most important step in the design of fuel controller system is the choice of fuel path for acceleration. The main objèctive of this module is to provide a graphical mean for fuel path selection. And it must also be noted here that fuel path selection is an iterative process and the path selected must be checked against the engine limit.

Having established the upper and lower limits for acceleration on fuel flow versus compressor speed, one is provided with a working area within which any acceptable pàth must remain. Depending on the engine application, an appropriate choice of the fuel path is made. It is expected that

(a) Paths staying close to steady state would yield sluggish time response but at the same time never exceed the engine limits;

(b) Paths staying close to upper limit would give a much better time response, but of course may not leave any safety margin for engine limits; and

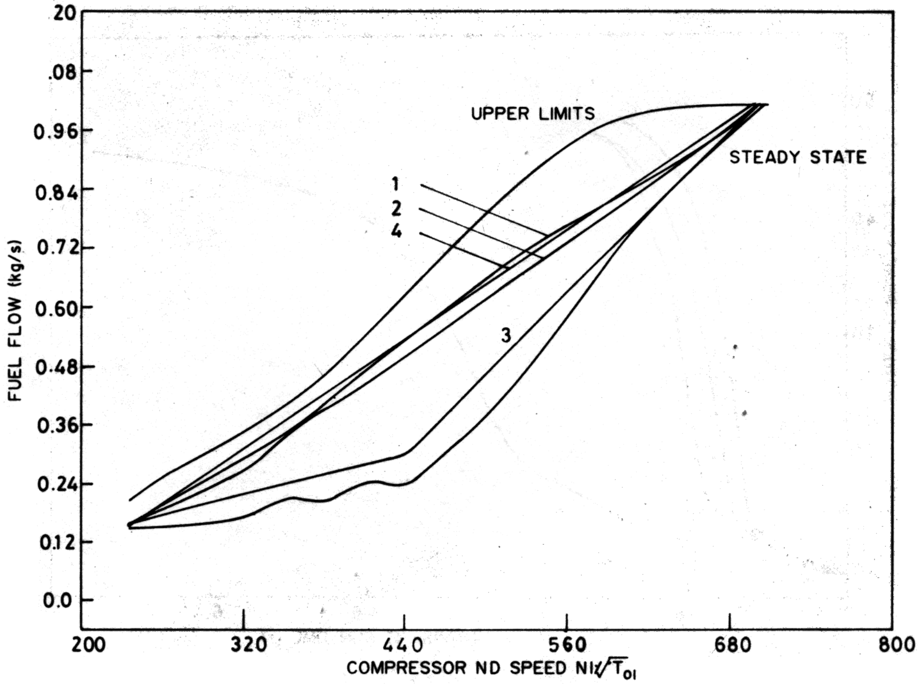


Figure 4. Fuel flow mapping and sample fuel schedules.

(c) Linear or multiple segment paths could be selected depending on whether conventional or digital fuel controllers are being employed.

Initially this step was carried out using manual plotting and hence 100 per cent optimisation was not obtained, but choices were made so as to have results which could indicate the effects of fuel path on various engine transient parameters. Later during the course of the project, work programs were made for plotting different results obtained from the modules discussed above. The final fuel paths selected for the study of transients are given in Fig. 4. This set of fuel paths was the result of 15 trials in which 60 different fuel paths were checked against the engine limit and after each trial the previous path was modified completely or partially using the feed-back from engine limit checks.

3.4 Engine Limit Check

This module calculates the engine parameters if the fueling was governed by the selected schedule. It assumes that instantaneous changes of properties for working gases to take place along constant non-dimensional speed, and the plant to satisfy compatibility of flow only.

The module provides the designer with four choices of fuel path, computes one at a time and outputs the engine parameters in the given files. After obtaining the results, the designer could check the engine limits and correct or verify one's choice of fuel path. In this study a linear fuel path, a fuel path remaining close to upper limit and a multiple segment fuel path were finally decided as shown in Fig. 4.

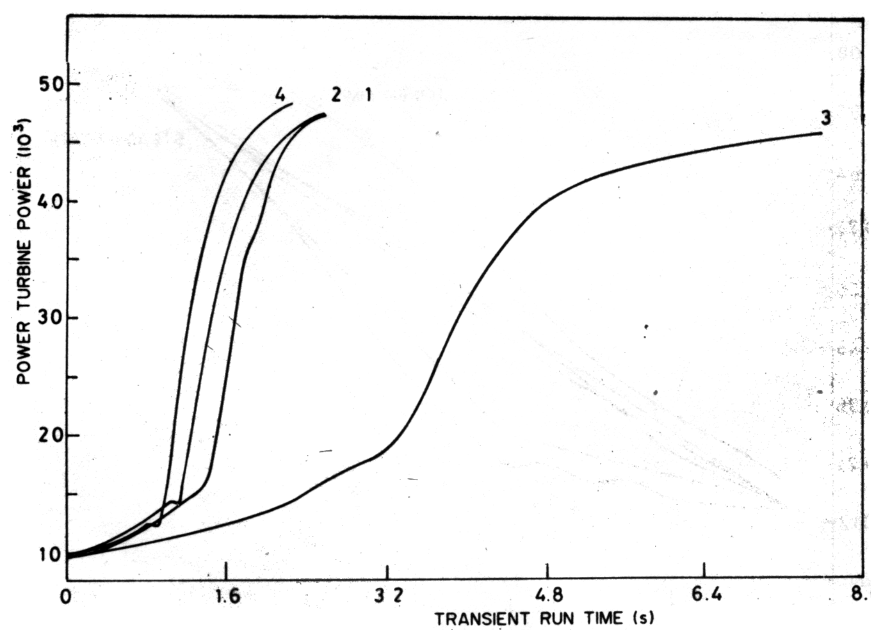
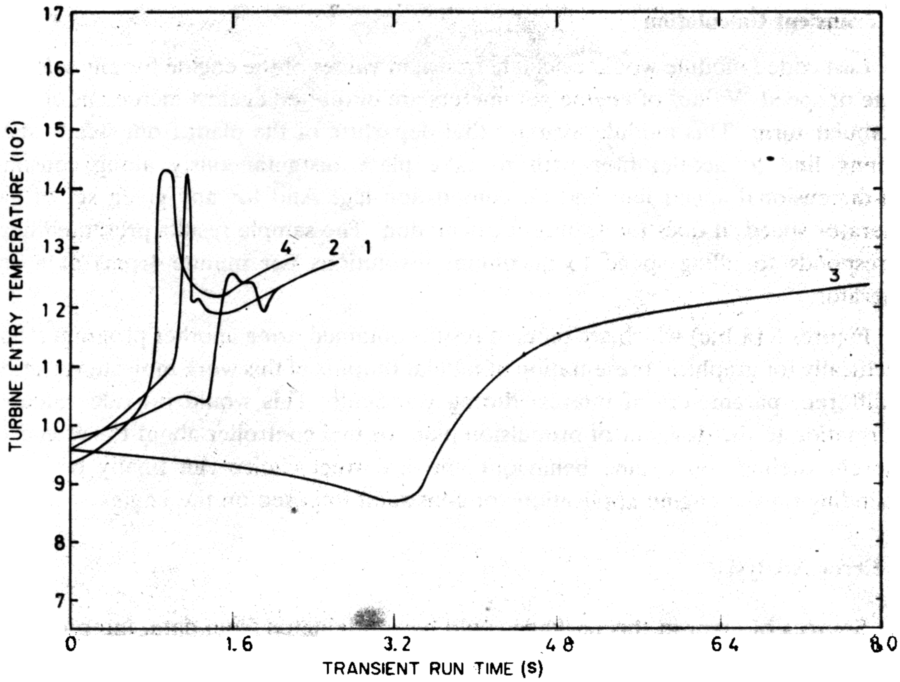
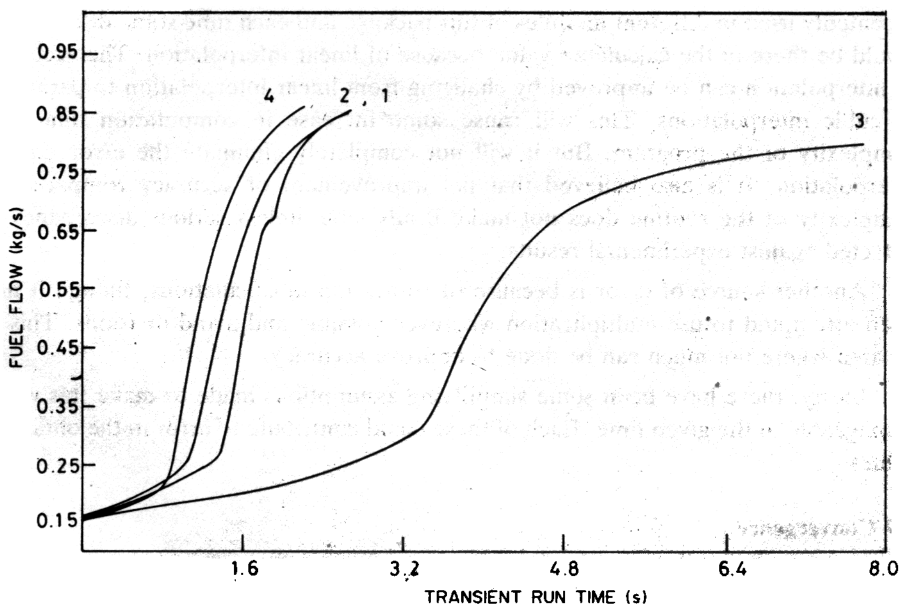


Figure 5 (a)



(b)



(c)

Figure 5. Single spool marine gas turbine transient results.

3.5 Transient Calculation

Last coded module would calculate transient values of the engine for any selected range of speed. Values of engine parameters are outputted against increment of time in tabular form. This module assumes that departure of the plant from steady state running line to acceleration path to take place instantaneously along constant non-dimensional speed line and no combustion lag. And for any given set of gas generator speed, it does the transient calculation. The sample results presented here corresponds to idling speed to maximum revolutions per minute (rpm) of a gas generator.

Figures 5 (a,b,c) which are plots of results obtained using another program made specifically for graphical presentation of tabular outputs of this work indicate variation of different parameters of interest during transients. This would provide valuable information to the designer of propulsion plant or fuel controller about the effects of different fuelings on engine behaviour and a correct choice can finally be made depending on the engine applications or constraint imposed on the engine.

3.6 Error Analysis

Sources of error in this package could have originated from data, interpolation, computation and simplifying assumptions.

Since the number of data points available for steady state analysis is limited and the accuracy of values is fixed, this will set a ceiling for the accuracy of the values obtained during transient calculations. Linear interpolation routines have been repeatedly used in different modules of this package and each time some discrepancy would be there in the calculated value because of linear interpolation. The accuracy of interpolation can be improved by changing from linear interpolation to parabolic or cubic interpolations. This will cause some increase in computation time and complexity of the program. But it will not completely eliminate the error due to interpolation. It is also believed that net improvement of accuracy compared to complexity of the routine does not make it advisable unless serious discrepancy is detected against experimental results.

Another source of error is because of truncation in calculations, though it has been attempted to use multiplication wherever possible and avoid divisions. This is an area where not much can be done to improve accuracy.

Lastly, there have been some simplifying assumptions made to make this work manageable in the given time. Each of these could contribute to error in the obtained values.

3.7 Convergence

The question of convergence of values may repeatedly arise in cases when the problems are solved on digital computers using various trial and error routines. Each time the cause of divergence may be different and each case must be treated separately. Generally in cases where changing the value of one parameter and offer a set of calculations to check the value of a different parameter, the convergence problem has to be faced more frequently.

4. DIGITAL FUEL CONTROLLER DESIGN

Recent trend in fuel controllers has been the introduction of microprocessor-based systems. Designs are becoming more and more involved with computers in this area for gas turbines. The present work attempts to provide flexible data to suit analog as well as digital design.

In contrast to conventional fuel controllers, it is essential to know the value of flow rate at a much smaller instance of time for digital controllers. Here, deciding a pattern for fuel scheduling which gives suitable behaviour from idle to maximum speed and repeating it for other acceleration cycles, will not suffice. It is also important in digital fuel control systems to know the value of fuel flow during the departure of plant from steady state operating line to accelerating path. It has been assumed that the plant moves from steady state to acceleration path instantaneously and at a constant speed. This assumption does not introduce large error over a complete accelerating cycle because the plant will face opposing effects at the beginning and finishing phases of an acceleration cycle. By assuming departure at constant speed, a lower speed is taken for the plant initially. Towards the end, by stopping acceleration and fueling on desired speed, the plant would gain a higher speed.

Nevertheless, for digital systems, the computer must be provided with the information of 'how much fuel to be provided during steady state to acceleration path?'. This leads to further work required to find out the effects of various departure paths and ways of optimising path selection[5].

5. DISCUSSIONS

5.1 Deceleration and Flame-out Consideration

Similar to acceleration, there must be a pattern decided for deceleration, so that deceleration transients are suitable to the engine application. Flame-out of combustion chamber, in most cases, is not desired and should be avoided both during acceleration and deceleration. General steps in determination of deceleration path is the same as selection of fuel schedules for acceleration. In this case, one has to establish the lower bound limit for fueling which would be mainly decided by combustion chamber characteristics and flame-out criteria[3]. Of course, flame-out condition must also be examined during acceleration from the experimental characteristics of combustion chamber.

5.2 Power Improvements

It was found from the result of simulation that the experimental engine has got a good potential for power improvement. Recent developments in blade material has made it possible to have turbine blades which can stand higher temperatures i.e., much more than the maximum TET used in this simulation. In addition the surge line located away from steady state running line suggests upon increasing maximum

TET with existing physical dimensions, the power and transient behaviour of this engine could be improved appreciably.

5.3 Analysis of Transient Results

Figure 5 shows the results obtained for a gas generator idling speed of 4,010 rpm to the maximum power of 10,500 rpm. It was possible to obtain similar results for other speed ranges, but the above provides a better indication of plant's total transient behaviour. It can be observed that path number 3, i.e., the path which was deliberately selected close to steady state running line, never comes close to any of the plant's limits as the gas turbine moves from idle to maximum power. But it almost takes three times as much to attain full speed, a phenomenon not greatly desired. Another observation from path 3 is the gradual increase of gas generator rpm against a sharp increase over a short period of time in the other three paths. This indicates that path 3 is smoother in operation.

Plot of TET versus transient time gives a good indication of how fuel path selection greatly influences the transient behaviour of the engine. Here it is noticeable that path 1 even though very much similar to paths 2 and 4, never exceeds engine's limits and at the same time provides the plant with the same response time, i.e., maximum power is obtained over a time of 2.8 s against 2.6 and 2.5 s for paths 4 and 2 respectively.

Another parameter of concern in gas turbine engines is how quickly the net power is available to facilitate a comparison plotting power versus transient time of the power turbine is made. It can be found that 90 per cent of maximum power will be available from the plant in 6.4, 2.5, 2.4 and 2.3 s from the paths 3, 1, 2 and 4 respectively. This indicates the latter part of path 3 is very slow and needs improvement. In general, obtained results matched with the behaviour expected at the time of fuel schedule selection. As it was mentioned, none of the paths were of optimum schedule. Primarily they were selected so as to offer a criteria for comparison.

For marine gas turbines, where smooth operation increases the service life of the engine, it can easily be concluded that a fuel schedule between 1 and 3 would be advisable. In the case of aircraft applications, path 1 or 2 would be a logical choice. It should be borne in mind that if the effects of combustion chamber transients and other simplifying assumptions were included, there would have been an increase in the response time of the plant. At the same time the values of TET would have become less. That is, all paths would have yielded satisfactory results as far as engine limits were concerned.

It can be concluded in general that reducing total transient time of a gas turbine plant need not necessarily improve the total dynamic behaviour of the plant. To come up with a complete quantitative comparison of two plants or two different control systems, one should also carefully look into the way engine parameters are varying during transients. The importance of a judicious choice of acceleration fuel schedule has been verified as it greatly influences the transient behaviour.

5.4 Ship Propulsion Data Requirements

This package provides power available from the plant at any instant of time. Map of torque versus speed can easily be constructed in the form of lines of constant power by using the following relations:

$$W_{pt} = 2\pi Q_{pt} N_{pt}/60 \quad (13)$$

hence

$$Q_{pt} N_{pt} = 60 W_{pt}/2\pi \quad (14)$$

The value of Q_{pt} N_{pt} for any particular value of W_{pt} is constant, and the lines of Q_{pt} versus N_{pt} can be drawn.

Such characteristic maps are used for matching the gas turbine set with ship's propulsion system. For a ship with gas turbines as prime movers, propulsion control systems are designed using the engine dynamic behaviour data as one of the main requirements.

6. CONCLUSIONS

Results obtained in this work indicate that accurate prediction of engine transients was possible using the developed package, and the importance and effectiveness of choice of fuel path selection can be easily observed from the plotted result. This package could be used for other single spool gas turbines as well. Because required modules are available to compute surge line and locus of maximum TET, any fuel path can be selected and transient values can be obtained. It has also been shown that complete operational qualities of a marine gas turbine could not effectively be stated in terms of response time only. But a total transient behaviour shall provide a true picture of the engine performance. Digital simulation based on thermodynamic modelling of gas turbine and component characteristics is highly flexible and provides valuable data at early stages of design, both for performance and control system designers.

Further studies can be carried out on the effect on transients of the engine on the selection of departure path from steady state to acceleration path; and ways of optimising and combustion chamber transients; heat transfer from engine main components; and time dependent changes of properties.

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