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Modeling of A Miso Control System For A Turboshaft Engine

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Abstract

The general configuration of a turboshaft gas turbine control systems model is presented. The control systems included the relationships between the engine and its limitations such as a compressor surge line limit, exhaust gases temperature, the speed of the engines spools. The control system is of Multi Input Single Output (MISO) type, where the inputs to the controller are the limitation signals and the demand whither the only single output is the fuel valve new setting. The main parameter that the system controls by is that the fuel mass flow rate and the device which is doing this job is the fuel controller. The control system changes the fuel flow according to the engine demands by changing the fuel valve angle (θ) .

The time responses of each effective parameter was predicted for a different fuel valve angle and introduce the most effective specifications of the time response of the system (delay time, rise time, settling time and maximum overshoot). The behavior of the maximum overshoot value (if founded) is increasing with the fuel valve increasing. The value of delay, rising, and settling times decreases with the fuel valve angle increases. The present results show a good agreement with the previous works.

نمذجة منظومة السيطرة(MISO) لمحرك توربيني غازي نوع (Turboshaft)

الخلاصة

قُدم في هذا ألبحث شكل عام مع دراسه تحليليه لمنظومه السيطره للمحركات التوربينيه الغازيه التي تنتج شغلاً من خلال محور الدوران. منظومة السيطره التي تم بناءها, تشتمل على العلاقه بين المحرك و محدداته مثل خط التمور بالنسبه للضاغطه (والذي يعتبر المحدد الاساسي اثناء عملية التسارع), درجة حرارة غازات العادم (والتي تعطي انطباع حول درجة الحراره القصوى او درجه حراره مدخل التوربين), السرعه الدورانيه للمحرك (لحماية المحرك من ازدياد السرعه فوق الحدود المسموح بها). منظومةالسيطره المقدمه في هذا البحث هي من نوع متعدد المدخلات- احادي الخرج , حيث المدخلات الى المسيطر هي اشاره المحددات و الطلب, بينما الاشاره الخارجه الوحيده هي اشارة زاويه صمام الوقود الجديده. الشئ الرئيسي الذي يمكن لنا التحكم من خلاله بمنظومه السيطره هو معدل جريا الكتله بالنسب للوقود والجهاز الذي يقوم بهذه المهمه هو جهازمسيطر الوقود, و تقوم منظومة السيطره بتغيير معدل جريان الوقود تبعاً للطلب على المحرك بواسطة تغيير زاوية صمام الوقود.

الاستجابه الزمنيه لكل عنصر من العناصر المهمه في المحرك استبطت في حالات متعدده من زوايا صمام الوقود (30, 40, 50, 60, و70 درجه), وتم تقديم الخواص المهمه بالنسبه للاستجابه الزمنيه للنظام (وقت التأخر, وقت الأرتفاع, وقت الاستقرار, و اعلى قمه في استجابه النظام).

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في هذا العمل تم الاخذ بعين الاعتبار اوقات التأخير (وقت التاخير في مضخة الوقود, زمن التاخير في غرفة الاحراق, و زمن التاخير في المتحسسات), وتاثير هذه القيم على استجابه المنظومه للطلب عند نقاط عمل مختلفه. تم ايضا دراسة سلوك العناصر المهمه في المحرك التوربيني مع تغير معدل جريان الكتله بالنسبه للوقود المستخدم ويمكن ملاحظة التغير بالاستجابه عند كل قيمه من قيم معدل الجريان. اظهرة النتائج توافق و تطابق جيد مع ما منشور سابقا.

Nomenclatures

A	Area	m^2
C	Air Velocity	m/s
Cp	Specific heat	kJ/kg.K
f	local grid frequency	Hz
G(s)	Transfer function of component	-
J	Polar moment of inertia	$kg.m^2$
Ke	Gain of Transfer function …	-
M	Mach number	
$\overset{\circ}{m}f$	Fuel flow rate	kg/s
$\overset{\circ}{m}fss$	Steady state value of fuel flow rate	kg/s
$\overset{\circ}{m}f(t)$	Fuel flow rate after fuel valve	kg/s
$\overset{\circ}{m}f(t-\lambda)$	effective value of Fuel flow rate	kg/s
Ng	Gas Generator Rotational speed	rpm
L	Number of Poles.	
ov	Maximum overshoot	-
P	Pressure …	N/m^2
Qg	Gas generator torque	N.m
R	Gas constant	kJ/kg.K
h_t	turbine efficiency	-
1,2..5	fuel valve angle cases and the relative parameters relevant with that cases.	

Introduction

Gas turbines are important and widely used prime movers in transportation systems such as aircrafts, trains, ships and boats. Besides, gas turbines can be found in power systems where they are the main power generators. Gas turbines have even found application in cars and trucks. The gas turbines are designed in many types according to its function and the development that occur on it.

The gas turbine engine is a complicated system and consists of a number of subsystems. Physical laws and principles governing the subsystems are used to determine system equations and hence a mathematical model is generated. These models incorporate the knowledge as to how the various devices would behave in response to inputs to these devices. Modeling and analysis are customarily divided into two types of approaches namely, the transfer function method (classical control), which is best for single input _single output systems (SISO), and for low order systems. The other method is the state space method (modern control method) which is suitable for multi input _ multi output systems (MIMO) and leads to automation control synthesis once performance index and model are determined. Typically, the development of an engine control system requires mathematical modeling, engine

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simulation - model derivation, model order reduction, controller design, simulation verification and experimental verification. Invariably the first and the last tasks are the most involved. The accuracy of the results is greatly dependent on the modeling procedure adopted. Modeling of a gas turbine engine can be approached by various known linear and nonlinear techniques. A piecewise linearized model can be used to approximate a nonlinear system near an equilibrium point by linearization. While linearized models are only an approximation to the nonlinear system, they are convenient to analyze and they give considerable insight into the behavior of the nonlinear system near the equilibrium point [1].

The gas turbine simulation model can be broadly classified into three categories namely: analog models; hybrid and digital simulation models. In the early days of digital computers, the computational requirement for calculation of engine dynamics was in excess of the capacity of digital computers, and attention was initially focused on analog computers because of their capacity to operate in real time.

In the nonlinear component models approach, each individual component is modeled using detailed thermodynamic analysis. This approach has an inherent advantage of representing the nonlinear aspects of the gas turbine, and is flexible in the sense that additional component models such as for inlet guide vane assembly can be easily added at a later stage. Further amendment models approach has become the more popular choice of gas turbine modeling [2].

Literature Survey

James D. Paduano, [3], this research discussed developments in axial compressor stability modeling over the last several years, and related work in active control of rotating stall and surge. Several major themes have emerged during this work. One theme is the interplay between hydrodynamic perturbations in axial compressors and instability inception. The former obeys linearized dynamical equations, but their resonance and instability can trigger a variety of nonlinear events leading to violent oscillations in the compressor flow. An understanding of the key physical phenomena associated with stall inception, as opposed to those governing fully developed stall or surge, is critical to alleviating stall by design means or through active control. Another theme is the utility of actuators for understanding compressor stability. Active control work has prompted the installation of high-response forcing devices in compressors; even without feedback these have yielded much new information about compressor unsteady behavior. Experiments have progressed from laboratory scale demonstrations to full-scale rig and engine tests in about a decade. Competing theories about the physical mechanisms, the difficulties associated with stabilization and the goals and control techniques for rotating stall have led to a rich research base on which compressor stability and control technology is being built.

J.R. Blow, and etal. [4], In the research they said that the Defense Standard

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requires the use of formal methods in the specification, and subsequent analysis, of safety critical control software. However, there has been reluctance from industry to adopt these methods. This has been due in part to the high costs of producing a formal specification compared with conventional specifications and the need for specially trained mathematicians to write and understand the formal software specification. In addition, formal specifications have generally only been used for small-scale projects as academic exercises, such as library systems, or in a limited way, for the most critical systems, such as nuclear plant protection. Examples of the successful use of formal methods within real time industrial control systems are, therefore, very limited. For example, the SHOLIS Technical Demonstrator. In an attempt to redress this and in doing so to make formal methods more accessible to control systems engineers, the Practical Formal Specification (PFS) technique was developed. Funded by the UK Ministry of Defense, it aims to provide the technology for formal development of engine control software. In doing this exercise, the intent was not necessarily to find aspects of the specification incorrect. However, it is worth noting that the errors that were found were inexpensive to correct at this stage in the development. A conventional approach may have found these errors during software testing or rig testing, at which point it would have been expensive to correct them.

C.J. Tomlin and M.R. Greenstreet [6] present in the research the optimization of a combined cycle power plant is accomplished by exploiting hybrid systems, i.e. systems evolving according to continuous dynamics, discrete dynamics, and logic rules. The possibility of turning on/off the gas and steam turbine, the operating constraints (minimum up and down times) and the different types of start up of the turbines characterize the hybrid behavior of a combined cycle power plant. In order to model both the continuous/discrete dynamics and the switching between different operating conditions we use the framework of Mixed Logic Dynamical systems was used. The economic optimization problem as a Model Predictive Control (MPC) problem was then addressed which allows optimizing the plant operations by taking into account the time variability of both prices and electricity/steam demands.

Youhong Yu, and etal.,[8], presented a simulation model of a marine three-shaft gas-turbine's digital-control system . Acceleration processes are simulated via a Matlab/Simulink program. The effects of some of the main variables on the system's performance are analyzed and the optimum values of parameters obtained. A simulation experiment upon a real gas-turbine plant is performed using the digital-control model. The results show that the simulation model is reliable.

Components of the gas turbine

There are five main parts of a turboshaft or any gas turbine engine, which play an important role in the engine's operation:-

a) Inlet

Air enters in to the engine through the inlet. The main task of the inlet is to straighten out the flow, making it uniform and without much turbulence. This is important because compressors need to be fed distortion-free air. Inlet is positioned just before the compressor. There are different types of inlets based on the speed of the aircraft like subsonic inlets, supersonic inlets and hypersonic inlets.

b) Compressor

A compressor is used to increase the pressure of the air entering through the inlet. The air is forced through several rows of both spinning and stationary blades. As the air passes each row, the available space is greatly reduced, and so the air that exits this phase is thirty or forty times higher in pressure than it was outside the engine. The temperature of the air also gets increased because of the increase in pressure. Axial flow compressor and centrifugal compressor are the two main types of computers used in turbofan engines. The compressor is mounted in front of the combustor.

c) Burner (combustor*)*

The burner is the component in which the actual reaction (combustion) takes place. The high pressure hot air coming out of the compressor is combined with the fuel and burned for combustion. The combustion results in very high temperature gases with high velocities. These high temperature exhaust gases are used to drive the turbine. Burners, placed just after the compressors, are made from materials that can withstand the high temperatures of combustion. Annular, can, can-annular burners are the three different types of burners mostly used.

d) Turbine

The turbine is located next to the burner. The power used to drive the compressors is obtained from turbines. The turbine extracts the energy of the high temperature gas flow coming out of the burner by rotating the blades. This energy is transferred to the compressors by connecting shafts. The air leaving the turbine has low temperature and pressure when compared with the air coming out of the burner because of the energy extraction. Turbine blades must be made of special materials that can withstand the heat, or they must be actively cooled. There can be multiple turbine stages for driving different parts of the engine independently like compressor, fan (turbofan) or propeller.

e) Nozzle (exhaust)

A nozzle is a specially shaped tube through which the hot gases flow. The actual thrust required to move the engine forward is produced in this nozzle which is positioned after the turbine stage in the engine. The thrust is developed by conducting the hot exhaust gases through this nozzle to the free stream of outside air. The speed and flow rate of the air leaving the nozzle provides the airplane with thrust. Both the temperature and pressure of the air or rather hot gases is reduced very much

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while passing through the nozzle. The inside walls of the nozzle are shaped so that the exhaust gases continue to increase their velocity as they travel out of the engine. Based on the geometry of the nozzle, it can be categorized under co-annular, convergent or convergent-divergent (CD) nozzle.

Control Theory Methods

Mainly the control system design theories are classified into two types, according to the signals that the theory dealt with. The theories are:

Classical Control theory

The classical control theory mainly depends on the frequency domain relationship between the input and the output of a system. The system serves Bode, Nyquist, Evans Root locus as design techniques. That theory suitable for simple control system and that of single input- single output problem and used LaPlace transformation to solve the plant differential equations [7]. This theory inherent use of gain and phase margins in the frequency domain reduces controller sensitivity to uncertainties in engine parameters.

Modern Control theory

This theory depends on the state space relationship between input and output of a system. The modern control theory used a pole placement, Liapunove second method and quadratic syntheses to analyze the relations. That method is suitable for multi input – multi output systems (MIMO) analysis and this method uses state-space theorems to solve plant differential equations. This method leads to automation of control synthesis once model and performance index are determined. This work used the simulink to solve the multi input- single output systems (MISO), and analyzing its behavior in time domain and gathered its parameters time response.

The Turboshaft control

The Turboshaft engine control system main goal is to cope with application that the Turboshaft used for. The main parameter which has to be taken in mind is that to keep the free turbine speed at a fixed value (with some acceptable fluctuated range), to deliver electrical power at approximately fixed frequency as shown in the equation below:

$$f=\frac{N*L}{60} \qquad \dots (1)$$

Where: - f: frequency (Hz)., N: Rotational Speed (rpm)., L: Number of pair pole.

The figure (1) below shows the control system of the Turboshaft engine:

The characteristic of the gas turbine and load

The gas turbine is a prime mover, its purpose is to deliver power and the primary control over this development power is the hydrocarbon fuel input. Exhaust pressure ratio, is probably the most accurate but is also the most complex from the transducer view point. In large fan engines compressor pressure ratio is preferred, but for a simple single shaft turbojet, gas generator speed as indirect method of power measurement can be used successfully. It is easier to expand this control to free turbine applications.

The major component which falls within the controlled processes is shown in figure (2). This is the initial block diagram

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used to understand the engine from which to derive the mathematical equations for analysis work and must include, therefore, all elements which will affect response to commands from operator.

The control systems fall into the multiple input – single output category (MISO), and as such can be analyzed by classical or modern control theory method. Any mathematical modeling of the engine

The output signal from the controller is the fuel valve angle or the valve position (θ), and then that signal is directed to block (**a**). The block (**a**) represents a relationship between the fuel valve angle and the fuel flow rate), which was gotten from the test bed information. Block (**b**), represents the fuel pump time constant effect .The block (**c**), is the combustion chamber dead time (λ), which causes a lagging in the system, and the output of that block is the fuel flow rate at time (t-λ),and at point(**d**) there's a subtraction operation between the recent signal of fuel flow rate and the steady state fuel flow rate which produces a signal of the fuel flow rate change. At point **(e)**, the production occurs between the signals that leave **(d)** and the torque to fuel change to produce the torque change signal (ΔQ), and then multiplies in the inertia, integral and transforming blocks **(f, g, h)**,to produce a gas generator speed signal in revolution per second (rps),(Ng) .

Combustion dead time

The normal method used to represent a dead time is to employ a second pade approximation [4]

needs to take into account the effects of ambient intakes pressure and temperature. It is usual to use the non-dimensional parameter form referenced to intake conditions of 15°C (288°K) and 14.7psi (101.325KPa). and is only satisfactorily analyzed using one of the modern control theories as described in the introduction The problem then becomes multiple input – multiple output (MIMO).

Where:

$$e^{-\lambda s} = \frac{\lambda^2 s^2 - 6\lambda s + 12}{\lambda^2 s^2 + 6\lambda s + 12} \qquad ..(2)$$

Gas Generator Dynamics (gas generator speed Ng (rpm))

A fuel input ($\dot{m}f$), engine torque (Qg), engine shaft speed (Ng) simulation of the prime mover usually suffices for the investigation of the required control system. The most serious limitation of such simulation is that does not represent a compressor surge except by indirect synthesize methods but otherwise it is perfectly adequate for the investigation of controller stability. The general block diagram of such a model is shown in figure (2).

The simulation based on the assumption that the gas generator dynamics can be represented by a function whose value varies with effective fuel flow ($\dot{m}f$ (t-λ)) and the spool rotational speed (Ng).

The relationship for a typical gas generator spool is:

$$\left(\frac{d}{dt}\mathrm{Ng}\right)= \left[\frac{g}{J_{eng}}\right] \{(m^{\bullet}f\ (t-\lambda) - m^{\bullet}fss*f(\mathrm{Ng}))*\left[\frac{\partial Q}{\partial m^{\bullet} f}*f(\mathrm{Ng})\right]\}\text{............ [1](3)}$$

This equation can be rewritten as the total accelerating torque:

$$\Delta Qg=\left[\frac{J_{eng}}{g}.\frac{2p}{60}\right]*N_{H}^{\bullet}=$$

$$\sum \Delta m^{\bullet} f\left[\frac{\partial Qg}{\partial m^{\bullet} f}*f(Ng)\right] \quad \text{...... (4)}$$

From this equation it can be seen that the torque available to accelerate the engine is the sum of the product of three variables.

Excess fuel is:

$$\sum \Delta m^{\bullet} f=$$

$$m^{\bullet}f\ (t-\lambda) - m^{\bullet}fss*f\ (\mathrm{Ng}) \quad \text{.. (5)}$$

For those more familiar with gas flow model of an engine there is a direct comparison between the flow and the torque/fuel model as follows.

In the gas flow model excess work of gas generator is

$$\frac{d}{dt}(\mathrm{Ng})=\frac{Ke}{J_{eng}}\left[m_4.C_{P4}.h_t.\Delta T_{34}-m_1.C_{P1}h_C.\Delta T_{12}\right] \quad .(6)$$

Gas generator compressor discharge pressure (P2 KPa)

This engine parameter is of a particular interest because it is usually the compressor surge sensitive parameter. A realistic simulation of this parameter would require a gas flow simulation which is very complex. For control purposes it is usually sufficient to use the model shown in figure (3). The equation for P2 derived from the engine characteristic is as follows

$$\mathrm{P2=p2SS*F\ (Ng)} +\{(m^{\bullet}f\ (t-\lambda))- m^{\bullet}fss*f(\mathrm{Ng})*\left[\frac{\partial P2}{\partial m\bullet f}\,f(Ng)\right]\} \quad \text{.. ... (7)}$$

The above partial deferential equation is synthesized from real engine data and represents a single shaft gas generator. As such it is in ideal form for solution by classical methods but it is as well to pause for a moment and consider the more complex situation of compressor surge in an actual aircraft.

The Compressor Discharge pressure (P2) Model

The figure (3) shows the structure of sub-system block that builds up the control system model of the compressor discharge pressure (P2), and the operation of the model is as follows:

1. At line (0), the gas generator speed signal is fed to blocks (1,and 2).
2. The block (1), represents the data from the test bed of the relationship between the steady state values of the compressor discharge pressure (P2), with the gas generator speed (Ng).
3. The block (2), represents the data of the relationship between the compressor discharge pressures to fuel flow rate change $\left(\frac{\partial P2}{\partial m\bullet f}\right)$, with the gas generator speed (Ng), and it represents the transient behavior.
4. The mark (3), represents a multiplicity point between the change of the fuel ($\Delta m^{\bullet}f$=

$(m^{\bullet}f\ (t-\lambda)-m^{\bullet}fss*f\ (Ng))$, and the signal that leaves the block (2).

5. The symbol (4), represent the summing point of the signals after the block (1) and (3).
6. At point (5), the value of the pressure is at time (t-λ), which represents the actual value.
7. The block (6), is the transfer function of the pressure sensor time constant which is a lagging time between the sensed time and the actual time.

$$G_{Psensor}(s)=\frac{1}{1+t_{psensor}*s}, \quad \text{... (8)}$$

8. At point (7), the pressure is sensed as a feedback to the controller and other displays.

Gas generator e gas temperature

Figure (4) shows a typical low speed engine characteristic of the very

Very high gain in engine temperature for a given amount of fuel against the base of the generator speed

The primary time constant for exhaust temperature (T4) sensed value can usually be represented by:

$$G_{tsensor}(s)=\frac{1}{1+t_{tS}*s} \quad \text{... (9)}$$

The equation for exhaust temperature (T4) is similar to that for pressure:

$$T4\ K=T4_{ss}*f\ (Ng)+\{(m^{\bullet}f\ \ (t-\lambda)-m\bullet f\ ss*f\ (Ng))\left[\frac{\partial T4}{\partial m^{\bullet}f}*f(Ng)\right]\} \text{.. (10)}$$

The matlab simulink of Turboshaft gas turbine engine

The matlab simulink program of a Turboshaft gas turbine control system and

The structure of sub-system

Turbine Exit Temperature Model

block that builds up the control system model of the turbine exit temperature (T4). The operation of the model is similar to that of compressor discharge pressure and show in figure (5), below:

the main parameter of that simulink can be described below and shown in figure (6).

1. The block (dqf/dmf), represents the relationship of the torque to fuel change with gas generator speed as shown in figure (3), and then multiplied with the fuel flow change to produce a change in torque (transient part).
2. The block (qfss), represents the steady state value of torque with speed of gas generator . It then adds to the transient part to get a new value of torque.
3. The blocks (gain, gain due to free turbine speed), is a scalar value change with (Nf) and then fed back to interact with other signals.
4. The blocks (gains, gain due to load), is a scalar value and that carry the effect anti-torque from the following equation:

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Power = torque* speed (Nf)*2π/60. Or

$P=Q*\omega f$ ..(11)

Where: $\omega=2\pi*Nf/60$ ..(12)

5. The block (gain2), is the effect of inertia of the free turbine and the coupling or the gear box and to convert the time unit from second to minute.
6. The block (integral 2), plays as an integrator whereas it integrate the acceleration to speed (Nf).

Results and Discussions

The gas turbine engine and for aircraft applications, it must be there is possibility of increasing or decreasing the power at the new set point on command to obtain the thrust required for any operating conditions, in the gas turbine engine the fuel control accomplished this function .The operator select a fuel flow condition by a power lever which in turn causes the fuel control automatic system to schedule fuel flow according to prevailing ambient conditions and engine air mass flow conditions.

Discussion of Turboshaft Gas Turbine Engine Results

The turboshaft gas turbine engine results obtained from the matlab simulink program (which operates under windows XP as an operating system), and from the modeling of the engine components are presented as a figures .

Figure (7), represents the assembled figure of all time responses of the gas generator speed (Ng1,2,3,4,5), at different fuel valve angles one can notice the difference in the response behavior at various power lever position, and shows that the value of speed increase with increasing valve angle and that is a reasonable result because the increasing of energy causes increase the gas atom angular momentum and that increase the absorbed energy from the blades and then increase the speed of the turbine .

Figure (8), represents the combined figure of all time responses of the compressor discharge pressure at various fuel valve one can notice the difference in the response behavior at various set points of power lever settings, one can be notice the characteristics of the response clearly and there is no significant overshoot.

Figure (9), represents the combined figure of all time responses of the turbine exit temperature at variable fuel valve. The overshoot increase with valve angle and the other specifications are decreases.

A verification of the developed models of the presented work is presented here through a comparison between the results of this work and the theoretical or experimental results of a pervious works.

Figure (11) represents the comparison between the Turbine Exit Temperature (T4) of the present work and the results of previous works presented in reference [5], at fuel valve angle of fifty degrees. The response delay time and rise time of both works are having excellent matching. The respond of the presented

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work has a small value of overshoot larger than the that of reference[5], and that coming from the real data used in this work, in spite of that the figures shows a reasonable matching between them.

Figure (10) represent the free turbine rotational speed and the control system .

Concluding Remarks

In the previous statements the following conclusions are obtained from those results:

1. It is obvious that the delay time of the responses of the free turbine spool speed, compressor discharge pressure, exhaust temperature, and the gas generator spool speed decrease with the increase of the power lever position (increase the fuel valve angle). The decrease in the delay time is due to the behavior of the fuel pump time constant, the combustion dead time, the sensors time constant where the value of these time constants decrease with gas generator spool speed and that leads to a decrease in the value of the delay time.
2. The maximum overshoot value of the time response of the exhaust temperature increase while the fuel valve angle increase. This is due to the cumulative energy of the combusted fuel and the spool speed is less sensitive because of the inertia effect of the rotor of the engine.

tend to keep that speed at an approximately fixed value (with small offset), to keep the local grid frequency at a fixed value (because the relationship between them is linear)as in equation(1).

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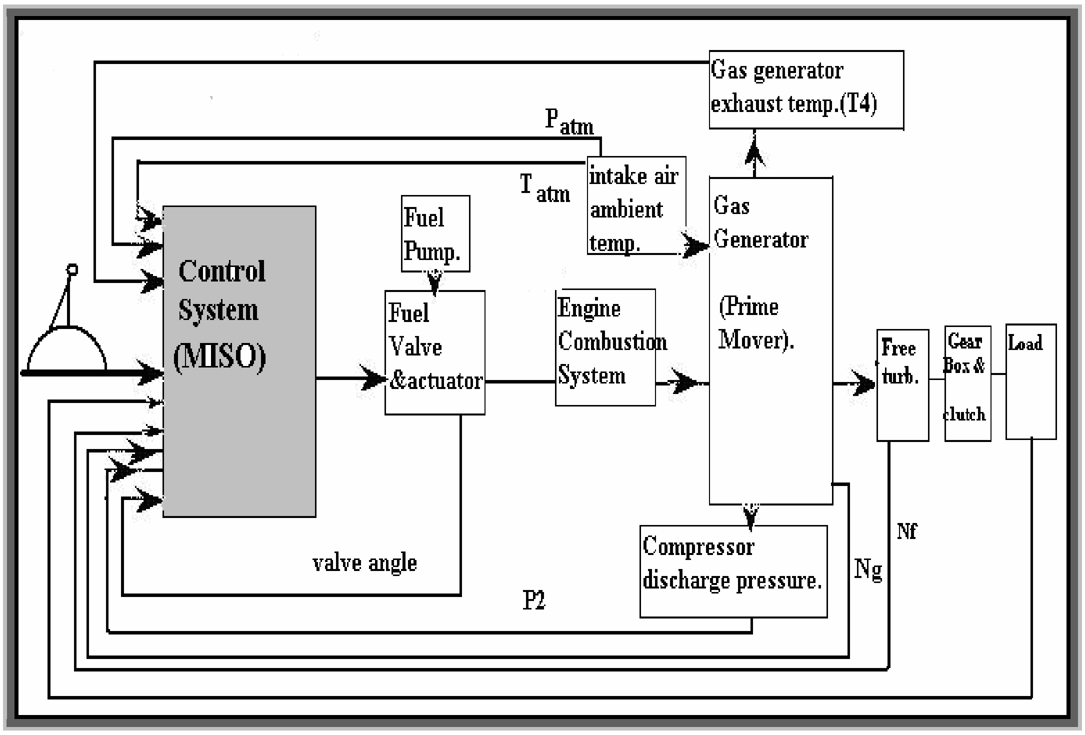

Figure (1) Overall Turbo shaft schematic control system [1].

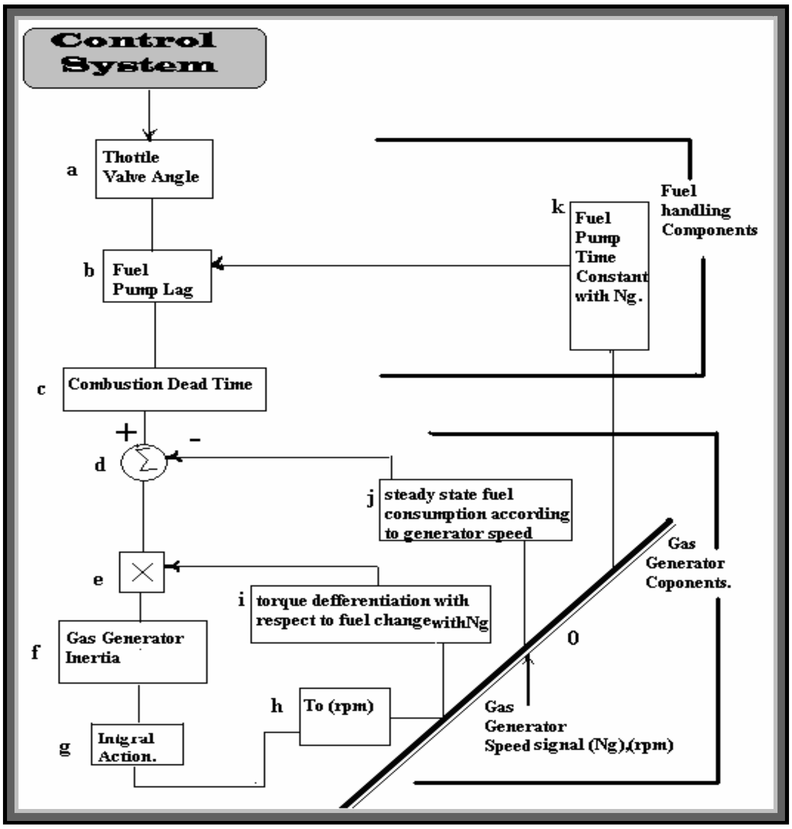

Figure (2) Basic Engine Components.

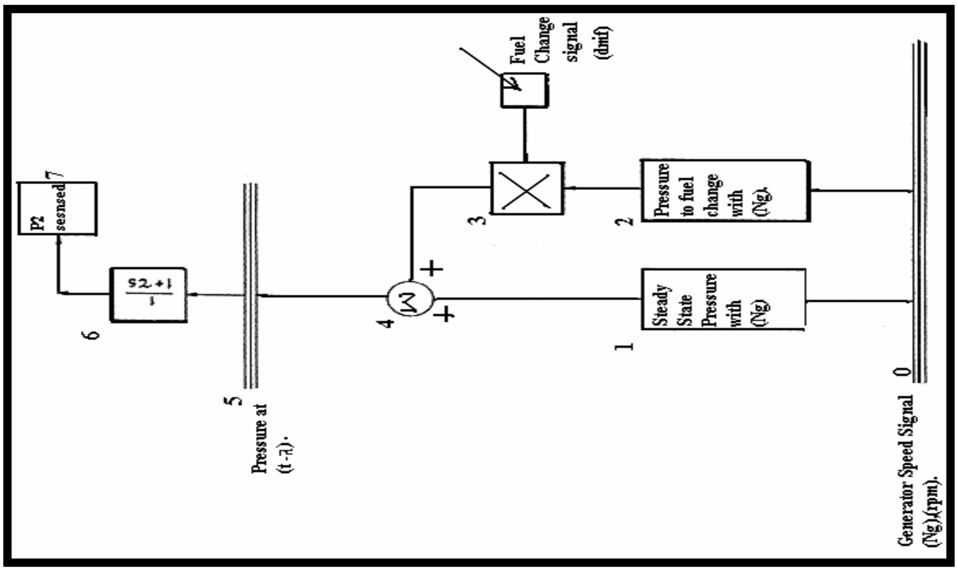

Figure (3) Model of Compressor discharge pressure (P2).

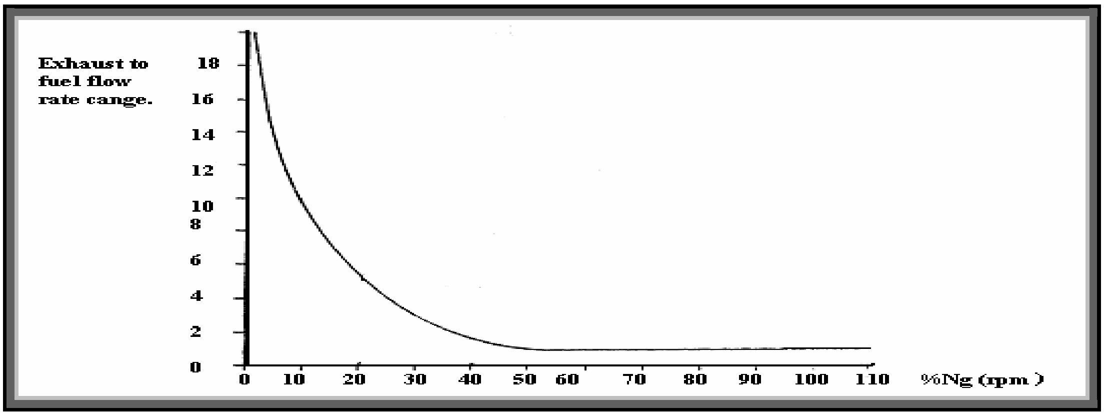

Figure (4) Temperature to fuel change with generator speed [1].

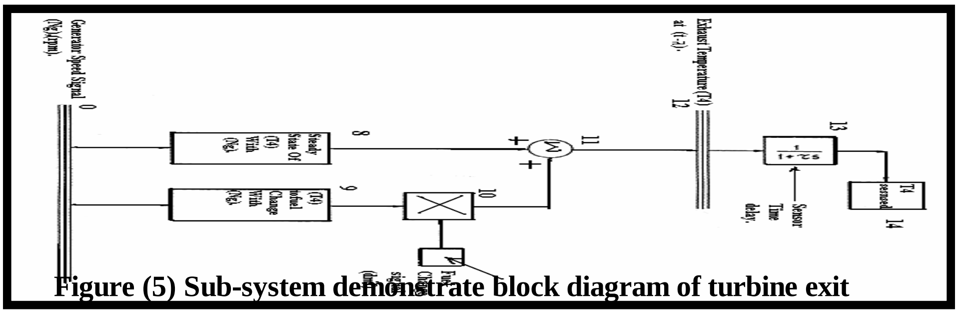

Figure (5) Sub-system demonstrate block diagram of turbine exit temperature (T4).

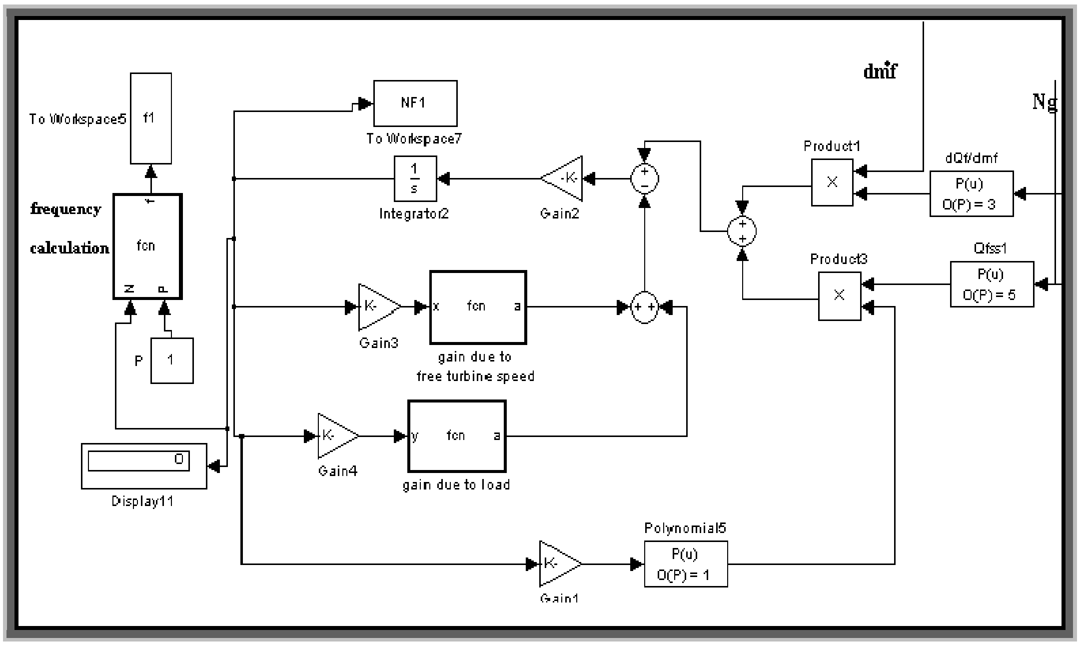

Figure (6) Matlab simulink sub-system of load.

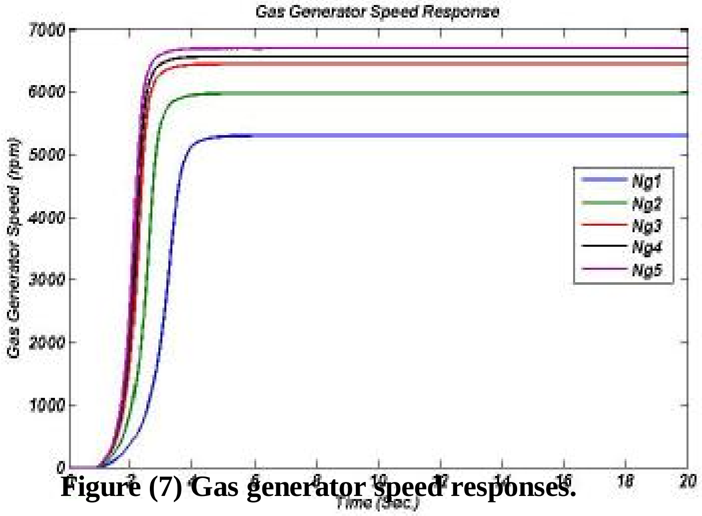

Figure (7) Gas generator speed responses.

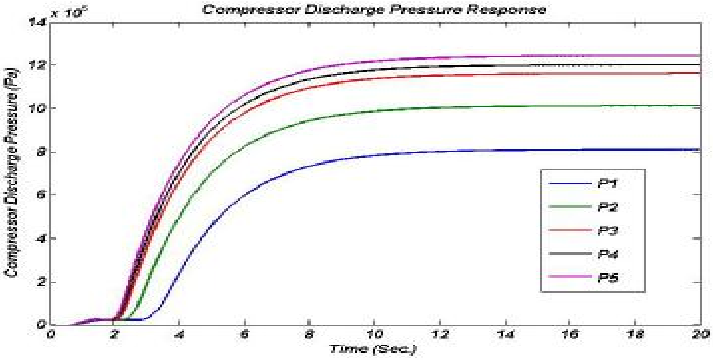

Figure (8) Compressor discharge pressure response.

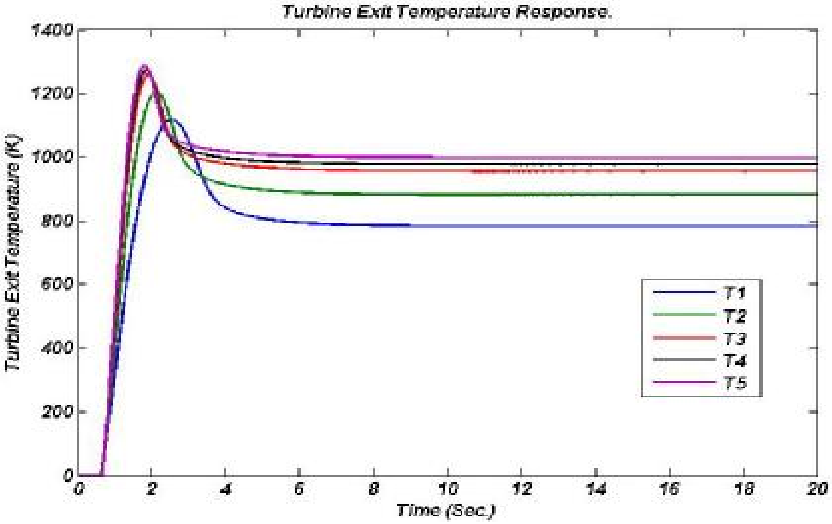

Figure (9) Turbine exit temperature response.

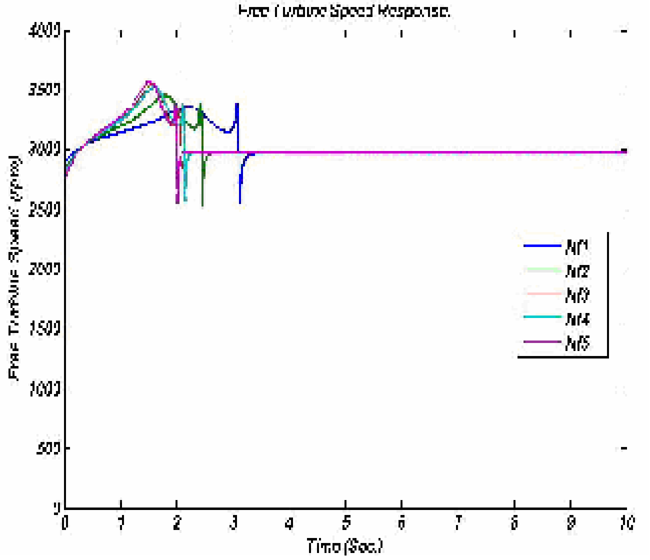

Figure (10) Free turbine speed response.