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Single Shaft Contra Rotating Axial Compressor

Bojja. Venkat Sai
Student, Department of Aeronautical
Institute of Aeronautical Engineering, Dundigal, Hyderabad-500043, Telangana State, India.

Basannagari Naveen Kumar
Assistant professor, Department of Aeronautical
Institute of Aeronautical Engineering, Dundigal, Hyderabad-500 043, INDIA.

Ms. Shaik Asma Sulthana and Mr. Shaik. Arif
Student, Department of Aeronautical,
Institute of Aeronautical Engineering, Dundigal, Hyderabad-500043, Telangana State, India.

Abstract
Generally, contra rotating propeller is 6% to 16% more efficient than traditional propeller (according to Wikipedia) so on rotating the alternative rotors of axial compressor in contra direction results in increase of efficiency. Here the method which is applicable to contra rotating propeller is not applicable in axial compressor because there is limit in using number of coaxial shafts which may result in complexity to use the method, further using two shafts in axial compressor for rotating the alternative rotors in counter direction is also a complex design.
In single shaft contra rotating axial compressor, Compressor rotors are made to connect by single shaft using internal gearing mechanism in such a way that for alternative rotors rotation is made in opposite direction.
Improvements in this method results in:
1) Increase in compressor efficiency
2) Decrease in compressor axial length

In this paper, design of "Single shaft contra rotating compressor" is discussed in great detail with new approach, and flow simulation results are compared with traditional compressor.

Keywords: Contra rotating compressor, Counter rotating compressor, efficient compressor, axial compressor, opposite rotating compressor, future compressor.

INTRODUCTION

COMPRESSOR: Compression process takes place in compressor; it takes air in and increase pressure substantially. Consider an example of traditional axial flow compressor as shown in figure 1. The compressor is vital to the operation of engine because it readies the air for the combustor. Work is done on the fluid by the compressor, which comes from turbine thereby the total pressure increases across the compressor, which is necessary for the combustion process and also in production of thrust [1].

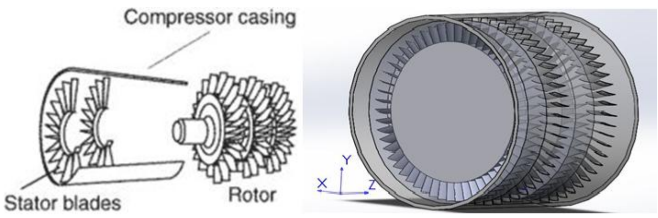

Figure 1: Traditional Axial Compressor

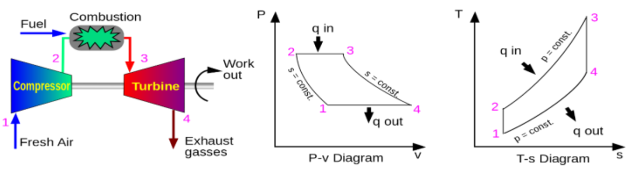

Figure 2: Brayton cycle

From Figure 2 the efficiency of jet engine can be written as equation 1 using Brayton cycle.

$$\eta_{th} = 1 - \left[\frac{v_3}{v_2}\right]^{\gamma-1} = 1 - \left[\frac{p_2}{p_3}\right]^{\frac{\gamma-1}{\gamma}} \qquad (1)$$

Where
P2 = compressor pressure at inlet.
P3 = compressor pressure at exit.
V2, V3 = compressor specific volumes at inlet and exit.
γ = specific heat ratio.

Typically, the total pressure ratio across the compressor ranges 5-35 as determined by the particular engine. By examining Eq. (1) for a closed cycle as pressure ratio of compressor increases thermodynamic efficiency increases. Considering the fact that Thrust specific fuel consumption (TSFC) of an engine decreases with increase in compressor pressure ratio [9]. In simple manner it says that as the pressure ratio increases, the required fuel flow decreases and the extracted power increases. So this pressure ratio of traditional compressor can increase as stated in the sense of new approach.

The significance of contra rotating compressor is similar to coaxial counter contra rotating propeller, so let us also discuss about it. The general idea of coaxial contra rotating propeller consists of two propellers are connected to two coaxial shafts which are rotated in counter direction as shown in figure 3. The energy of the tangential velocity created by first propeller is wasted, so placing second propeller which utilize the wasted energy of tangential velocity in producing thrust[3].

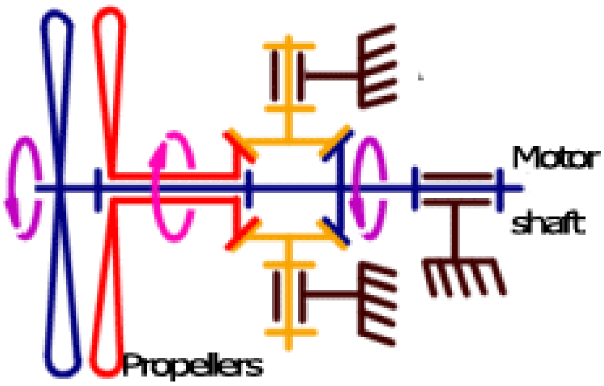

Figure 3: "Coaxial Contra rotating propeller"

If "contra rotating propeller" is designed in sophisticated way then net rotational flow becomes zero which results in low energy loss, high performance occurance takes place and it also deals with conventional propeller whose net torque made equal to zero (see P-factor[7]) [3]. According to Wikipedia it is proved that by using contra rotating propeller the efficiency of propeller can be made to increase by 6% to 16%.

So by dealing with contra rotating compressor vanes the efficiency of axial flow compressor may increase. To make compressor vanes rotate in contra direction the principle used in coaxial contra propeller cannot be applied in axial compressor because a traditional axial compressor consists of 6 to 16 stages and each stage has one rotor and a stator. To make them rotate in contra direction we require 12 to 32 coaxial shafts, which is too complex and very difficult. So a new approach introduction comes to rotate the compressor vanes in contra rotating direction using a single shaft.

In past, few experiments were conducted on topic counter rotating turbine, (counter rotating is different from contra rotating) historically we can distinguish this problem according to B. A. Ponomariev and J. F. Louis papers [4], [5], [8]. The result of these experiments were most satisfactory.

METHOD:

The principle behind single shaft contra rotating compressor is the elimination of tangential velocity, which is considered as a loss in performance and efficiency. In single shaft contra rotating compressor, rotors are made to connect to a single shaft as shown in the figure 4.

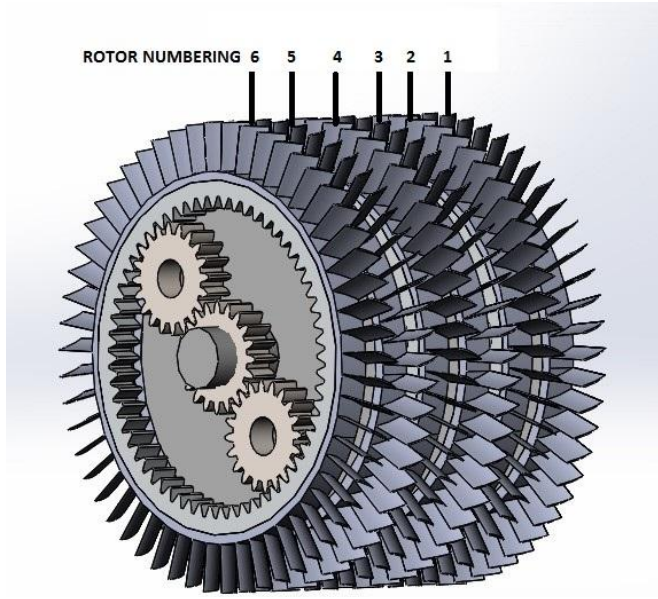

Figure 4: Single shaft contra rotating axial compressor

From figure 5, Taking internal gearing mechanism in to account of rotors 2, 4, 6. Here gear 1 is pursuing the shaft and made to rotate as it is directly connected to shaft. Then gears2 are rotated in reverse direction to shaft by gear1, finally gear 3 and vanes are made to rotate in reverse direction to shaft by gear2, pursuing opposite direction of gear1 as shown in figure5. Rotors 2, 4 and 6 are made to connect to shaft which pursues the same gearing mechanism and rotate in counter direction.

For example say shaft and gear1 rotate in anticlockwise direction. Gears2, gear3 rotate in clockwise direction, as blades are connected to gear 3 so they also rotate in clockwise direction as shown in figure 5.

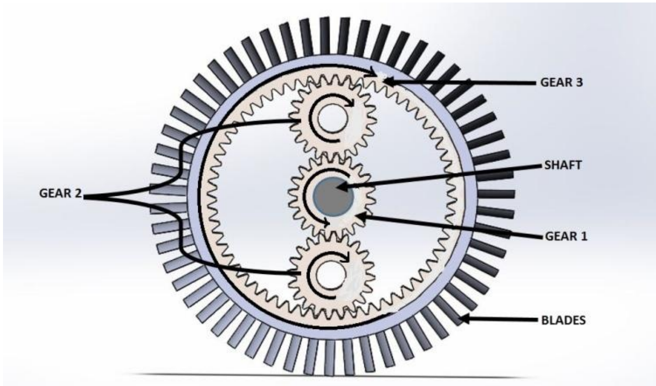

Figure 5: Rotors 2, 4, 6.

Rotors 1, 3, 5 are directly made to connect to shaft, so blades also rotate in same direction of shaft. Say shaft rotates in anti-clockwise direction then blades also rotate in anti-clockwise direction as shown in figure 6.

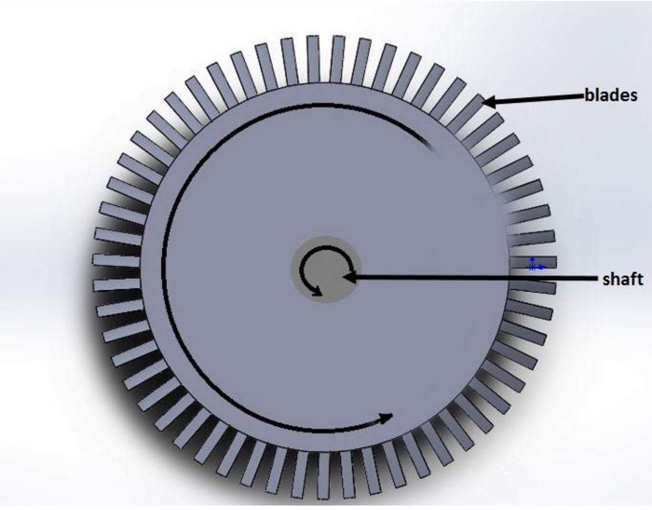

Figure 6: Rotors 1, 3, 5.

After summarizing above information, say a turbine rotates in a direction, the compressor vanes 1, 3, 5 also rotate in same direction of turbine, but vanes of compressor 2, 4, 6 rotate in contra direction.

Now consider figures 4, 5, 6 to deal with the flow simulation and velocity triangles of contra rotating compressor.

FLOW SIMULATION

Flow simulation is done on the single stage contra compressor, two stage traditional compressor and four stage traditional and contra rotating compressor. The results obtained for single stage contra rotating compressor are as shown in figure7.

Figure 7 indicates the variation of tangential velocity across the blades.

Table 1: Initial values

Rotational speed of rotor1	4000 RPM
Rotational speed of rotor 2	2500 RPM
Blade length	0. 095 m
Distance between two rotors	0. 108 m
Chord length	0. 062 m

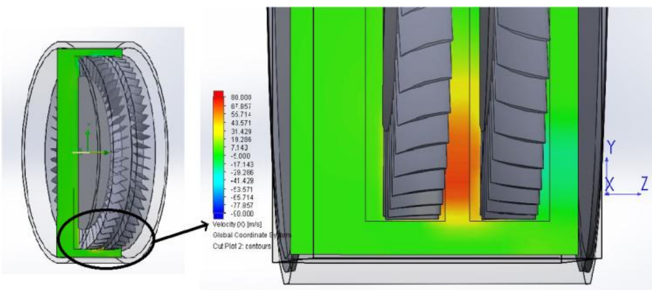

Figure 7: Variation of tangential velocity across single stage contra rotating compressor blades

From figure7 velocity triangles of single stage contra rotating compressor are plotted as shown in figure8.

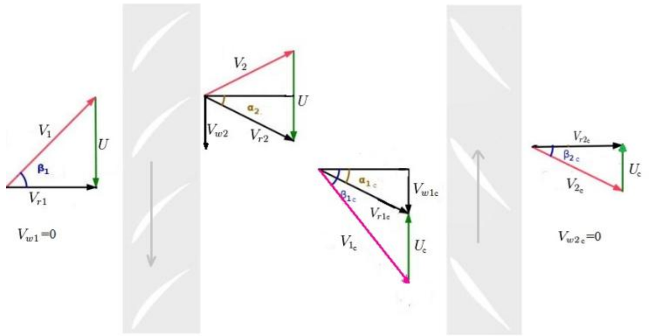

Figure 8: Velocity triangles of single shaft contra rotating compressor.

Here the rotational speed (U_c) of rotor2 is less when compared to rotational speed (U) of rotors 1 due to internal gearing mechanism of rotor2

V_1, V_2, and V_{w1}, V_{w2} are the absolute and swirl velocities at the inlet and outlet of Rotor 1 respectively.

V_{r1}, V_{r2} are the terms for blade-relative velocities of rotor1 at the inlet and exit.

V_{1_c}, V_{2_c}, V_{r1_c}, V_{r2_c} are the absolute and blade relative velocities of rotor2(contra rotating rotor) at the inlet and exit part respectively.

V_{w1_c}, V_{w2_c} are the terms for swirl velocities of Rotor 2 at the inlet and exit portion.

U, U_c are the linear velocities of blade of Rotor 1, 2 respectively.

Let guidevane angle be α.

The pressure ratio across the rotor1 can be written as equation 2, for derivation refer [6]

$$\frac{(p_{02})}{p_{01}} = \left(1 + \frac{\eta_{\text{stage}} U \frac{(V_{w2} - V_{w1})}{c_p}}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} \quad (2)$$

As the inlet has no tangential velocity as shown in figure7 $V_{w1} = 0$, equation 2 becomes

$$\frac{(p_{02})}{p_{01}} = \left(1 + \frac{\eta_{\text{stage}} U \frac{(V_{w2} - 0)}{c_p}}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} \quad (3)$$

Rotor tips rotate with high radial velocity generating large vortices, contra rotating rotors create vortices that rotate in two opposite directions that is counter clockwise and clockwise direction, which significantly reduces the vortices by cancellation. The diameters of gear 1, 2, 3 are selected in such a way that the tangential velocity at exit of each stage (consists of two rotors) becomes zero (V_{w2_c}=0). So the pressure ratio across rotor 2 becomes

$$\frac{(p_{02})_c}{p_{01_c}} = \left(1 + \frac{\eta_{stage} U_c \left(\frac{0 + V_{w1c}}{c_p}\right)}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (4)$$

Note: In above equation positive sign indicates the direction of V_{w1c} is opposite to U_c

So the pressure ratio across stage can be written as

$$\frac{(p_{02})}{p_{01}} + \frac{(p_{02})_c}{p_{01_c}} \qquad (5)$$

Similarly the results obtained by doing flow simulation on traditional compressor is as shown in figure9.

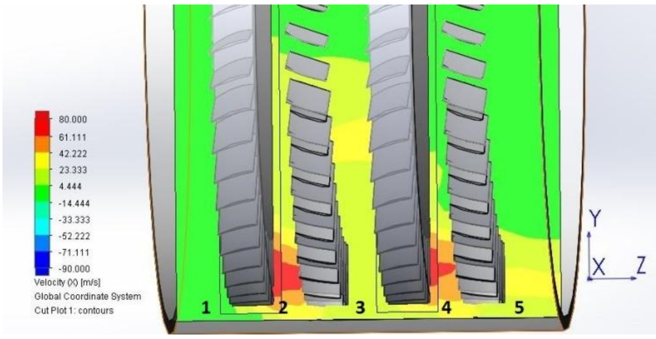

Figure 9: Variation of tangential velocity across two stage traditional compressor

The pressure raise across stage1 is equal to pressure raise across rotor1 because the total pressure raise across stator is zero, so pressure raise across stage1 can be written as

$$\frac{(p_{02})_1}{p_{01_1}} = \left(1 + \frac{\eta_{stage} U \left(\frac{V_{w2} - 0}{c_p}\right)}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (6)$$

Similarly pressure raise across stage2

$$\frac{(p_{02})_2}{p_{01_2}} = \left(1 + \frac{\eta_{stage} U \left(\frac{V_{w4} - V_{w3}}{c_p}\right)}{T_{01}}\right)^{\frac{\gamma}{\gamma-1}} \qquad (7)$$

Where V_{w1}, V_{w2}, V_{w3}, V_{w4} are tangential velocities at respective rotors as shown in figure9.

The total pressure increase across two stage traditional compressor can be written as

$$\frac{(p_{02})_1}{p_{01_1}} + \frac{(p_{02})_2}{p_{01_2}} \qquad (8)$$

On comparing equation 5, 8 roughly we can conclude that the pressure raise across single stage contra rotating axial compressor is equal to total pressure raise across two stage traditional axial compressor. Hence the shaft length of traditional compressor is made to decrease by 30% to 40% and stators can also be eliminated by employing contra rotating compressor.

Thereby pressure ratio is directly proportional to efficiency from equation1, hence the efficiency of contra rotating compressor may be made to increase from 16% to 30% when compared to traditional compressor.

Table 2: Comparison four stage traditional axial compressor with four stage contra rotating axial compressor.

	Traditional compressor	Contra rotating compressor
Velocity(z direction)	180 m/s	257 m/s
Density	1. 09 kg/m^3	0. 82 kg/m^3
Temperature	328 K	425. 6 K
Pressure	96. 9 kpa	100. 35 kpa

Special attention is sure while selecting the optimum rotational speed, diameter of planetary gears and flow radial equilibrium conditions.

DISCUSSION

Similar concept applied in contra rotating compressor is internal gearing mechanism which can also be used for rotating the turbine in contra direction.

Software used

Solid works Flow simulation (Multi Rotating frames).

RESULT

1) The total pressure raise across single stage contra rotating compressor is greater than total pressure raise across two stage traditional compressor.
2) In this way of approach the contra rotating compressor is noisy when compared to axial flow compressor.
3) Due to weights of the gears which are added the efficiency of the contra rotating compressor is reduced and also the mechanical complexity is another challenge.
4) The efficiency of contra rotating compressor is more than traditional compressor

CONCLUSION

In detail discussion of design of contra rotating axial compressor and flow simulation results of contra rotating compressor compared with traditional compressor. Variation of flow properties at exit of four stage traditional compressor compared with variation of flow properties of four stage contra rotating axial compressor.

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