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The Influence of a Variable Capacity Compressor in the Performance of a Variable Cycle Engine

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Abstract **- Supersonic engines are usually used in military aircraft. They have not been used in civil aviation or for transport due to numerous operational reasons. There are dissimilar concepts, which are being proposed for supersonic civil transport. One of the concepts that presented in this paper is Variable Cycle Engine (Adaptive Cycle Engine). Variable cycle engines would be able to change their bypass ratios, for optimum efficiency at any combination of speed and altitude within the aircraft's operating range, despite traditional engines with fixed airflow. A supersonic highly loaded high pressure (HP) compressor was designed for a VCE in the conditions of both single and double bypass modes in accordance with the similarity principle. The blade profiles were designed by means of NACA airfoil. Then, 3D numerical simulations were performed on the HP compressor of both working conditions with different thermodynamic cycle parameters to confirm the design methods and results. The one equation turbulence model of Spalart-Allmaras was applied to solve Reynolds's averaged Navier-Stokes equations. The results of simulation indicate that the compressor performances are satisfactory in both working conditions with high efficiency. Further research reveals wave structures in the supersonic compressor, behaviour of tip clearance flow and the phenomenon of transition flow in boundary layer.**

1. NOMENCLATURE

$\dot{m}$ = rate of mass flow

$\acute{m}$ = rate of reduced mass flow

ρ_1 = density of inlet airflow

A = area of compressor exit

C_{a1} = axial velocity component at inlet

r_t = tip radius

r_r = root radius

r_m= mean radius

R = gas law constant

P_1 = inlet static pressure

T_1 = inlet static temp.

U_t= blade axial velocity

n = blade rotational speed

H = blade height

ΔT_{0S} = temperature rise per stage

S = rotor pitch

C = chord length

η_p = polytropic efficiency of compressor

x = number of blades on rotor/stator

μ = dynamic viscosity coefficient

C_p = pressure coefficient

$\acute{N}$ = reduced power

$\acute{n}$ = reduced wheel speed

C_θ = whirl speed component

2. INTRODUCTION

An engine that works with two or more thermodynamic cycles can be termed as Variable Cycle Engine (VCE). VCE is an aero engine for which thermodynamic cycle can be adjusted by varying few components' shape/ size / position, and the cycle parameters, like pressure ratio, mass flow, bypass ratio and thrust. It can be varied between those of a turbojet and a turbofan to combine the advantages of both. This will help engine to get optimal thermodynamic cycle. Additionally, it improves adaptability to various flight envelopes [1].

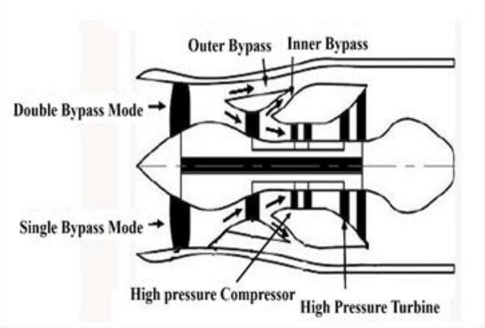


Figure 1: Work mode of VCE

To address high specific thrust requirement (example take-off, acceleration and supersonic cruise), this engine could act as turbojet. . To address low fuel consumption, requirements like standby and subsonic cruise, this engine could work as the turbofan. When we consider VCE in future supersonic, the biggest plus point could be considerable range improvements (versus conventional engine). Additionally we could get a low emission combustor and afterburner. Additionally, it can give accepted noise level at take-off per FAR part 36 norms. We can say that the future VCE will be environmentally accepted [2].

One of major factor which can impact performance of any VCE is achievement of predicted technology level improvements. This research on VCE is for improving off-design performances so as to satisfy broad flight envelope needs, bigger combat radius and longer cruise duration [3].

Single bypass mode -: Entire amount of air passes through Core Drive Fan Stage (CDFS) and selector valve is closed. The core engine is bypassed by fan bypass flow and passed through the inner bypass duct to get remixed with core flow downstream of the LPT. For the purpose of shifting loading on high pressure shaft so that added work of CDFS is managed, nozzle is kept full open. Simultaneously, expansion ratio and flow rate is raised so that there is increase in the specific thrust with low bypass ratio under supersonic.

Double bypass mode: In this case nozzle is closed and selector valve is opened fully. This will unburden HP turbine and LP turbine is loaded. The by-pass ratio rises to get optimum specific fuel consumption for subsonic cruise and best exhaust velocity conditions so as to get more noise suppression on take-off [4].

3. COMPRESSOR DESIGN METHOD

Below flowchart shows steps to design an axial flow compressor;

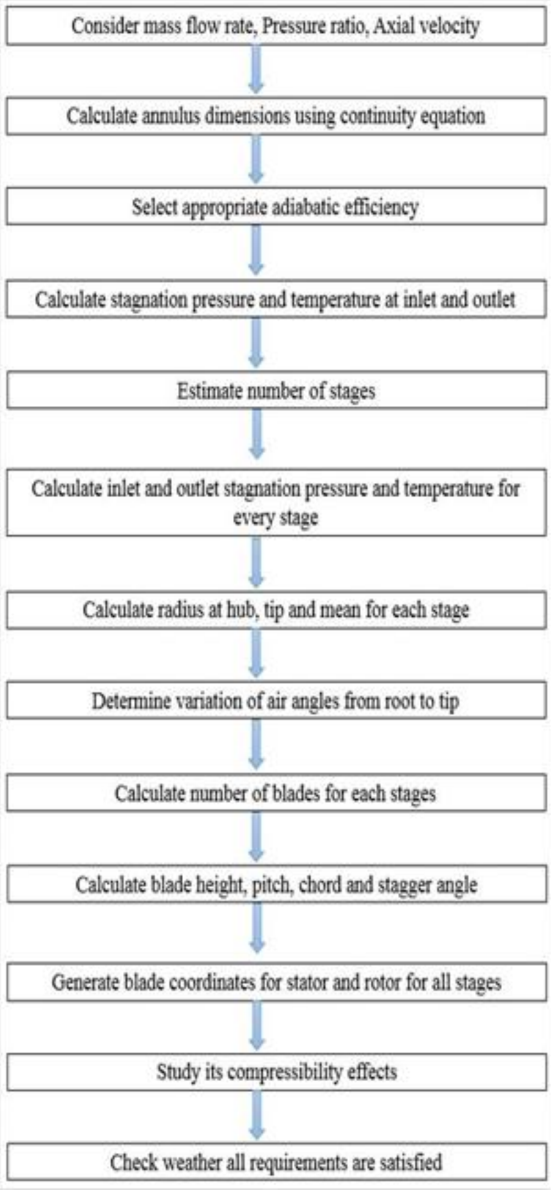


Figure 2: Compressor design strategy

The required annulus area at entry is calculated by using specified mass flow, assumed axial velocity, and ambient conditions, using the continuity equation.

To satisfy continuity equation:

$$\dot{m} = \rho_1 A C_{a1} = \rho_1 \pi {r_t}^2 \left[1 - \left(\frac{r_r}{r_t}\right)^2\right] C_{a1} \quad \dots (1)$$

From the above equation,

$${r_t}^2 = \frac{\dot{m}}{\pi \rho_1 C_{a1}[1 - (r_r/r_t)^2]} \quad \dots\dots\dots\dots\dots (2)$$

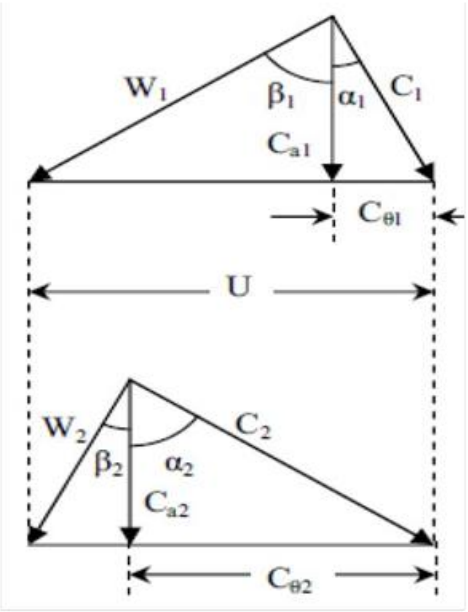


Figure 3: Velocity triangle at compressor inlet

Where $\left(\frac{r_r}{r_t}\right)$ is considered as hub to tip ratio and density is calculated from the relation

$$\rho_1 = \frac{P_1}{RT_1} \quad \dots\dots\dots (3)$$

Using atmospheric pressure, temperature and cycle calculations, required pressure ratio, mass flow rate, and compressor inlet temperature can be determined. Using this information the static pressure, temperature at the first stage of compressor is determined.

Considering assumed axial velocity, tip radius will be the function of hub to rip ratio.

Blade speed equation is:

$$U_t = 2\pi r_t n \quad \dots\dots\dots (4)$$

$$\gg n = \frac{U_t}{2\pi r_t} \quad \dots\dots\dots (5)$$

We iterate and find out the tip radius by appropriate hub to tip ratio $\left(\frac{r_r}{r_t}\right)$ and rotational speed (n). This is used to get mean radius as follows;

$$r_m = \frac{r_t + r_r}{2} \quad \dots\dots\dots (6)$$

For mean line design methodology, mean radius remain constant for all stages.

In case of exit area:

$$A = \frac{\dot{m}}{\rho_1 C_{a1}} \qquad \dots\dots\dots.(7)$$

Blade height:

$$H = \frac{A}{2\pi r_m} \qquad \dots..(8)$$

The compressor radius at exit (final stage) is as calculated using:

$$r_t = r_m + {}^{H}\!/_{2} \qquad \dots\dots.(9)$$

$$r_r = r_m - {}^{H}\!/_{2} \qquad \dots\dots..(10)$$

No. of stages is calculated by dividing total temperature rise in all stages by temperature rise per stage.

Formula for the temperature rise for a stage is:

$$\Delta T_{0S} = \frac{\lambda U C_a (C_{\theta 2} - C_{\theta 1})}{C_p} \qquad \dots..\dots(11)$$

We get the whirl components of velocity using velocity triangles per Figure 4.

Aerofoil chord length of the blade is determined by proper selection of aspect ratio $\left(\frac{H}{C}\right)$ based on the application.

The pitch and no. of blades for the rotor is found by using below formula,

$$S = \eta_p C \qquad \dots\dots(12)$$

$$x = \frac{2\pi r_m}{S} \qquad \dots\dots\dots.(13)$$

4.1 THE APPLICATION OF SIMILARITY PRINCIPLE:

Similarity principle can be used to forecast performance of one machine from the results of tests on a geometrically similar machine. Additionally it is useful to estimate the performance of same machine under conditions different from the test conditions. Condition for using similarity application is two machines should be kinematically similar and velocity vector diagrams at inlet and outlet of the rotor must be comparable [10].

When the HPC was design for VCE, we considered two conditions; single bypass mode and double bypass mode. Meaning that HP compressor must adjust the bypass ratio variation, which makes the flow rate and compression ratio vary within wider range [7].

Air flow gets compressed when air flows into the inner bypass when VCE modifies its working conditions. This increases mass flow of HPC.

Different working conditions for VCE matching with different bypass ratios. Let us consider that the VCE works in *n* conditions. Then HP compressor must correspond with *n* series of parameters as follows:

Condition 1 $P_{in,1}\ T_{in,1}\ \dot{m}_1\ \mu_1\ n_1\ C_{p,1} \ \geq\ \eta_1$
Condition 2 $P_{in,2}\ T_{in,2}\ \dot{m}_2\ \mu_2\ n_2\ C_{p,2} \ \geq\ \eta_2$
Condition i $P_{in,i}\ T_{in,i}\ \dot{m}_i\ \mu_i\ n_i\ C_{p,i} \ \geq\ \eta_i \dots$
Condition n $P_{in,n}\ T_{in,n}\ \dot{m}_n\ \mu_n\ n_n\ C_{p,n} \ \geq\ \eta_n$

For turbo machinery, the total efficiency depends on ten parameters,

$$\eta = \left(P_{in}, T_{in}, C_p, \dot{m}, R, \gamma, \mu, n, D, N\right) \quad \dots\dots(14)$$

The following equations can be acquired from the similarity principle in turbo machinery.

$$\eta = (\pi_1, \pi_2, \pi_3, \pi_4, \pi_5\ ) \qquad \dots\dots\dots(15)$$

Where,

Compression ratio $\pi_1 = C_p = {}^{P_o}\!/_{P_{in}}$

Reduced mass flow rate $\pi_2 = \acute{m} = \dot{m}\left(\frac{\sqrt{T_{in}}}{P_{in}}\right)$

Reynolds number $\pi_3 = \frac{P_{in}}{\mu\sqrt{T_{in}}}$

Reduced power $\pi_4 = \acute{N} = \frac{N}{P_{in}\sqrt{T_{in}}}$

Reduced wheel speed $\pi_5 = \acute{n} = \frac{n}{\sqrt{T_{in}}}$

Both π_1 and π_4 are the qualitative parameters and can be represented into:

$$\pi_1 = C_p = f_1\,(\pi_2, \pi_3, \pi_5) \qquad \dots\dots(16)$$

$$\pi_4 = \acute{N} = f_2\,(\pi_2, \pi_3, \pi_5) \qquad \dots\dots(17)$$

Thus, the efficiency is also represented into:

$$\eta = f_3\,(\pi_2, \pi_3, \pi_5\ ) \qquad \dots\dots(18)$$

π_3 Effect is negligible if Re is bigger than second critical Re number in turbo machinery. Equation (18) is reduced as:

$$\eta = f_3\,(\pi_2, \pi_5\ ) = \left(\dot{m}\left(\frac{\sqrt{T_{in}}}{P_{in}}\right), \frac{n}{\sqrt{T_{in}}}\right) = f_3\,(\acute{m}, \acute{n}) \qquad \dots\dots\dots\dots\dots(19)$$

So if we establish equations both (20) and (21) for HPC of VCE, multi-conditions compressor for VCE can be treated as the conventional compressor to be designed.

$$\acute{m} = \dot{m}\left(\frac{\sqrt{T_{in,1}}}{P_{in,1}}\right) = \dot{m}\left(\frac{\sqrt{T_{in,i}}}{P_{in,i}}\right) \qquad \dots.(20)$$

$$\acute{n} = \frac{n}{\sqrt{T_{in,1}}} = \frac{n}{\sqrt{T_{in,i}}} \qquad \dots\dots\dots(21)$$

As a result, the mass flow rate and inlet parameters of HPC are altered into any kind of condition among *n* series of conditions when VCE regulates its bypass ratio. Efficiency of compressor is only influenced by the compression ratio.

4. ANALYSIS OF DESIGN USING CFD

ANSYS Fluent 16.0, a CFD tool has been used to simulate the 3D steady flows and to validate the aerodynamic performances of designed HPC for VCE for both single bypass and double bypass mode.

Analysis of design involves following steps:

5.1 CREATING A GEOMETRY/MESH

Per American practice based on numerous families designed by the National Advisory Committee for Aeronautics , the most popular being the 65-series family [8]. NACA 65410 [9] Airfoil is used here to create blade coordinates as in Figure 4.

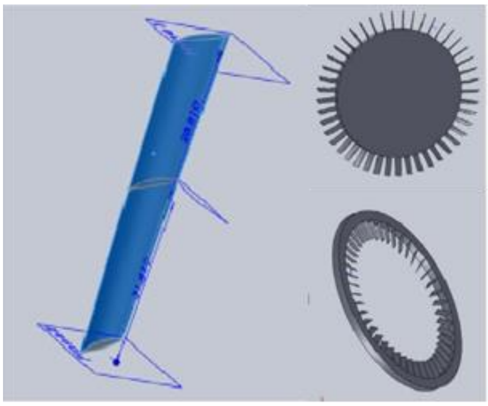


Figure 4: Geometric models of blade, rotor and stator

Geometry is grated using NX UNIGRAPHICS 9.0 software. NACA 65410 airfoil coordinates are imported to software. Meshing (Figure 5) has been carried out by Hyper Mesh. Element type used is Tetrahedral.

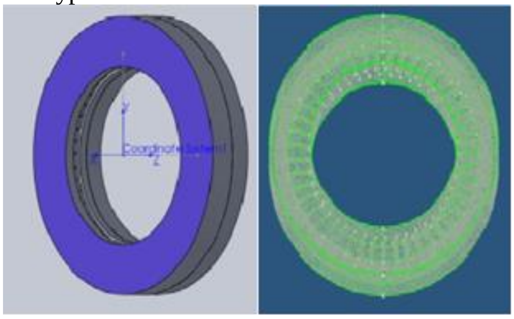


Figure 5: Assembly of zones and meshing

5.2 DEFINING THE PHYSICS OF THE MODEL

This includes specification of type of fluid, defining the domains, Inlet and Outlet Boundary conditions, type of analysis, turbulence model, and heat transfer model etc. Assumptions for defining physics are-

- Steady state condition
- No leakage losses
- Friction between walls and fluid is neglected.

5.3 SOLVING THE CFD PROBLEM

The solver parameters are specified as follows:

- Working fluid - Air as an Ideal gas.
- The one-equation turbulence model of Spalart-Allmaras has been applied to solve Reynolds's averaged N-S equations. This model is applicable to separation flow simulations of viscous fluid under high pressure gradient.
- Temperature, pressure and turbulent viscosity are prescribed at inlet. Gas entry is axial. Static pressure is applied at outlet as shown in Figure 7.
- Used two domain interfaces - Rotor domain (rotating) and stator domain (stationary) (Figure 6).

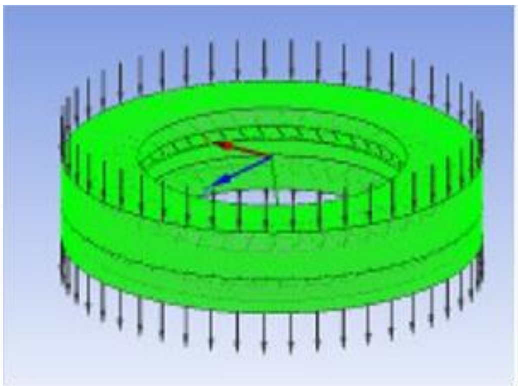


Figure 6: Applying boundary conditions

Results are analysed with using CFD Post.

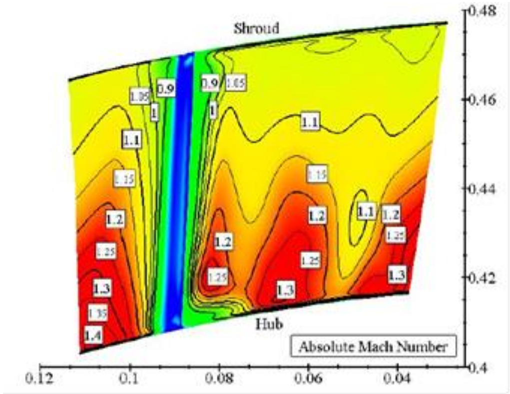
5.4 CFD ANALYSIS RESULTS

- Mach number distribution on the blades
- Vortex movement
- Pressure coefficient distribution on blades in two modes

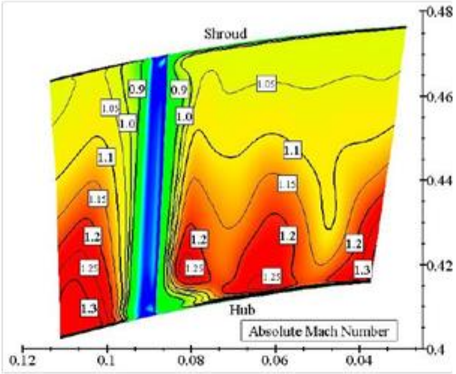
6 RESULT ANALYSIS

The results of simulation indicate that satisfactory aerodynamic performances are available in both operating conditions, and designed HPC has attained expected targets.

Isolines distributions of absolute Mach number at stator outlet in each mode represent the characteristics of supersonic wave flow as depicted in Figure 8. The channel characterized as uneven at different blade heights carries high temperature gas. The uneven of flow parameters in the flow fields causes radial movement from blade bottom to the top and corner vortex (Fig. 8) near both hub increasing apparently.



(a) Single bypass mode



(b) Double bypass mode

Figure 7: Mach number at stator outlet in different operating modes

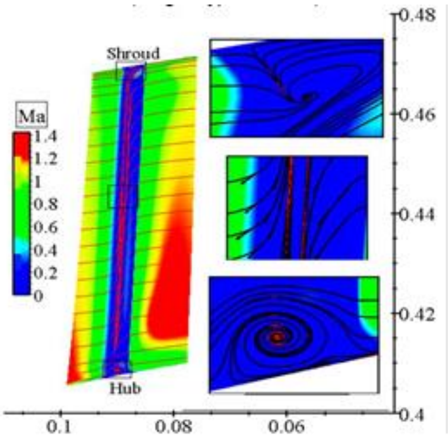
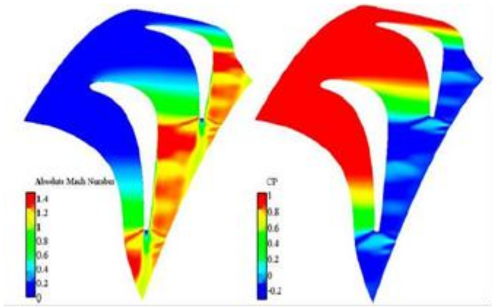


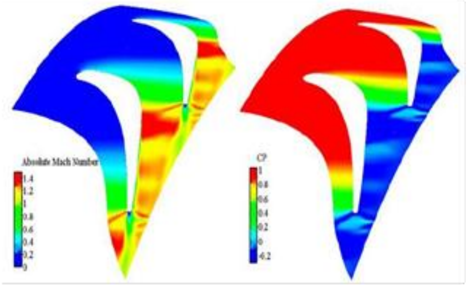
Figure 8: Corner vortex movement at stator outlet in single bypass mode

This secondary flow is mainly responsible for the aerodynamic loss in a supersonic compressor.

Wave structures of supersonic compressor are analysed by the difference of absolute Mach number and pressure coefficient at one particular blade height (Figure 11). Gas flow out the trailing edge along pressure surface, forms detached shock. By the variations of Mach number and pressure coefficient, we conclude that detached shock is reduced and dissipated by the set of expansive waves. This means effect of detached shock is limited to the flow fields near the trailing edge, while the expansive wave can occupy most space in the tapered-cut region.



(a) Single bypass mode



(b) Double bypass mode

Figure 9: Mach number and pressure coefficient in both modes

7 CONCLUSION

In present paper, a high loaded high-pressure compressor stage with high compression ratio has been designed by NACA profile based on similarity principle. Three-dimensional calculations have been carried out under different thermodynamic cycle parameters to simulate flow fields in the two operating conditions (Single bypass mode and double bypass mode). It reveals the characteristics of supersonic wake flow in a compressor and the formations of tip clearance flow. Wave structures in the channel and aerodynamic loss in the flow fields have been analysed.

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