GAS TURBINES TRANSIENT PERFORMANCE STUDY FOR AXIAL COMPRESSOR OPERATION CHARACTERISTICS

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Abstract. *At design point the gas turbines operate efficiently and safely because all their components are well matched and the flow aligned with the blades passages to avoid high losses. Unfortunately, gas turbines are required to operate at off-design over a wide range of operation conditions, which depend on the engine applications whether at land, sea or air, both civil and military. The components matching should be analyzed for engine performance improvement. In this work, the results of transient performance simulation are evaluated based in the axial compressor characteristic operation specially designed with VIGV to improve its efficiency, so two different computational codes are used, one to calculate the compressor design and off-design characteristics and other to calculate the engine transient performance. The model used in the transient calculation considers the shaft and volume transient phenomena.*

Keywords: *Gas turbine, propulsion, axial Compressor, transient simulation, performance, variable geometry and design.*

1. INTRODUCTION

The gas turbine operation behavior depends on the efficiency of its components like compressor, combustion chamber and turbine. A good matching among gas turbines components result in good fuel consumption and good efficiency at all operation conditions of interest for both steady-state and transient regimes. All components are designed to operate efficiently at design point, but unfortunately at off-design the efficiency deteriorates.

Some factors contribute directly to the gas turbines technology: the improvement of the metallurgy allowing operations at high turbine inlet temperature; the development of the aero-thermodynamic models for the blade profile design with low losses (friction and separation) and the cooling of turbine blades.

The new computer hardware is another important factor during engine design. Simulation is used to reduce the experimental work and costs through optimizations. The impossibility of experimental measurements usually requires computational effort to the access restricted or to simulate dangerous operatins conditions. Therefore, numerical simulations become an indispensable tool for engines designers.

For years the specialists are studying and developing robust computational codes that reproduce the results of experimental data design aiming at and improvement. Many mathematical formulations were created and it used to calculate geometry and flow behavior in blade passages.

This work deals with a study of transient behavior components and engine using an axial compressor with variable geometry to aiming at the increase of the efficiency at off-design. The compressor performance was calculated for rotational speeds of interest, using the computational code named AFCC (Axial Flow Compressor Code) and the engine deck GTAnalysis tor the calculation of the engine performance. The axial compressor designed, its performance details and the engine transient behavior is discussed below.

2. NOMENCLATURE

Clv_{opt}	Optimum lift coefficient
D	Hydraulic diameter
h/t	Hub-tip-ratio
$(i_0)_{10}$	Incidence for zero camber angle at 10% chord
$(i_D - i_{2D})$	Deduced variation of average rotor reference incidence angle minus low speed two dimensional cascade rule reference incidence angle with relative Mach number
i_{ml}	Minimum loss incidence
i_{stall}	Stall incidence
$\dot{m}$	Mass flow
K_i	Thickness correction for zero camber incidence
L	Angular momentum
m	Mass
M_n	Relative Mach number
n	Slope factor
pr	Pressure ratio
P_t	Total or stagnation pressure
$\dot{q}$	Heat flow
R	Constant dos gases
R_x	Viscous force
s/c	Space-chord-angle
t	Time
t/c	Thickness-chord-ratio
T	Static temperature
T_t	Total or stagnation temperature
u	Internal Energy
U_t	Tip speed
V	Velocity
x	Axial dimension
$\alpha_{2_{opt}}$	Optimum outlet flow angle
β_1	Inlet blade angle
β_2	Outlet blade angle
θ	Camber angle
δ	Deviation
δ_{opt}	Optimum deviation ratio
ζ	Blade stagger angle
ξ	Friction coefficient
η_{is}	Isentropic efficiency
ρ	Density
τ_{ext}	External torque

3. THE AXIAL COMPRESSOR

The design parameters for the axial compressor related in this work is show in Tab. 1.

It is a 5-stages compressor. The channel was designed with constant outer diameter (COD) as in Fig. 1.

Some design parameters were carefully analyzed in order to take care of stress limitations. Tip speed was limited to 450 m/s (Saravanamuttoo *et al.*, 2001; Walsh and Fletcher, 1998 and Giampaolo, 2003). Hub-tip-ratio and blade chord were selected to take account of blade loading (Day, 2006) and stall (Eqs. 1 and 2).

Figures 2, 3 and 4 show the relative inlet Mach number, flow coefficient and axial velocity distributions at design point. In this work, the criteria adopted for incidence angles follows (Tomita, 2003; Tomita and Barbosa, 2004 and Johnsen and Bullock, 1956). Fig. 5 shows the stall and minimum loss incidences.

$$i_{stall} = f(\alpha_{2_{opt}}; Clv_{opt}; \beta_1; \beta_2; i_{opt}; \theta; \delta_{opt}; s/c; \zeta) \tag{1}$$

$$i_{ml} = K_i(i_0)_{10} + n\theta + (i_D - i_{2D}) \tag{2}$$

To account for high speed flows (Mach number greater than unity), the Eq. (2) is corrected as indicated in Eq. (3).

Table 1. The axial flow design parameters.

Parameters	Values
P_t at inlet (Pa)	101325
T_t at inlet (K)	288.15
M_n at inlet	0.55
M_n at outlet	0.25
pr	5.0
η_{is} $(\%)$	88.5
U_t (m/s)	375
h/t at inlet	0.42
$\dot{m}$ (kg/s)	8.0

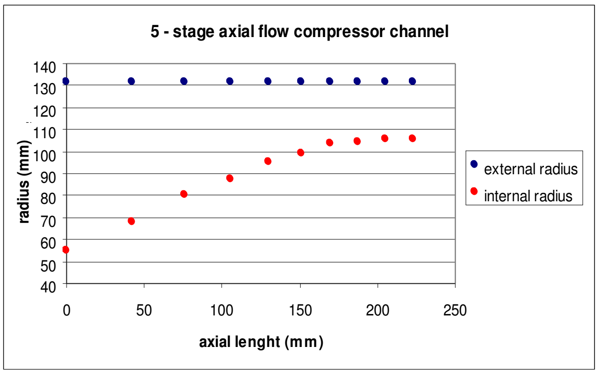

Figure 1. Axial compressor channel (COD).

$$i^*_{ml} = i_{ml} + 0.5 \left\{ a \tan \left[\frac{4\left(\frac{t}{c}\right)}{\theta} \right] \right\} \left[1 + \sin\left(\frac{\pi}{2} \frac{M_{n\ relative} - M_n}{1 - M_{n\ relative}} \right) \right] \tag{3}$$

This compressor was designed with variable inlet guide vanes (VIGV's) and Bleed-of-Valve (BOV) to avoid problems of high flow losses (Walsh and Fletcher, 1998 and Serovy and Kavanagh, 1968) when the engine runs at part-load. As result, the compressor efficiency increases and the stability margin is improved.

The VIGV's angles and the percentage of flow bleed are presented in Tab. 2.

Table 2. VIGV and flow bleed for each rotational speedy.

N (%)	VIGV (°)	Bleed (%)
1	0	0
0.95	10	0
0.9	15	0
0.85	20	10
0.8	20	10
0.78	22	10
0.75	25	10
0.72	27	10
0.68	30	15
0.65	30	15
0.62	30	15
0.58	30	20

The BOV was considered installed between fourth rotor and fourth stator rows. The axial flow compressor performance and its efficiency characteristics are shown in Figs. 6 and 7.

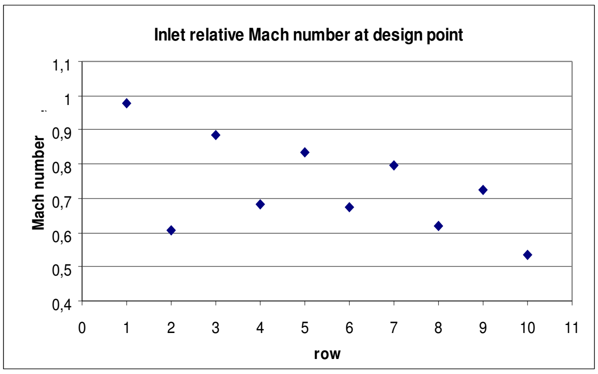

Figure 2. Relative Mach number for each row.

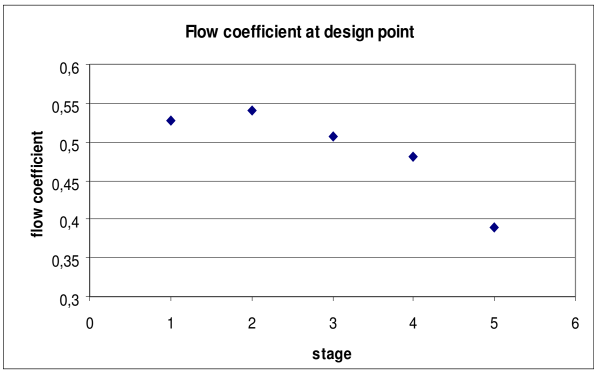

Figure 3. Flow coefficient for each stage.

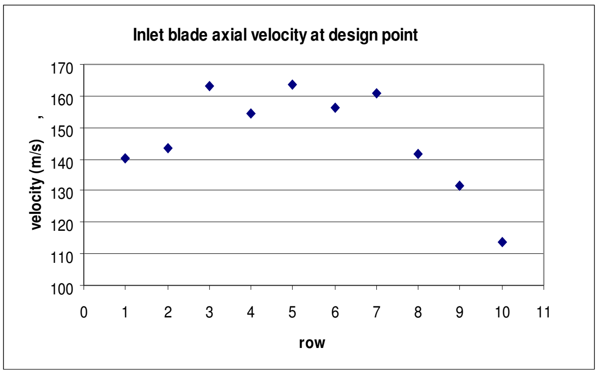

Figure 4. Axial velocities distributions.

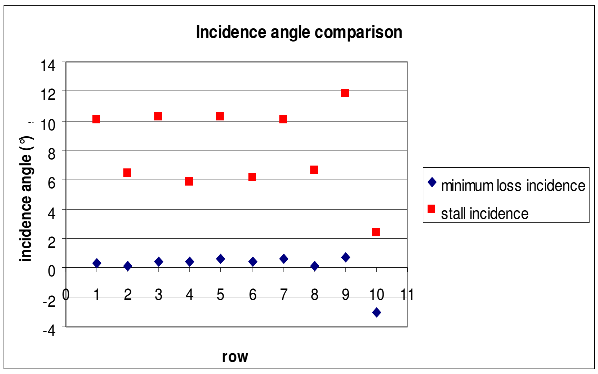

Figure 5. Stall and minimum loss incidences.

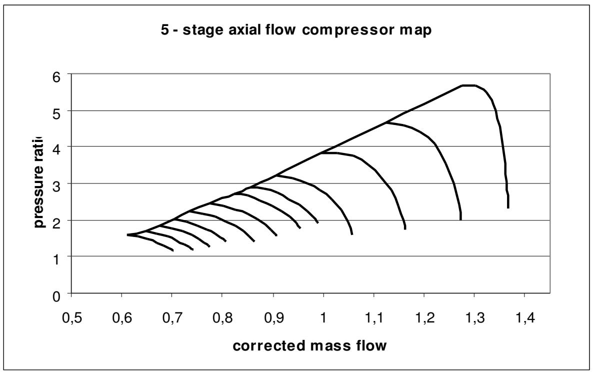

Figure 6. Axial flow compressor performance.

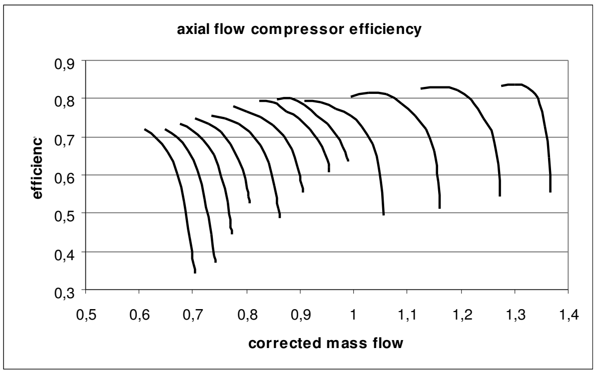

Figure 7. Axial flow compressor efficiency.

The compressor characteristic data was exported to the engine deck for the calculation of the running line and for the transient.

4. GAS TURBINE PERFORMANCE

Some special operation points for both steady and transient regimes, must be known in advance to avoid instabilities and risk of operation very close of the surge line.

GTAnalysis is a computer program (Bringhenti, 1999), that is able to simulate engines, numerically, at in steady-state or transient regimes (Silva, 2006). Almost all gas turbine configurations (turbo-shaft, turbojet, gas generator with free turbine and turbofan), with or without variable geometry can be analyzed (Bringhenti, 2003). The heat transfer at the engine metallic, as well as the variations of engine dimensions were not taken into account, so that only shaft and volume transients were considered.

4.1 Important transient aspects

It is important to know in advance the engine performance characteristics. The accurate engine performance predictions at transient operation in of the engine in reasonable time affects directly the design, maintenance and operation costs. The transient phenomena occur during acceleration or deceleration process when the engine thrust is changed.

The transient behavior depends on several parameters including the engine type, the characteristics of the components like compressor, combustion chamber and turbine and the operation conditions as altitude (Ganji *et al.*, 1993).

On turbojet engines the performance variation is caused basically by variation of maximum temperature in the cycle. High turbine inlet temperature increases the turbine power. The deceleration occurs in an inverse process. Temperatures, pressures, mass flow, rotational speed and thrust, for example, change during transients.

The engine accelerations and decelerations are executed constantly. Setting fast engine acceleration cause the fuel to increased up to 20 times greater than the values observed at steady-state and causes high levels of temperature, and the components life reduction (Kotsiopoulos *et al.*, 1997). On the order hand if acceleration is slow, the fuel flow is varies slowly causing less live degradation. Time of acceleration can be the limiting value for military applications.

5. SIMULATIONS

The simulations were performed considering shaft and volume transients. The mass, momentum and energy changes determine the behavior of the transient operation.

Shaft transient: relates to the torque and rotating parts and its changes with the time. The shaft transient is highly dependent of the inertia distribution of the rotational parts.

Volume transient: relates to the gas dynamics effects in the engine volume, generating high pressure variations (Ramos and Sirignano, 1981). The components with high volumes like combustion chamber, ducts and heat exchangers, have strong influence on transient. In these volumes the mass is stored with consequent difference between inflow and outflow fluxes, that contributes to the unbalancing of power between compressor and turbine.

The influence of the fluid dynamic motion is neglected, being more significant the effect due to inertia of the rotating parts and the heat transfer of the metallic parts (Peretto and Spina, 1997 and Saravanamuttoo and Issac, 1982). The transient of volume is important mainly for fast power changes. The combustion chamber usually has is of large volume becoming very important in this context.

5.1 Mathematical modelling

The models implemented for shaft transient simulations are derived from law that establishes the relation between the external torque that act in the system, as displayed in Fig. 8, and the variation of angular momentum, as show in the Eq.(4).

$$\tau_{ext} = \frac{dL}{dt} \tag{4}$$

Conservation of mass, Eq.(5), momentum, Eq.(6) and energy, Eq.(**??**), together with the equation of perfect gas, Eq.(10 are used to calculate the transient of volume.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho V)}{\partial x} = 0 \tag{5}$$

Momentum equation:

$$\frac{\partial V}{\partial t} + V\frac{(\partial V)}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + 2\xi\frac{V^2}{D} = 0 \tag{6}$$

with

$$\xi = \frac{T_w}{\frac{1}{2}\rho V^2} \tag{7}$$

and

$$D = \sqrt{\frac{4A}{\pi}} \tag{8}$$

Energy equation:

$$\frac{\partial u}{\partial t} + V\frac{\partial u}{\partial x} + \frac{p}{\rho}\frac{\partial V}{\partial x} - 2\xi\frac{V^3}{D} - \dot{q} = 0 \tag{9}$$

Perfect gas equation:

$$p = \rho R T \tag{10}$$

5.2 Numerical simulation results

In this section, the results of the transient calculations are presented. The configuration of the turbojet engine is shown in Fig. 8.

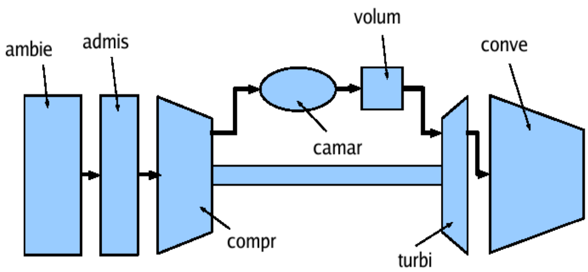

Figure 8. Engine configuration Diagram.

For this simulation the turbine inlet temperature is decrease 300K from the design point and a time of 70s is wanted until stabilization at the new steady state. Then the turbine inlet temperature is increased to the design point value and sustained until the stabilization. The time-step used for numerical integration is of 0.02s.

This temperature variation results in the variation of the engine parameters such as speed, thrust and fuel consumption as presented in Fig. 9, as percentages of the design point values.

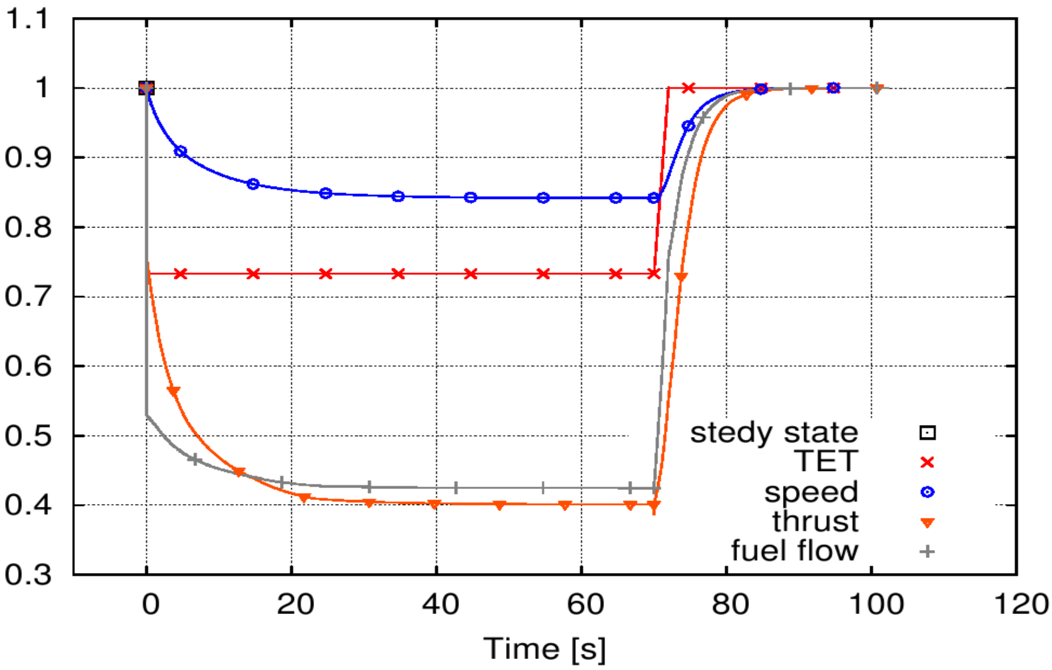

Figure 9. Engine parameters variations.

The operation curves are close to the surge line in the acceleration process (red line). During the deceleration an inverse process occur in the engine (blue line). The variations of mass flow and pressure can be observed when the transient process is started, as indicated in Figures 10 and 11.

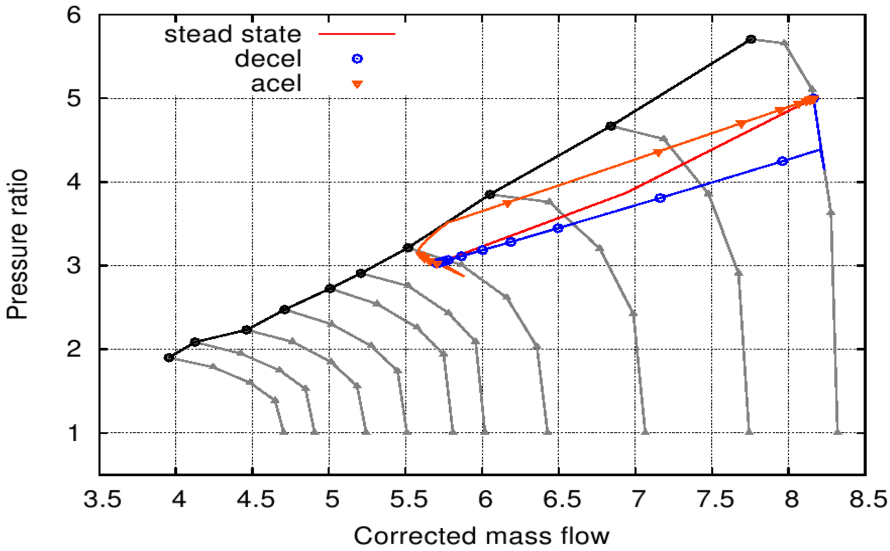

Figure 10. Characteristics compressor.

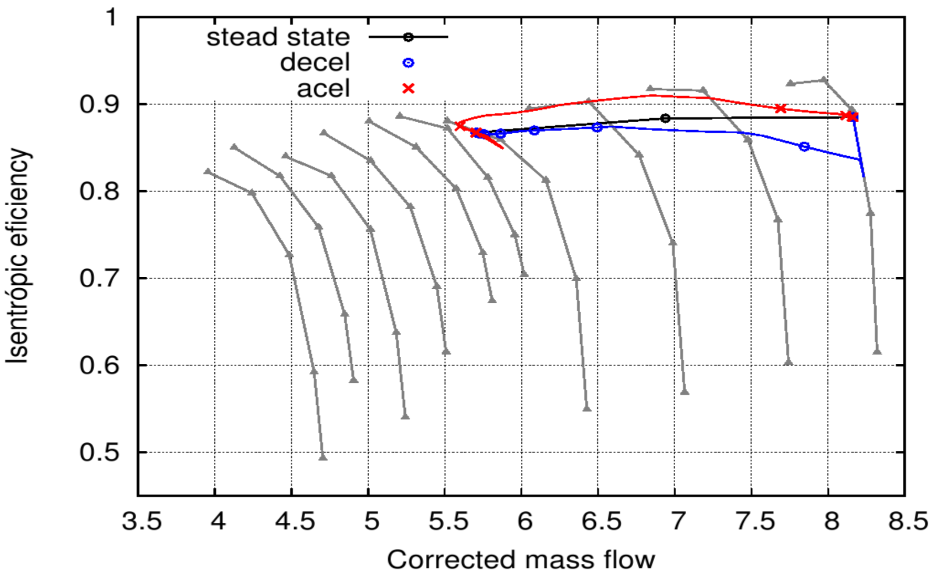

Figure 11. Stall and minimum loss incidences.

The engine running line draw superimposed to the compressor characteristic show the operation too near the surge line indicating a good efficiency during the acceleration process as show in Fig. 11.

For other part-load speed, such as 75% the time-step applied in the time integration was lowed to avoid numerical instability problems and consequently numerical divergence.

6. CONCLUSIONS

The design of a good axial flow compressor equipped with VIGVs and BOV, to increase the stability area and consequently the compressor efficiency, is very important to avoid premature stall and surge during the engine transient operation mainly during the accelerations process.

The numerical scheme implemented to calculate the transient behavior must be robust to guarantee convergence and accuracy of the solution. Numerical convergence for low speed can be a problem due to the physical aspect of flow losses that occur in the blade passages in the engine channels.

At low speed convergence is more difficult to achieve. Time step may be reduced to get converged solution.

7. ACKNOWLEDGEMENTS

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