TRANSIENT PERFORMANCE OF A SINGLE-SPOOL TURBOJET ENGINE

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ABSTRACT

The transient performance (acceleration and deceleration) analysis of turbojet gas turbine engine has been carried out in the present work. Transient simulation of the engines is based on the compatibility of flow and rotational speed but not of work. Gas turbine simulation is a general-purpose simulation developed for steady state (matching) study. Matching is achieved by zeroing the difference in mass flow rate of adjacent components, and work of compressor-turbine pairs. Steady state is taken as an initial condition for transient simulation of the engine. The factors indicating engine limits such as surge margin, engine maximum temperature, and combustion chamber flameout that affect transient response has been studied. The results show that there is sudden change in the investigated parameters during transient operation, except for the rotational speed and the engine flow rate. Increasing the compressor surge margin and /or maximum turbine inlet temperature improves engine acceleration and decreases the acceleration time. Comparison with previous experimental work showed good agreement.

الخلاصة

في هذا البحث،تمت دراسة وتحليل أداء ومحاكاة الحالة غير المستقرة (التعجيل والتباطؤ) لمحرك توربيني نفاث حيث اعتمدت المحاكاة للحالة غير المستقرة على التطابق بالجريان والسرعة الدورانية لا على التطابق بالشغل . محاكاة التوربين الغازي تستخدم بصورة عامة للحالة المستقرة والتي تعتمد على الموائمة لاجزاء المحرك والانسجام مع خرائط هذه الأجزاء .أنجزت الموائمة بالوصول ألى إلغاء الفرق بالجريان للأجزاء المتجاورة والغاء الفرق بالشغل لكل زوج من التوربين والضاغطة .تستخدم حسابات الحالة المستقرة كظروف ابتدائية لحسابات الأداء للحالة غير المستقرة . تضمنت الدراسة أيضا معرفة تأثير العوامل التي تحدد استجابة المحرك للحالة غير المستقرة مثل منطقة التمور ودرجة الحرارة المحرك القصوى وإنطفاء غرفة الاحتراق ، وتم رسم مساقط الحالة غير المستقرة . أظهرت النتائج تغيراً في كل المتغيرات التي تمت دراستها أثناء التشغيل العابر عدا السرعة الدورانية ومعدل تدفق الهواء . كما بينت أن زيادة حد منطقة التمور للضاغطة ودرجة الحرارة الدخول للتوربين حسنت من التعجيل المحرك وقللت من وقت التعجيل. أظهرت مقارنة

النتائج مع نتائج عملية سابقة تطابقاً جيداً. تمت مقارنة النتائج الحالية مع النتائج العملية والنظرية للبحوث السابقة وأظهرت توافق كبير مع هذه النتائج.

KEY WORDS

Turbojet Engine, Single Spool, Transient Performance

INTRODUCTION

The aircraft gas turbine engine is usually checked at steady state operating condition on the test bed and ground test while flight tests deal mainly with engine transient operation. Also, there are applications where a rapid response is desirable in cases where emergencies are to be avoided. Under these circumstances, power change must occur quickly and safely and therefore a knowledge of the dynamic response of the engine is required during design phase so that a control system can be designed to give the required response rate and safety margins.

The importance of good acceleration and deceleration behavior or handling from aircraft gas turbine engine is well known throughout the industry and particular attention must be given to the subject at all phases of an engine development, from an initial concept through the effect of deterioration during service (Maltby 1987).

In the aircraft engines, the pilot interacts with the engine by setting the position of a power lever, which in turn makes an input to the control system, but the pilot does not directly control any of the control variables such as fuel flow rate. Instead, the power lever position select a thrust level from idle to maximum and control manipulates the control variables to give the desired thrust level. But the more excess or deficiency in the fuel flow rate may cause the damage of the engine due to compressor surge, turbine blade melting, or flameout the combustion chamber.

The aim of this work is to develop a computational model for the investigation of the transient performance of the turbojet gas turbine engine and understanding of the influence of engine control system on the engine performance during changing the throttle setting. Also to explain the events taking place during the transient phase of gas turbine engine operation when components operate close to their performance limits. In particular, surge in the compressors, high temperatures in the turbines and, in some cases, rotor over speeding.

OFF-DESIGN PERFORMANCE

The performance prediction methods for aircraft vary from simple methods to be used in early preliminary design studies to sophisticated methods based on detailed procedures on the characteristic of aircraft and engines derived from test data. In these off design conditions the component efficiencies are assumed be known with the same values required for design point calculations. The following assumptions are made throughout this work, see **Fig. (1)**

a- Constant specific heats for air and for combustion gases, upstream and down stream of the combustion chamber.

b- The pressure drop through the burner is function of compressor pressure ratio only.

The compressor pressure ratio can be found from the work balance between the compressor and turbine as follows (Mattingly1996)

$$\dot{m}_2 cp_c \left(T_{t3} - T_{t2}\right) = \eta_m \dot{m}_4 cp_t \left(T_{t4} - T_{t5}\right) \qquad (1)$$

$$\left(\tau_c - 1\right) = \frac{T_{t2}}{T_{t4}} \left[\frac{cp_t}{cp_c} \eta_m \left(1 + f\right)\left(1 - \tau_t\right) \right] \qquad (2)$$

The term in square brackets can be considered constant if turbine temperature ratio (τ_t) is constant (the case of choked exhaust nozzle).

Thus;

$$\tau_c = 1 + \frac{(T_{t4}/T_{t2})}{(T_{t4}/T_{t2})_R}(\tau_{cR} - 1) \tag{3}$$

$$\pi_c = \left[1 + \frac{(T_{t4}/T_{t2})}{(T_{t4}/T_{t2})_R}\left(\pi_{cR}^{\frac{\gamma_c}{\gamma_c - 1}} - 1\right)\right]^{\frac{\gamma_c - 1}{\gamma_c}} \tag{4}$$

An equation for engine mass flow rate can be obtained from flow compatibility between the compressor and turbine and from the mass flow parameter (MFP(M)) at turbine inlet (choked flow) as follows;

$$\dot{m}_0 = \dot{m}_2 = \frac{\dot{m}_4}{(1+f)} \tag{5}$$

$$\dot{m}_0 = \frac{P_0 \pi_r \pi_d \pi_c}{\sqrt{T_{t4}}}\left[\frac{\pi_b A_4}{(1+f)} \mathrm{MFP}(1)\right] \tag{6}$$

The terms within the square brackets are considered constant thus;

$$\frac{\dot{m}_0 \sqrt{T_{t4}}}{P_0 \pi_r \pi_d \pi_c} = \frac{\pi_b A_4}{(1+f)} \mathrm{MFP}(1) = \left(\frac{\dot{m}_0 \sqrt{T_{t4}}}{P_0 \pi_r \pi_d \pi_c}\right)_R \tag{7}$$

Solving for the engine mass flow rate, gives;

$$\dot{m}_0 = \dot{m}_{0R} \frac{P_0 \pi_r \pi_d \pi_c}{(P_0 \pi_r \pi_d \pi_c)_R} \sqrt{\frac{T_{t4R}}{T_{t4}}} \tag{8}$$

From compressor design analysis the loading coefficient is given by (Agrawll and Yunis1982);

$$\psi = \frac{cp_c (T_{t3} - T_{t2})}{(\omega r)^2} \tag{9}$$

$$\tau_c - 1 = K_\psi N_{c2}^2 \tag{10}$$

Where;

$$K_\psi = \psi \left(\frac{2\pi r}{60}\right)^2 \frac{cp_c}{T_{ref}} \tag{11}$$

And ;

$$N_{c2} = \frac{N}{\sqrt{\theta_2}} \tag{12}$$

The compressor temperature ratio is related to the compressor pressure ratio through the efficiency by;

$$(\tau_c - 1) = \eta_c \left(\pi_c^{\frac{\gamma_c - 1}{\gamma_c}} - 1 \right) \tag{13}$$

Combining eqs. (10), (12) and (13), rearranging into variable and constant terms, and equating the constant to reference values gives;

$$\frac{\pi_c^{\frac{\gamma_c-1}{\gamma_c}} - 1}{N_{c2}^2} = \frac{K}{\eta_c} = \frac{\pi_{cR}^{\frac{\gamma_c-1}{\gamma_c}} - 1}{N_{c2R}^2} \tag{14}$$

$$N = N_R \sqrt{\frac{\tau_r}{\tau_{rR}} \frac{\pi_c^{\frac{\gamma_c-1}{\gamma_c}} - 1}{\pi_{cR}^{\frac{\gamma_c-1}{\gamma_c}} - 1}} \tag{15}$$

TRANSIENT OPERATION

During transient operation, the gas turbine can be considered to satisfy compatibility of flow and rotational speed but not of work. The excess or deficiency of power applied to the rotor can be used to calculate its acceleration or deceleration. The problem then becomes one of calculating increments of net torque associated with increments of fuel flow and integrating it to find the change of rotor speed (Palmer and Yong-Gen 1985).

The following assumptions are made for the calculation of transient operation;

a- The flow through the turbine nozzle is choked along transient period.
b- The efficiency of all components is constant.
c- Combustion chamber pressure drop is constant.
d- All components are of fixed geometry.
e- The torque available is constant through a small time step.
f- The surge margin is between the pressure of surge line and pressure of steady state at constant corrected mass flow.

In the transient conditions time is introduced as a further variable into the dynamic equation of engine and so the balance constraint conditions can no longer be applied. The difference between delivery power of the turbine and power absorbed by the compressor will generate a derivative of rotational speed with respect to time (i.e. acceleration or deceleration). From Newton's second law of motion the relation between excess torque (ΔG) and angular acceleration $(\dot{\omega})$ is (Palmer and Yong-Gen 1985);

$$\Delta G = I\dot{\omega} \tag{16}$$

$$\dot{\omega} = \frac{2\pi}{60} \frac{dN}{dt}. \tag{17}$$

Also;

$$\Delta G = G_t - G_c \tag{18}$$

$$G_t = \dot{m}_0 (1+f) \Delta H_t / \omega = \dot{m}_0 (1+f) \Delta H_t \frac{30}{\pi N} \tag{19}$$

$$G_c = \dot{m}_a \Delta H_c / \omega = \dot{m}_a \Delta H_c \frac{30}{\pi N} \qquad (20)$$

Therefore;

$$\dot{m}_a (1+f)\Delta H_t - \dot{m}_a \Delta H_c = \left(\frac{\pi}{30}\right)^2 I \cdot N \cdot \frac{dN}{dt} \qquad (21)$$

To obtain the power of the turbine ($\dot{m}_a(1+f)\Delta H_t$ (and the power of the compressor) $\dot{m}_a \Delta H_c$ (considering the acceleration between two operating points on the running line of the compressor characteristic. When the engine is accelerated the fuel flow and thus the turbine entry temperature is increased as follows:

$$f = \frac{\dot{m}_f + \Delta\dot{m}_f}{\dot{m}_o} \qquad (22)$$

Where $\dot{m}_f$:steady state fuel mass flow rate, and $\Delta\dot{m}_f$:increase in fuel mass flow rate.

And from energy balance through the burner, the turbine inlet temperature T_{t4} is;

$$T_{t4} = \frac{cp_c T_{t3} + f \cdot h_{PR} \cdot \eta_b}{cp_t (1+f)} \qquad (23)$$

The turbine pressure and temperature ratios can be calculated from eq.(18), then the power of the turbine can be calculated as;

$$\dot{m}_o (1+f)\Delta H_t = \dot{m}_o cp_t (1+f) T_{t4} (1-\tau_t) \qquad (24)$$

The increase in the turbine inlet temperature can provide an increase in the turbine torque resulting in an increase in spool speed. However due to inertia of the spool the speed will not change instantaneously. Since the turbine nozzle is choked and its capacity measured as ($\dot{m}_o\sqrt{T_{t4}} / P_{t4}A_4$) is therefore fixed. The rise in turbine entry temperature (T_{t4}) must be matched by either a fall in mass flow or a rise in the pressure ratio, the result is a rise in the compressor pressure ratio towards the surge line. This rise can be obtained as follows;

From flow compatibility, the air mass flow rate through the compressor plus the fuel mass flow rate is equal to that through the turbine i.e.;

$$\dot{m}_o (1+f) = \dot{m}_4 \qquad (25)$$

And from eqs. (6) and (7) gives;

$$\frac{\dot{m}_4\sqrt{T_{t4}}}{P_{t4}} \frac{\pi_c P_{t2}}{\dot{m}_o} = (1+f_x)\frac{\sqrt{T_{t4x}}}{\pi_{cx}} \qquad (26)$$

$$\pi_c = \pi_{cx} \frac{(1+f)}{(1+f_x)} \sqrt{\frac{T_{t4}}{T_{t4x}}} \qquad (27)$$

$$\tau_c = \left[\frac{\left(\pi_c^{\frac{\gamma-1}{\gamma}} - 1 \right)}{\eta_c} - 1 \right] \qquad (28)$$

It must be noted that the step of fuel mass flow increase is limited by the surge line and/or the maximum turbine inlet temperature, see **Fig. (2)** When the amount of fuel flow is increased, which is generally following the change in the position of power lever, the control system of the engine will limit the increase in fuel flow. The control system gives the engine (combustion chamber) steps of fuel flow proportional to the compressor surge line and maximum turbine inlet temperature at that rotational speed.

The power of the compressor then can be obtained as;

$$\dot{m}_0 \Delta H_c = \dot{m}_0 cp_c T_{t2} (\tau_c - 1) \qquad (29)$$

Substituting eqs. (24) and (29) into eq.(21) gives;

$$\frac{dN}{dt} = \frac{\dot{m}_0}{\left(\frac{\pi}{30}\right)^2 I \cdot N} \left[cp_t T_{t4} (1 - \tau_t) - cp_c T_{t2} (\tau_c - 1) \right] \qquad (30)$$

A numerical solution can be adopted to solve eq. (30) to find the increase in the rotational speed. Modified Euler method can be applied with time step (Δt) which can be selected in the range from 0.001 to 0.1 second without instability problems

$$N_{i+1} = N_i + \frac{1}{2}(K_1 + K_2) \qquad (31)$$

Where

$$K_1 = \Delta t \cdot f(t_i, N_i) \qquad (32)$$

$$K_2 = \Delta t \cdot f(t_{i+1}, N_i + K_1) \qquad (33)$$

$$f(t, N) = \frac{\dot{m}_0}{\left(\frac{\pi}{30}\right)^2 I \cdot N} \left[cp_t T_{t4} (1 - \tau_t) - cp_c T_{t2} (\tau_c - 1) \right] \qquad (34)$$

An increase in rotor rotational speed will be followed by an increase in air mass flow rate ($\dot{m}_0$) as follows;

$$\dot{m}_0 = \rho A_{ann} V_a = \frac{P}{R \cdot T} A_{ann} V_a \qquad (35)$$

$$V_a = \pi \cdot N \cdot D \cdot \Phi \qquad (36)$$

$$\dot{m}_0 = \frac{\delta}{\theta} \frac{A_{ann} \cdot \pi \cdot N \cdot D \cdot \Phi}{R} \frac{P_{ref}}{T_{ref}} \qquad (37)$$

$$\dot{m}_0 = \dot{m}_{0R} K_\Phi \frac{\sqrt{\theta_{2R}}}{\sqrt{\theta_2}} \frac{N}{N_R} \qquad (38)$$

K_Φ is obtained from steady state performance using interpolation method This procedure is repeated many times to provide a transient running line (acceleration) starting from convenient equilibrium running point. The safety margin between the acceleration running line and surge line is about 14%. During deceleration the operating point moves a way from surge line and the turbine inlet temperature is decreased. The only problem that arises is "flame-out" of the combustion chamber because of very week mixtures. The main parameters affecting the operation of a single-spool turbojet engine is shown in **Fig (3).**

Results and Discussion.

Fig. (4) presents the fuel mass flow ($\dot{m}_f$) with compressor corrected mass flow ($\dot{m}_{c2}$) at steady state and transient operation. The fuel flow normally follows a power lever position change. During acceleration, the acceleration line is characterized by four stages. The first stage is a sudden rise in fuel flow rate at constant corrected mass flow due to the sudden opening of the fuel valve. The second stage is an increase of fuel flow with increase of the corrected mass flow. This stage is limited by the compressor surge line. The third stage is limited by the maximum turbine inlet temperature, in which the slope of increasing of the fuel flow is less than the slope of the previous stage. The fourth stage is a constant fuel mass flow rate i.e. the change in fuel flow by control system is equal only to the required change. During deceleration, the deceleration line is characterized by the three stages. The first stage is the sudden decrease in the fuel flow rate at constant corrected mass flow. The second stage is a decrease of the fuel flow with the decrease of the corrected mass flow and this stage limited by flameout of the combustion chamber. The third stage is a constant fuel flow.

Fig. (5) presents the compressor pressure ratio (π_c) with compressor corrected mass flow ($\dot{m}_{c2}$) at steady state and transient operation. The acceleration line is also characterized by four stages. The first stage is the sudden rise in compressor pressure ratio to match the rise in the turbine inlet temperature. The second stage is an increase of compressor pressure ratio with the increase of the corrected mass flow and this stage is limited by the compressor surge line. The third stage is limited by the maximum turbine inlet temperature, in which the slope of increasing of the compressor pressure ratio is less than the slope of the previous stage. The fourth stage is a rise of compressor pressure ratio to reach the steady state value at the end of acceleration. The slope of increasing of the compressor pressure ratio is also less than the slope of the previous stage. The deceleration line is characterized by three stages. The first stage is a sudden decrease in compressor pressure ratio at constant corrected mass flow. The second stage is a decrease of the compressor pressure ratio with the decrease of the corrected mass flow and this stage is limited by flameout of the combustion chamber. The third stage is a decrease of the compressor pressure ratio with the decrease of the corrected mass flow to reach steady state at the end of deceleration.

Fig. (6) presents the main fuel mass flow ($\dot{m}_f$) with time at acceleration and deceleration. There is a time lag with fuel flow change in both acceleration and deceleration, this time comes from a power lever transducer time lag and fuel system time lag.

Fig. (7) presents the turbine inlet temperature (T_{t4}) with time at acceleration and deceleration.). The acceleration line is also characterized by four stages. The first stage is the sudden rise in turbine inlet temperature due to the increase of fuel flow rate. The second stage is increase of turbine inlet temperature with the increase of the time and this stage is limited by the compressor surge line. The third stage is limited by the maximum turbine inlet temperature, in which the turbine inlet temperature is constant. The fourth stage is a decrease of turbine inlet temperature to reach steady state value at the end of acceleration. During deceleration the stages are a sudden decrease in turbine inlet temperature at constant rotational speed, a decrease limited by flameout of the combustion chamber limitations, and then the rise of turbine inlet temperature to reach the steady state at the end of deceleration. The change in the fuel flow rate will change the energy releases from the combustion chamber and then it will change the turbine inlet temperature. The change of fuel flow inside the combustion chamber will lead to another time lag, which is the combustion dead time. This lag time usually happens due to an increasing of the fuel flow rate (during acceleration only).

Fig. (8) presents spool rotational speed (N) with time (t) at acceleration and deceleration. The change in the rotational speed at a beginning of transient is large as the net torque available for transient is a large and decreases with an increase of the time, therefor the rotational speed change becomes slowly at the end of the transient operation. No distinctive stages during acceleration and deceleration can be found and the change in the rotational speed is nearly continues with the time.

A comparison between the calculated values in the present work and an experimental values of a pervious work (Craij et al 1953) has been made. The comparison shows the variation with time of the rotational speed N **Fig. (9)**, compressor pressure ratio π_c **Fig. (10)**, and the turbine exit total temperature Tt_5 **Fig. (11)**. The comparison shows a good agreement.

Concluding Remarks

For turbojet engines during transient operation (acceleration and deceleration), there is sudden change in the fuel flow rate, turbine inlet temperature, compressor pressure ratio, turbine torque, compressor torque, net torque, angular acceleration, thrust, and specific fuel consumption. There is no sudden change in the rotational speed, engine mass flow rate, corrected mass flow. Increasing of the compressor surge margin and/or maximum turbine inlet temperature improve engine acceleration and decrease the acceleration time.

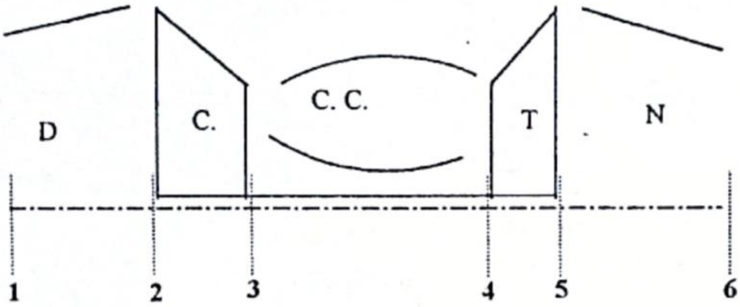

Figure (1). Schematic Diagram of Single-spool Turbojet Engine.

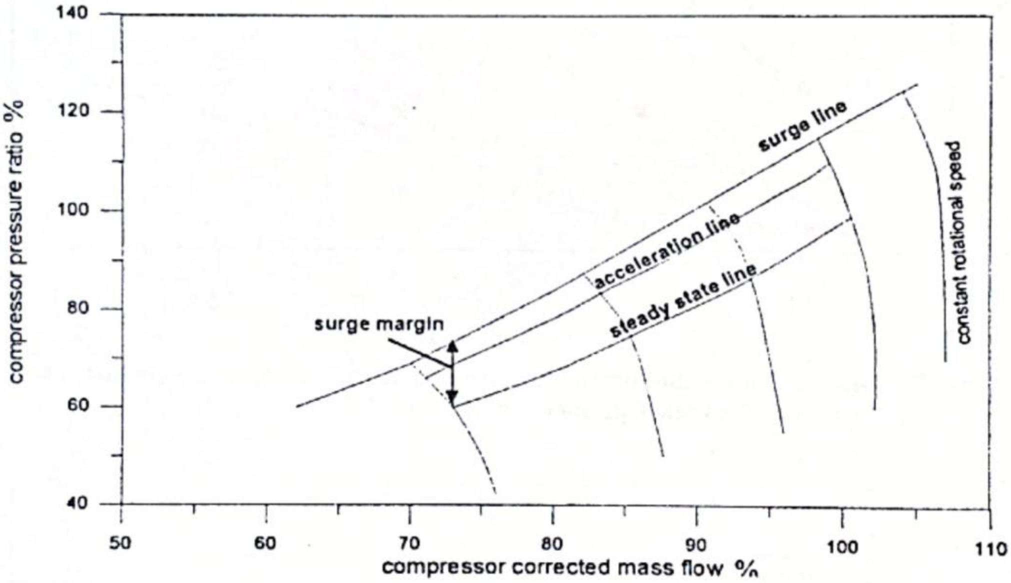

Figure (2): Compressor Map Characteristics

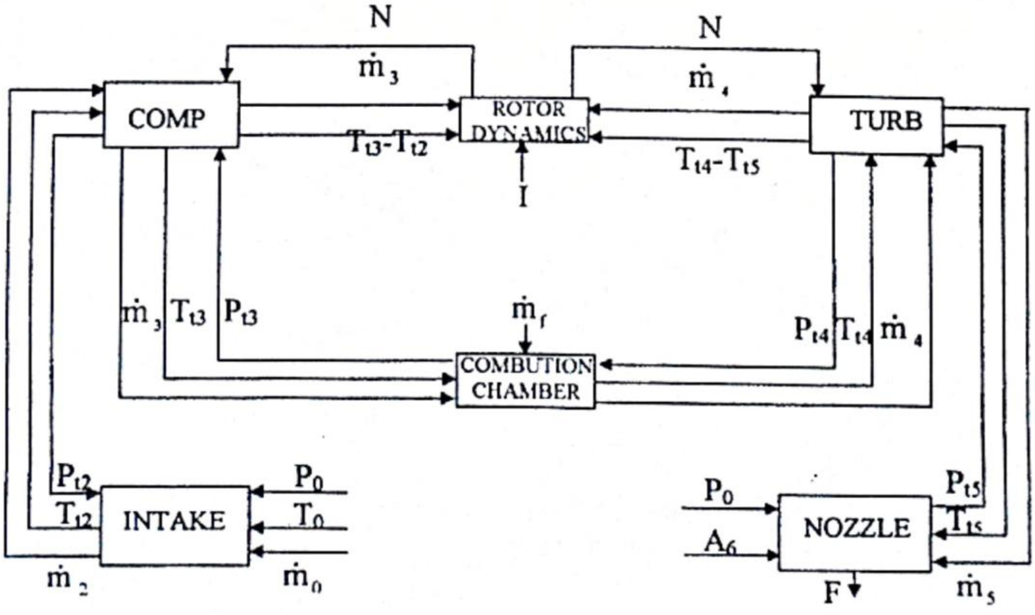

Figure (3): Single-Spool Turbojet Flow Chart

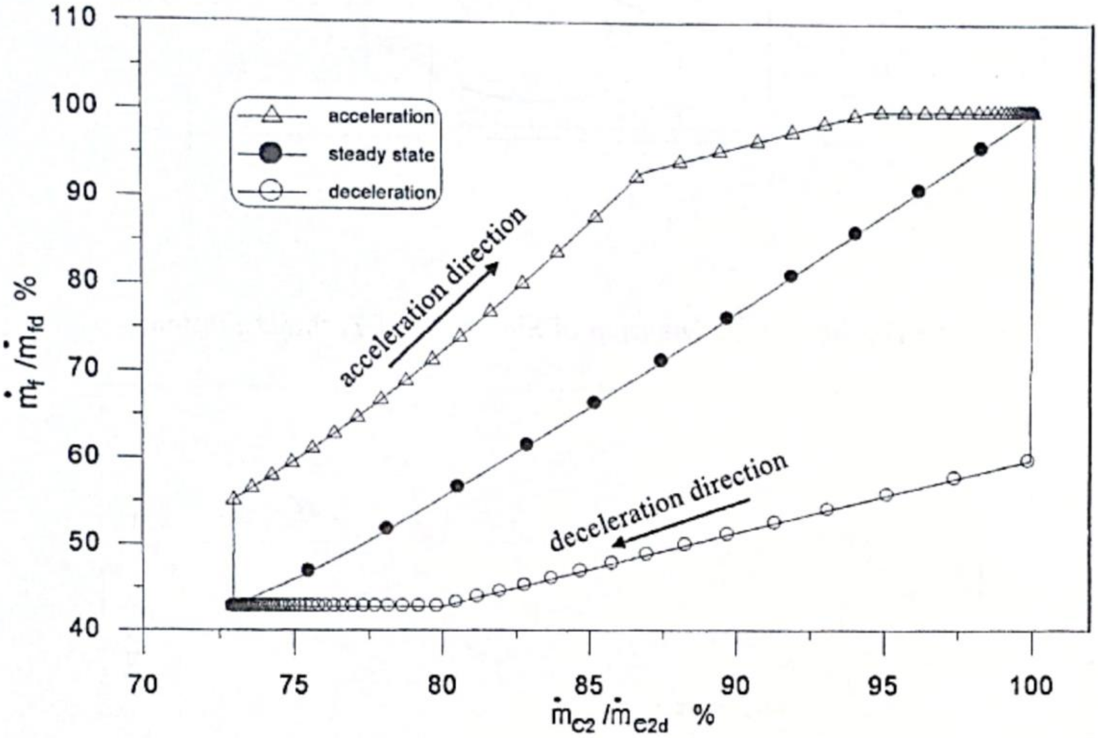

Figure (4) Main Fuel Flow with Compressor Corrected Mass Flow rate at Steady State and Transient Operation for a Turbojet Engine.

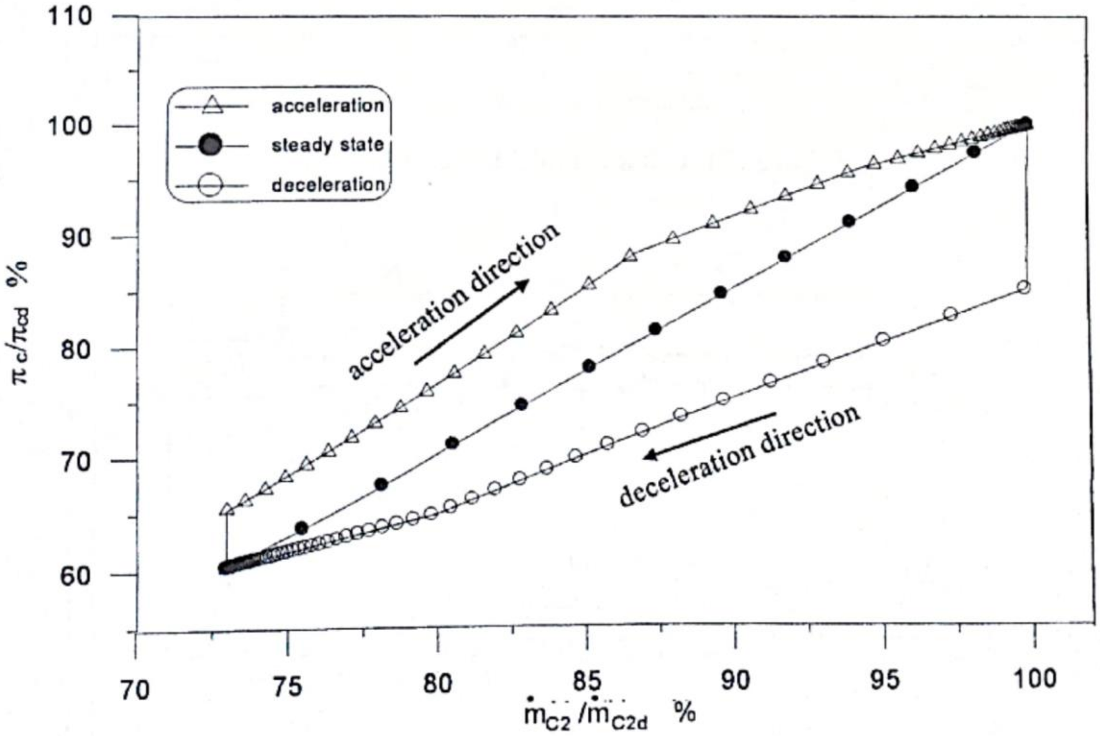

Figure (5) Compressor Pressure Ratio with Compressor Corrected Mass Flow Rate at Steady State and Transient Operations for a Turbojet Engine

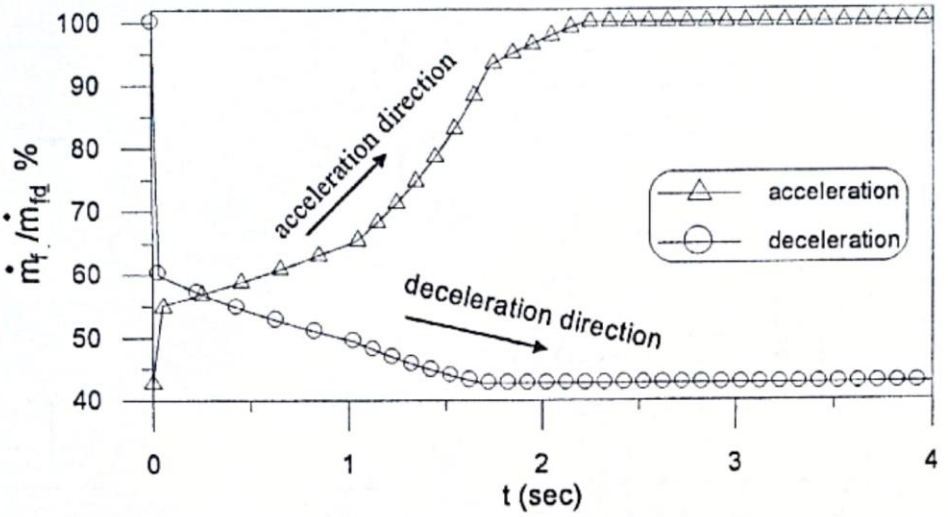

Figure (6) Fuel Flow Rate with Time at Acceleration and Deceleration for a single-spool Turbojet Engine.

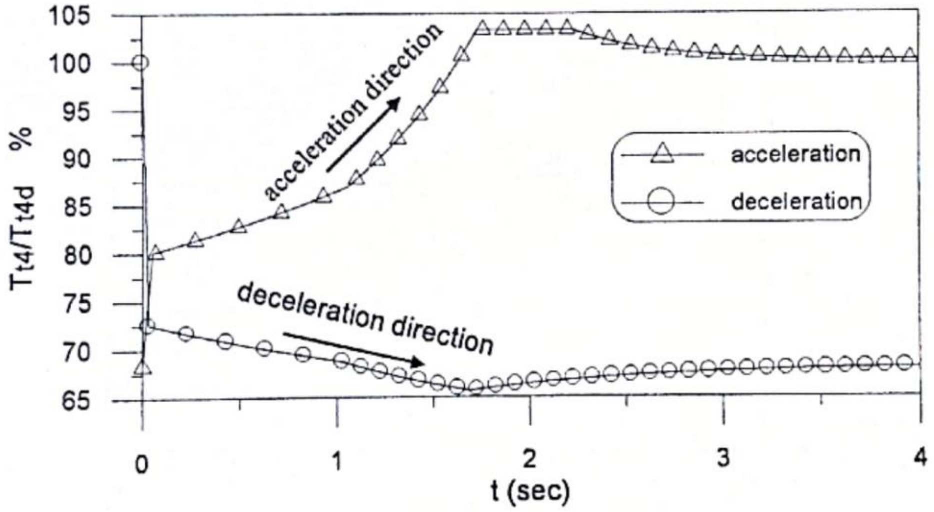

Figure (7) Turbine Inlet Temperature with Time at Acceleration and Deceleration for a single-spool Turbojet Engine.

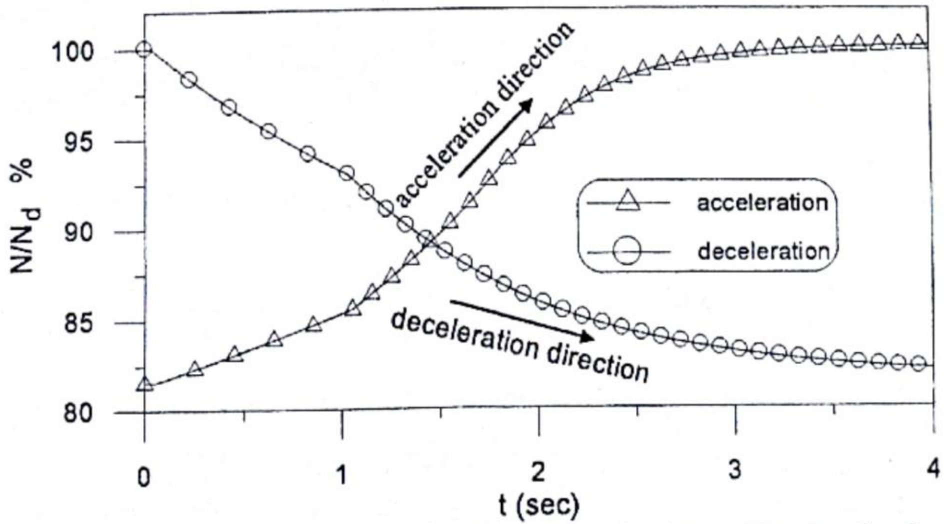

Figure (8). Rotational Speed with Time at Acceleration and Deceleration for a single-spool Turbojet Engine.

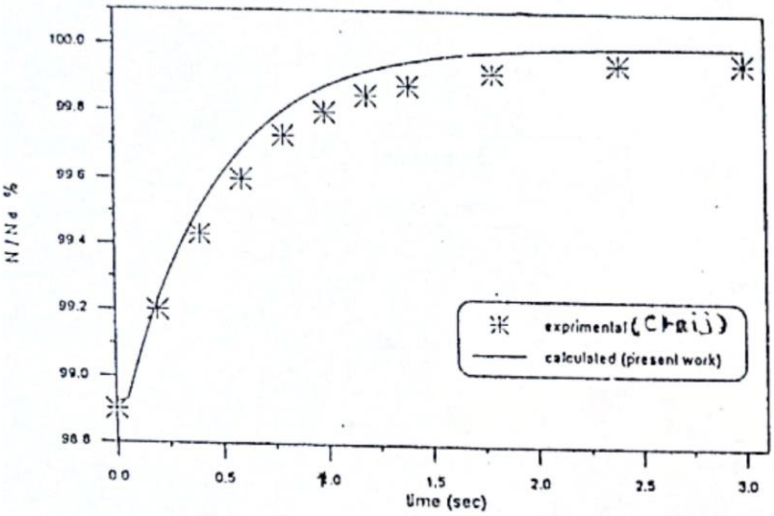

Figure (9). Rotational Speed with Time at acceleration for a Turbojet Engine.

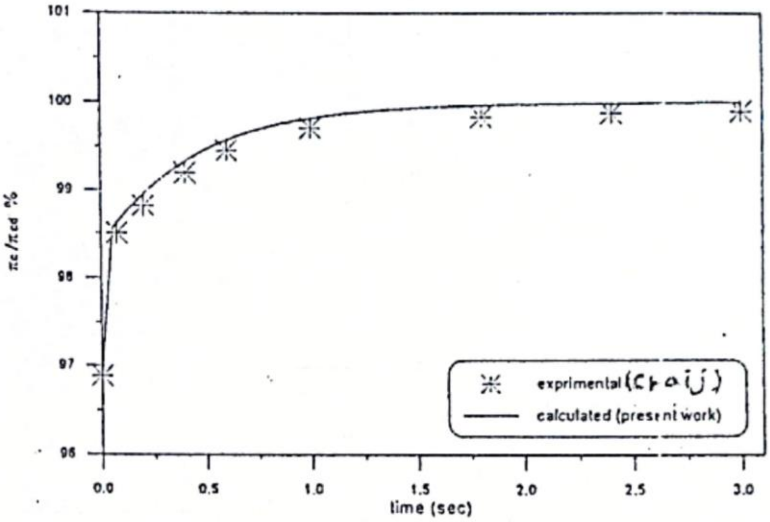

Figure (10). Compressor pressure ratio with Time at acceleration for a Turbojet Engine.

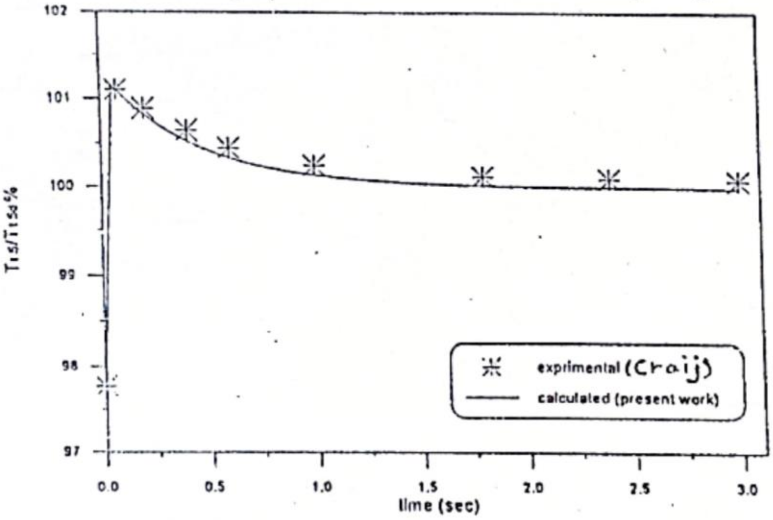

Figure (11) Turbine Exit Temperature with Time at acceleration for a Turbojet Engine.

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NOMENCLATURE

Latin Symbol

A	Area [m^2]
Cp	specific Heat [kJ/(kg.K)]
D	Diameter [m]
e	Polytropic Efficiency
F	Thrust [kN]
f	Fuel/Air Ratio
G	Torque [N.m]
g	Acceleration of Gravity [m/s^2
H	Enthalpy [kJ/(kg.K$^{\circ}$)]
H_{PR}	Fuel Calorific Value [kJ/(kg)]
I	Polar Moment of Inertia [kg.m^2]
M	Mach Number
MFP	Mass flow parameter
N	Rotational Speed [rev/min
P_t	Stagnation Pressure [kN/m^2]
R	Gas Constant [kJ/(kg.K$^{\circ}$)]
S	Specific Fuel Consumption
t	Time [sec]
T_t	Stagnation Temperature [K$^{\circ}$]
V	Axial velocity [m/s]
W	Work [kW]

Greek Symbols

Δ	Difference [m/s]
γ	Specific Heat Ratio
η	Isentropic Efficiency
θ	Corrected Temperature (T_t/T_{ref})
δ	Corrected Pressure (P_t/P_{ref})
ρ	Density [kg/m^3]
τ	Temperature Ratio (T_t exit /T_t inlet)
π	Pressure Ratio (P_t exit /P_t inlet)
$\dot{m}$	Mass Flow Rate
ω	Angular Velocity [rad/s]
$\dot{\omega}$	Angular Acceleration [rad/s^2]
Φ	Flow Coefficient

Subscript

a	Atmospheric conditions
b	Burner
C	Corrected
c	Compressor
t	Turbine
f	Fuel
m	Mechanical
n	Nozzle
R	Reference (Design Condition)
s	Isentropic