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TRANSIENT DYNAMICS OF GAS TURBINE ENGINES

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ABSTRACT

Transient response of gas turbine engines depends on several parameters including engine type, components' characteristics, and operational condition. This paper briefly describes the general methodology and approach for transient sensitivity analysis of various gas turbine engines, and the results of a computer program for analysis of the transient behavior of a single spool turbojet. Based on the method of intercomponent volumes, the general methodology applicable to transient analysis of any gas turbine based system has been developed. The method results in a set of stiff, time dependent non-linear ordinary differential equations (ODE) which can be solved by an appropriate ODE solver. The coefficients of the differential equations depend on the design and operational condition of the components represented by the component maps. The initial conditions of the ODE can be any steady state operating point of the engine. A steady state engine model provides these initial conditions. The program has the capability to match the components, and obtain a steady state operating point for the engine, accept a fuel protocol and predict the transient behavior of the engine. The program has produced satisfactory results for step, ramp and sinusoidal fuel inputs, as well as ramp variation in nozzle exit area.

LIST OF SYMBOLS

c_p	specific heat at constant pressure
V	velocity
c_v	specific heat at constant volume
v	volume
FAR	fuel air ratio (mass)
I	moment of inertia
k	specific heat ratio (c_p/c_v)
m	mass flow rate
N	rotational speed
p	pressure
Pr	pressure ratio
R	gas constant
T	temperature
t	time
W	power

Subscripts

a	air
B	burner (combustion chamber)
c	compressor
e	exit
t	turbine

Greek Symbols

δ	non-dimensional pressure
η	efficiency
Θ	non-dimensional temperature

INTRODUCTION

Transient operation of a gas turbine engine is encountered when the input(s) of the engine are altered, and the operation of the engine changes from one steady state condition to another. Start up and shut down are special cases of transient operation.

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Sensitivity and reaction of both aviation and stationary gas turbines to the changes in engine inputs can have significant implications on the transient behavior of these systems. These include surge, stall, overspeeding, overheating of the components, etc. The question of whether an engine will produce the desired response within the desired period of time depends on the safe operational range, the dynamics of the interaction of components, the operational condition, as well as the limits imposed by its control system.

This paper briefly reviews some major previous works on the subject of transient behavior of gas turbines, and describes the methodology for development, and the results of a computer program for transient analysis of turbojet engines. The present work is the first step in development of a comprehensive, user friendly PC-based computer program for transient simulation of a wide range of aviation and stationary gas turbine systems.

BACKGROUND

There have been numerous efforts to simulate the transient behavior of gas turbine engines. Early work on the subject goes back to Gold and Rosenzweig (1952), who developed a simple model for transient behavior of gas turbines based on characteristic response time of the engines. Comprehensive steady state and dynamic engine simulation in NASA started in the 1960s. Fishbach (1980) has reviewed the gas turbine simulation programs used in the United States. Szuch and his coworkers at NASA Lewis Research Center developed a hybrid computer program called HYDES, to study the dynamics of turbojet and turbofan engines (Szuch, 1974). The general procedure used in HYDES as well as the details of the interfacing between the digital and analog computer is described by Szuch, et al. (1982). DYGEN, developed by Sellers and Daniele (1975), has been one of the first digital computer programs for simulation of the dynamics of turbo-engines in NASA. It simulates some fixed configurations of turbojet and turbofan engines. DIGTEM (DIgital computer program for Generating dynamic Turbofan Engine Models) developed by Daniele, et al. (1983) is the digital version of HYDES and an advanced version of DYGEN. It has the flexibility to model engine configurations which are subsets of a two spool, two stream turbofan engine. DIGTEM is well documented and nearly a hardware independent program that has been well maintained. The program lacks pre and post-processors and includes many hard coded features which make it difficult to modify. Another effort for improvement of NASA's transient simulation capabilities has been undertaken by Sadler and Melcher (1985) in the development of Dynamic Engine ANalysis (DEAN) program. The program is modular, with extensive interactive features for construction of engines from basic components. Pre- and post-processing features have also been implemented in DEAN. Despite many advanced features of DEAN, due to the complexity and hardware dependency, it has not been maintained.

Another series of extensive investigation on dynamics of turbo-engine performance have been reported by Saravanamuttoo and his co-workers. They have used analog, digital and hybrid computers in their simulation. Fawke and Saravanamuttoo (1971) present a clear methodology for simulation of both turbojet and turbofan engines, and have compared the simulation results with experimental data. MacIsaac and Saravanamuttoo (1974a and 1974b) have discussed different aspects of modeling of turbo-engine transient operation. Saravanamuttoo's approach is summarized in the text by Cohen, et al. (1987) and with more detail by Saravanamuttoo and MacIsaac (1982).

The interest and demand for stationary gas turbines for power production, and health monitoring of both aviation and stationary gas turbines has prompted a new surge in studying the dynamics of these systems. Schobeiri (1986) has developed a computer program called COTRAN for rather detailed simulation of stationary gas turbines. His methodology utilizes one dimensional conservation equations for different stages of the turbine, compressor and combustion chamber. Its implementation requires detailed information on the design parameters of individual components of the engines, which are usually proprietary in nature and often not available. The author also includes the effect of heat transfer to the hardware during the transient operation, but does not discuss the sensitivity of his calculation to this phenomenon. Schobeiri and Haselbacher (1985) have applied COTRAN to simulate the transient behavior of a compressed air storage gas turbine facility with satisfactory results.

Another recent work on transient performance of aviation gas turbines has been reported by Pilidis and MacCallum (1985) and MacCallum and Pilidis (1986). In contrast to other studies discussed so far which have used the method of intercomponent volumes, they have used the method of continuity of mass flow in their analysis. This is an iterative method in which speed calculation lags one time step behind the other state variables of the engine. In this method the mass continuity is satisfied first, and then the change in the rotor speed is calculated using the work imbalance of the turbine and the compressor. The two methods have been discussed and compared by Fawke and Saravanamuttoo (1971). In the work of Pilidis and MacCallum, the effect of heat transfer to the hardware, and compressor clearance has been considered and reported. They have concluded that hot engines have a more rapid acceleration and greater surge margin usage compared to cold engines. They conclude that the adiabatic assumption in transient simulation of gas turbines results in higher acceleration compared to the case that heat transfer is taken into consideration.

Khalid (1992) has recently reported the role of dynamic simulation in engine design and development in Pratt & Whitney. Although he does not provide any details on the models and the computer program used in the simulation, he discusses the application of dynamic simulation in flow path design, control-system design, and development testing.

MATHEMATICAL MODELS

The method of intercomponent volumes for dynamic simulation of gas turbines is explained in this section. In this methodology, the storage of mass associated with any transient process is assumed to occur in the intercomponent volumes between the components. Intercomponent volumes substitute for the mass and energy storage capacity of the components in the system. The state variables in each intercomponent volume are assumed to be

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those at the interface of the components. In reality, gradients exist for all state variables in the fluid along each component, but because of the complexity of inclusion the properties' gradients in the conservation equations, the energy and mass storage is assumed to occur at uniform (in space) conditions. The volume of intercomponent volumes can be taken as weighted average of the upstream and downstream components. Fig. 1 shows the schematic of a single spool turbojet and Fig. 2 shows the equivalent block diagram including the inter-component volumes, according to which a single spool turbojet is modeled.

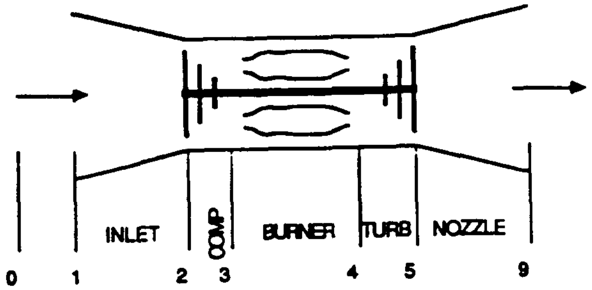

Fig. 1 - Schematic flow diagram of a single spool turbojet.

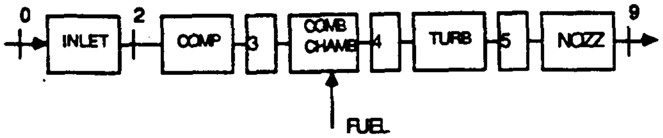

Fig. 2 - Block diagram for a single spool turbojet.

The flow in each component is assumed to be one dimensional, and the properties at each station in the system, such as those shown in Fig. 1 are average values across each cross section. Another assumption made in the developed models is that there is no heat transfer to the hardware during the transient operation of the engine. For small transients this is quite a valid assumption, while for large transients it may mildly influence the simulated response.

In the transient analysis, the performance parameters of the components such as efficiency of the compressor, pressure drop in the combustion chamber, etc. have been assumed to relate to the state variables of the components in a quasi-steady form. As an example, in the transient model of the compressor, the relationship between the efficiency, mass flow rate and pressure ratio at any instant is the same as in steady state conditions. The validity of this assumption is under study by the authors. Finally, it is assumed that the gases along the flow path have the ideal gas behavior.

Using the above methodology and general assumptions, and based on the fundamental principles, steady state and transient models for the components and the engine can be developed. The steady state models are used both for matching the components to find a suitable initial condition for the transient simulation, and also for calculation of component performance during the transient operation.

For each component, the performance maps relate the performance parameters to each other. A typical compressor performance map is shown in Fig. 3. For a variable geometry compressor, a map similar to Fig. 3 specifies the compressor performance for each value of stator angle.

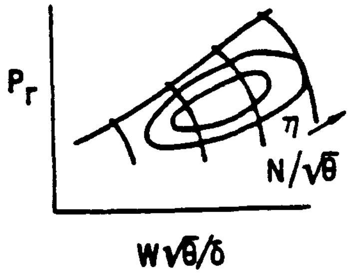

Fig. 3 - A typical map for a fixed geometry compressor.

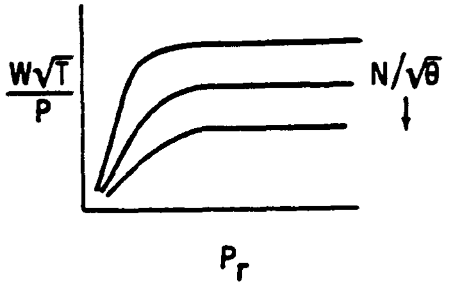

Fig. 4 - A typical turbine map.

The pressure drop across the combustion chamber can be derived by applying the momentum equation across the chamber. The result is:

$$P_e = P_i - m_i^2 (T_i/P_i) K_B$$
$$\text{where } K_B = f\,(\text{FAR, Geometry}) \qquad (1)$$

Efficiency and K_B are empirical parameters for each combustor. They can also be calculated from detailed computer models of the combustion chamber.

In a turbine; pressure ratio, efficiency (or enthalpy drop), non-dimensionalized mass flow rate and rational speed are related through turbine maps. A typical turbine map is shown in Fig. 4.

In modeling the transient behavior of each component, basic mass and energy conservation equations have been applied to the component and the results are two time dependent ordinary differential equations. As an example, the equations describing the transient behavior of the compressor without any bleeding will be:

$$(v/R_e T_e)\, dP_e/dt - (P_e v/R_e T_e^2).\, dT_e/dt = m_i - m_e \qquad (2)$$

$$(P_e v/R_e T_e).dT_e/dt = m_i k_i T_i - m_e k_e T_e - (m_i - m_e) Te + W_c/c_{ve} \quad (3)$$

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In the final form, Eq. 3 can be substituted into Eq. 2 to convert it into a form containing the time derivative of P_e as a function of T_e and P_e. Bleeding for turbine cooling, accessory drives, etc. is taken from the intercomponent volumes and reinjection into the flow path is also into the intercomponent volumes downstream of the components into which the air is injected.

The balance of turbine and compressor work will cause the rotor and all the attached components to speed up (accelerate) or slow down. Conservation of angular momentum will result in the dynamic equation for the rotor as follows:

$$dN/dt = (W_t - W_c)/(4\Pi^2 IN) \qquad (4)$$

To construct the transient model of an engine as a whole, engine components and the associated intercomponent volumes must be interfaced, so that conforming with the configuration, inputs and outputs of the models of the components match with each other. As a result, mathematical representation of the model will be a set of ordinary differential equations, with time as the independent variable. The number of equations representing the transient behavior of the engine depends on the number of components which influence the transient dynamics of the engine. Table 1 identifies the components and also the number of equations that should be solved in the transient model of some of the common aviation engines.

The system of ODE under consideration is of the explicit form. This system can be written in the form:

$$dy_i/dt = f_i\,[t, y_1, y_2, \ldots, y_N] \qquad (i = 1, \ldots, N)$$

where y is the vector of dependent variables, and t is the independent variable. N is the number of differential equations. The initial values of the dependent variables are provided by matching the engine components for a desired steady state operation of the engine. The ODE system representing the transient operation of gas turbine systems is of stiff type and demands application of special solvers. ODE solver package, developed by Hindermarsh (1983), has been used in this work. The solver can be used for both stiff and non-stiff systems of the form dy/dt=f. In the stiff case, it treats the Jacobian matrix df/dy as either a full or a banded matrix, and as either user-supplied or internally approximated by difference quotients. It uses Backward Differentiation formula (BFD) in the stiff case.

Each component in a turbo-engine has a range of operation, which is determined by its performance map(s). For the components to be operable in an engine, they should match with each other. Matching is achieved by satisfying the basic conservation principles (mass, energy, and momentum), along with any physical relationship such as the rotor connection(s) of the gas generator. The basic method for matching engine components has been explained by Fishbach (1980). A modified version of the method described by Fishbach has been used in the developed computer program.

COMPUTER PROGRAM

The developed computer program is designed to predict and produce the response of an engine to a time dependent disturbance in one or more of its input parameters which can be independently varied by the user. The program has been written in Fortran-77 and executed on a 486 platform using DOS. The execution of the program takes approximately five minutes of computer CPU time per second of simulation.

Fig. 5 shows an overview diagram of the system. In the program, the engine module is responsible for providing the information about the performance of each component to the dynamic calculation module at any instant. The dynamic module is responsible for preparing the information for, and driving the ODE solver that produces the transient behavior of the engine at any instant. A main program controls the execution of the whole program.

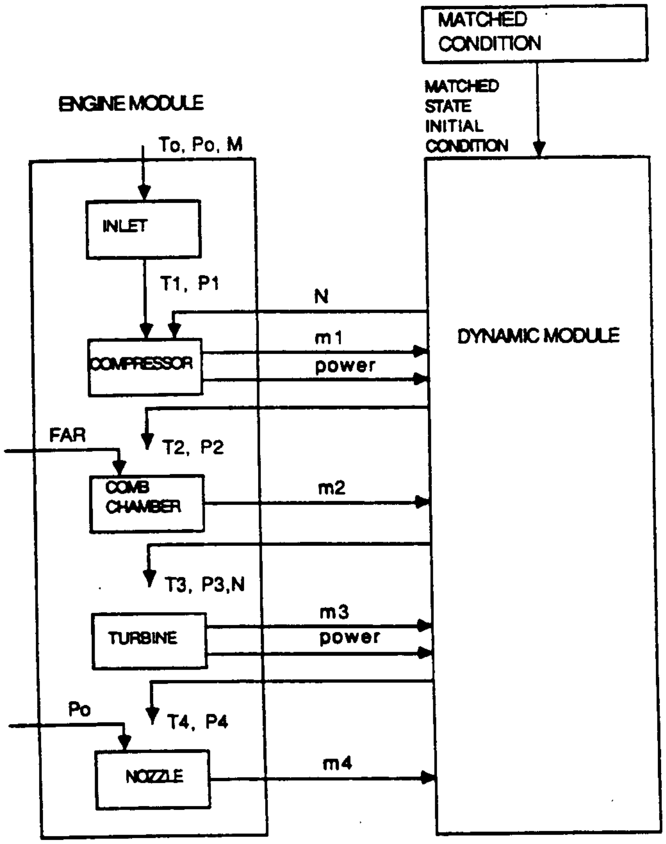

Fig. 5 - Interaction between match, dynamic and engine modules.

RESULTS AND DISCUSSION

In this section, some typical results produced by the developed computer program will be presented and discussed. The method has been preliminarily applied to a fixed geometry single spool unaugmented turbojet constructed with the turbine and compressor for which detail performance maps have been reported by Szuch, et al. (1982). The design point data considered and generated from the performance curves are presented in Table 2.

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Table 1 - Components and number of transient dynamic equations that should be solved for simulation of the transient behavior of some aviation engines.

	Engine	Components	No of Equations
1	Single spool turbojet (no augmentor)	compressor, combustor, turbine and rotor	7
2	Single spool turbojet (with augmentor)	compressor, combustor, turbine, augmentor and rotor	9
3	Twin spool turbojet with augmentor	two compressors, combustor, two turbines, two rotors and augmentor	14
4	Twin spool turbofan with augmentor	fan, compressor, duct, combustor, two turbines, two rotors and augmentor	16
5	Triple spool turbofan with augmentor	fan, two compressors, duct, combustor, three turbines, three rotors and augmentor	21

Table 2 - Design point data considered and/or generated for the test engine.

Parameter	Parameter Value
Mach number	0
Rotor speed (RPM)	5600
Ambient Pressure (Psia)	14.7
Ambient temperature (R)	540
Engine air flow rate (lb/sec)	34.3
Compressor pressure ratio	9.
Turbine pressure ratio	1.94
Turbine inlet temperature (R)	2700
Combustion chamber pressure drop	3%
Thrust (lbf)	3700

Fig. 6 shows the variation with respect to time for the three cases of step (S), ramp (R) and sinusoidal (SI) fuel flow rate into the combustion chamber. Figs. 7 and 8 demonstrate the response of the combustion chamber to the fuel input schedules specified in Fig. 6. Comparison of Figs. 7 and 8 reveals that the temperature response is much faster (up to an order of magnitude) compared to the pressure response. Although the turbine inlet temperature have a slight time lag with respect to the input, it closely follows the fuel flow rate variation, meaning that the frequency response of the system is much higher than the 1.5 Hz of fuel input frequency.

Figs. 9 and 10 show the response of the rotor speed and the inlet mass flow to the fuel protocols of Fig. 6. They have similar responses to the fuel input, which is expected. This is due to the fact that the mass flow rate in the compressor is a very strong function of speed and not very sensitive to the pressure ratio of the compressor. Compressor pressure ratio and consequently its exit pressure, respond much slower compared to the speed and air mass flow rate.

Variation of engine thrust with respect to time for the fuel protocols shown in Fig. 6 is presented in Fig. 11. A step increase in fuel flow rate will result in a sharp increase in thrust first, followed by a mild drop, and finally a much smoother rise in the thrust. The slight drop in thrust is a result of the initially faster response of the combustion chamber and turbine compared to the compressor. After the compressor catches up, the rate of increase becomes smoother. Thrust response to the sine wave variation in the input fuel flow rate shows that it does not exactly follow the fuel variation. It shows an overshoot in thrust while the fuel has already leveled off. This is a result of the time lag of air mass flow with respect to the increase in temperature in the combustion chamber.

Fig. 12 shows a schedule for variation of nozzle exit area with respect to time. The throat area remains constant. The effect of ramp increase of nozzle exit area on thrust is demonstrated in Fig. 13. The sharp increase in thrust shows that the flow in the divergent section of the nozzle is supersonic and with increase in exit area, the flow approaches a more fully expanded state at the nozzle exit. Because the nozzle does not influence the operation of the other components in the system, there is no thermal or mechanical inertia effect, and consequently the thrust response to the variation in the nozzle exit area is almost instantaneous.

The results presented in this section demonstrate the soundness of the approach and the developed computer program. The methodology and the program is readily expandable for analysis of various aviation and stationary gas turbines. The methodology can be used for transient flight simulation in the case of aviation gas turbines, and load variation simulation and control system design and analysis for both aviation and stationary gas turbines.

The program is presently being expanded to analyze a variety of aviation gas turbine based engines. It will include the following features:

1 - Incorporation of the engine control system in the program.
2 - Incorporation of full stability and engine installed limitations in the program.
3 - Man-machine interface (MMI) for on screen construction of the engine from its components. The MMI establishes the linkage between appropriate components and generates the main program for analysis of the engine.
4 - Post-processor for generating trend plots.

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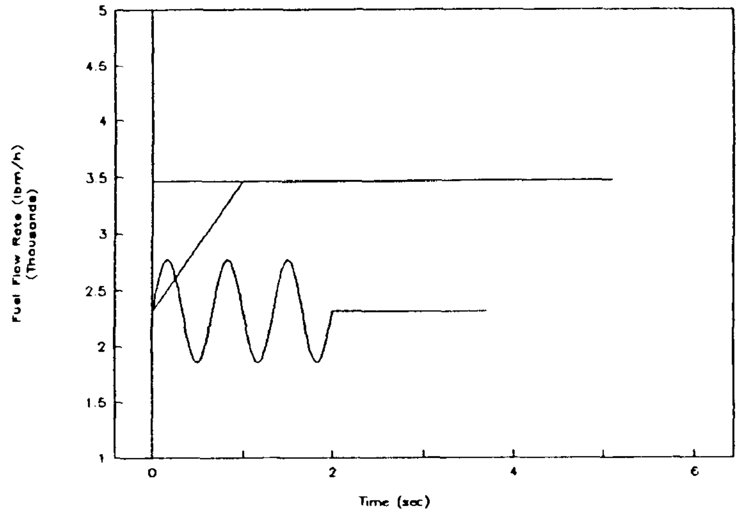

Fig. 6 - Variation with respect to time of the input fuel into the combustion chamber for three cases of step (S), ramp (R), and sinusoidal (SI).

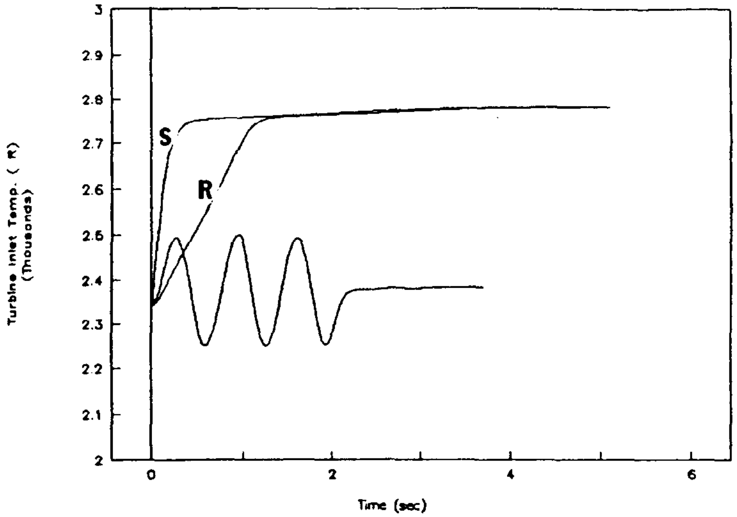

Fig. 7 - Response of the turbine inlet (combustor exit) temprature to the fuel variation specified in Fig. 6

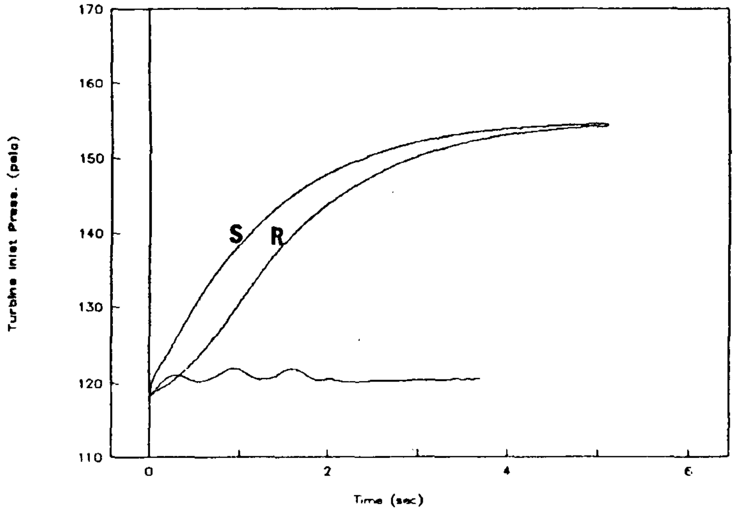

Fig. 8 - Response of the combustion chamber pressure to the fuel variation specified in Fig. 6.

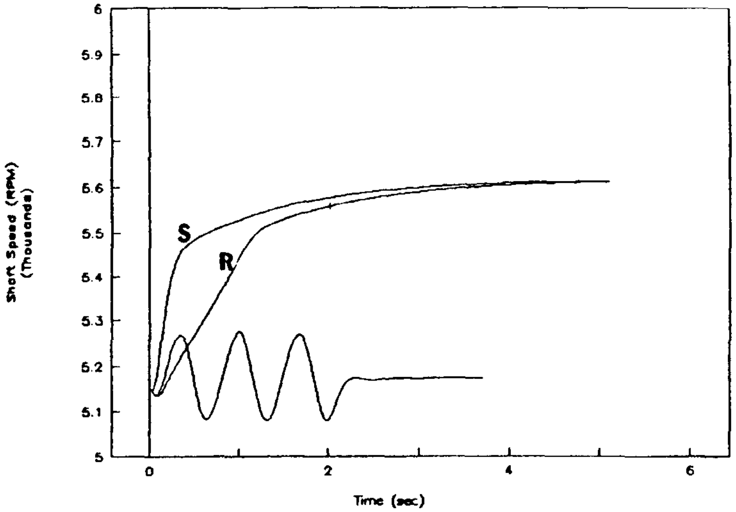

Fig. 9 - Variation of the rotor speed with respect to time following the fuel variation specified in Fig. 6.

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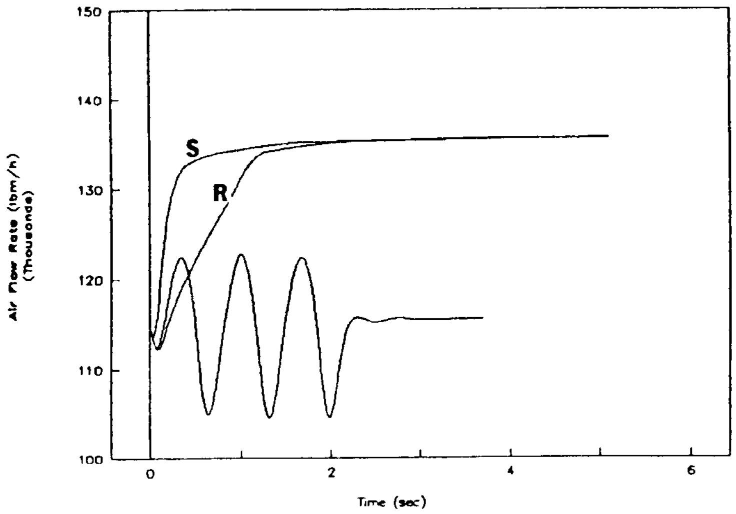

Fig. 10 - Variation of the inlet air mass flow rate with respect to time in response to the fuel variation specified in Fig. 6.

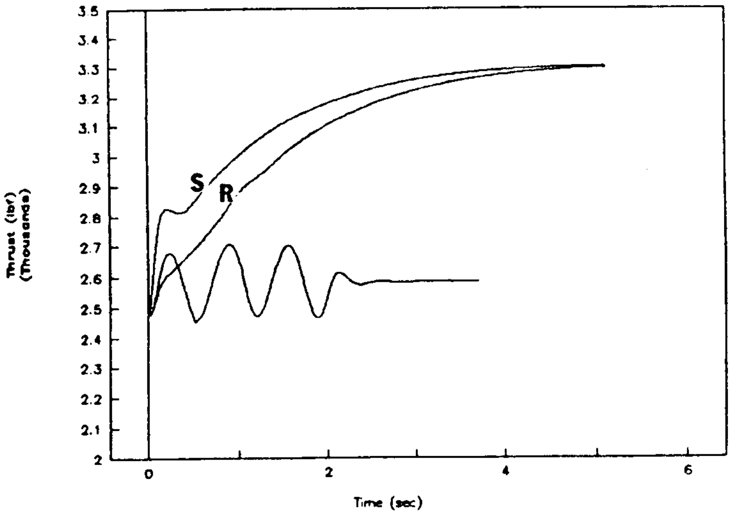

Fig. 11 - Engine thrust with respect to time in response to the fuel variation specified in Fig. 6.

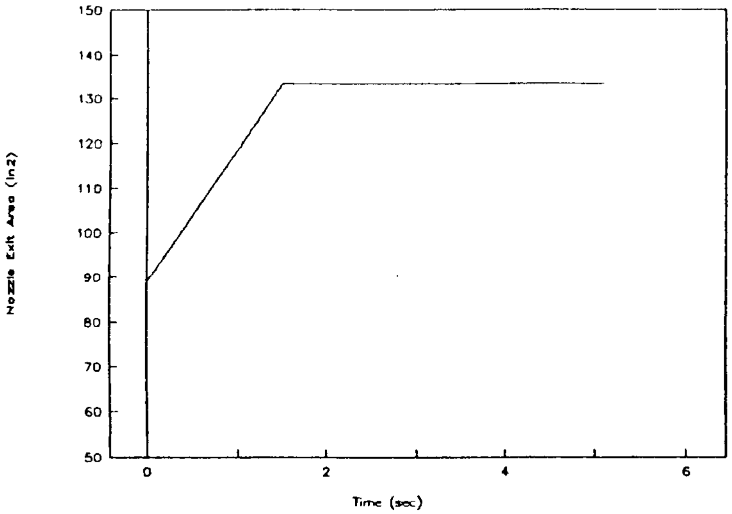

Fig. 12 - Variation with respect to time of the nozzle exit area, as an input for transient analysis.

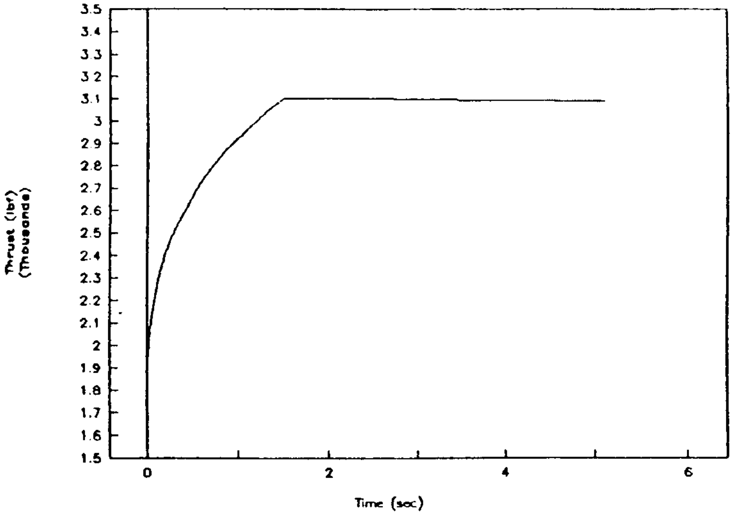

Fig. 13 - Response of the engine thrust to the nozzle exit area variation specified in Fig. 12.

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