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QUASI THREE DIMENSIONAL COMPRESSOR DESIGN FOR A TWIN-SPOOL LOW BYPASS RATIO TURBOFAN ENGINE

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ABSTRACT
This paper presents the preliminary design of a three stage fan for a twin-spool low bypass ratio turbofan aeroengine. Design produre has been initialized with the specification of technical requirements obtained from the parametric cycle analysis. With this information, a suitable baseline engine is selected that has the closest technical specifications. The design process continues with the determination of the number of fan stages and other stage parameters. The next step is the designation of the blade airfoil profiles such that they have adequate stall margin in subsonic conditions. Airfoils are designed to avoid both positive and negative stall situations. Hub profiles have noticeably larger cambers due to lower linear speeds in comparison to tip profiles. By stacking up airfoil profiles in the radial direction form hub to tip a quasi three dimensional design is reached. Finally, solid models of the rotor and the stator parts were produced.

Keywords**:** *Compressor design, Blade airfoil, Compressor aerodynamics.*

DÜŞÜK BYPASS ORANLI ÇİFT MAKARALI BİR TURBOFAN MOTORUNUN SANKİ ÜÇ BOYUTLU KOMRESÖR TASARIMI

ÖZET
Bu çalışmada düşük tali akım (bypass) oranına sahip, çift makaralı bir turbofan motorunun başlangıç tasarımı anlatılmıştır. Tasarıma parametrik çevrim analizinden elde edilen teknik isterlerin özellikleriyle başlanmıştır. Bu bilgiyle teknik özelliklere uygun bir temel motor seçilmiştir. Tasarım süreci fan kademe sayısının diğer kademe parametrelerinin belirlenmesiyle devam etmiştir. Bir sonraki aşama sesaltı koşullarında gerekli sonuçları veren kompresör kanatçık profilinin seçilmesi olmuştur. Profiller pozitif ve negatif tutunma kaybı durumlarından kaçınacak şekilde tasarlanmıştır. Kök profillerin seçiminde uç profillere nazaran düşük lineer hızlarda çalışmasından ötürü kamburluğun bu profillerde büyük olmasına dikkat edilmiştir.Radyal yönde profillerin düzenli bir şekilde dizilmesinden dolayı sanki üç boyutlu bir tasarıma ulaşımıştır. Son olarak, rotor ve stator kısımlarının katı modeli çizilmiştir.

Anahtar Kelimeler: *Kompresör tasarımı, Kanatçık profili, Kompresör aerodinamiği.*

1. INTRODUCTION

In this paper, fan design for a low bypass ratio aeroengine is performed according to pre-specified design objectives. Such engines are typically utilized in fighter aircraft. F-100 engine shown in Fig. 1 is a typical example. This engine is also used as a baseline for this study. Detailed design requirements for the whole aircraft and also for the engine can be found in [1]. After a through constraint [2] and parametric cycle analyses [1], the engine is sized to breathe an air mass flow rate of 201.8 kg/s. Moreover, the low pressure compressor (fan) is required to deliver a pressure ratio of 3.8. Incoming Mach number is also dictated by nominal flight conditions, however it can be altered through an area change at the inlet. Other relevant design point values are throughly discussed at appropriate locations within the article.

Note that in aircraft gas turbines the design engineer is more concerned with maximizing the work done per stage while trying to maintain an acceptable level of overall axial compressor efficiency. On the other hand, increased stage loading translates into certain

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aerodynamic constraints. Low aspect ratio blading is preferred since its introduction in the 1970s. Although it might seem counter-intuitive as this blading increases the aeroengine weight, this disadvantage is far off-set by high loading capacity, high-efficiency and good range [3].

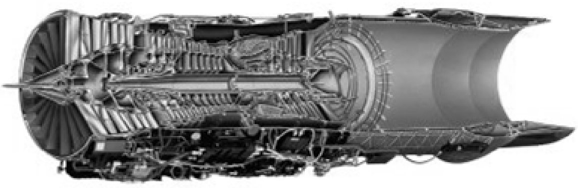

Figure 1. A Low Bypass Ratio Aeroengine (Image:Courtesy of Pratt & Whitney).

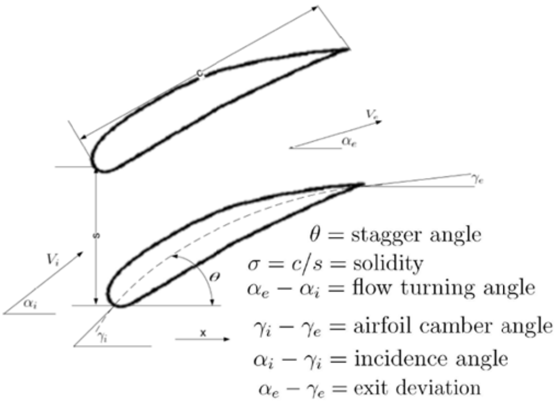

Figure 2. Cascade Airfoil Nomenclature [4].

The flow field inside an axial compressor is quite complex, a reason that explains the proliferation of research and development activities over the years [3]. The primary aim of this study is to reach a three dimensional design that can be used for further fine tuning and optimization. This is achieved by following some well established design procedures and common practice. The paper begins with a brief reminder on compressor aerodynamics and addresses key issues on fixed mean radius repeating-row-repeating stage compressor design. Afterwards the nominal operating point is selected and number of stages are determined, lastly aerodynamic design issues are addressed and results are briefly discussed.

2. COMPRESSOR AERODYNAMICS

The very first stage in a compressor design task is the understanding of compressor aerodynamics. One axial compressor stage consists of a rotor and a stator. Rotor adds kinetic energy to the flow whereas this kinetic energy is turned into pressure in the stator. The stator also provides the correct flow angle for the upcoming stage. A compressor stage consists of moving and stationary airfoils termed as blades (rotor) and vanes (stator) respectively. A cascade airfoil arrangement is shown in Fig.2. The ratio of airfoil chord length c to airfoil spacing s is termed as solidity and is denoted by σ. Also note that the at the design point the incidence angle is practically zero to achieve best aerodynamic performance.

Further elaborating on aerodynamics, Fig. 3 shows velocity triangles for a compressor stage. The absolute velocity at the rotor entrance is , whereas is the relative velocity of the flow with respect to an observer on the rotor. Similarly absolute and relative velocities are also defined for stations two and three. Angle is the angle between the absolute flow velocity and the compressor axis. Similarly, angle β is the angle between the relative flow velocity and the compressor axis.

Design procedure is iniated with the following assumptions [4],

- Repeating row/repeating airfoil cascade geometry ($\alpha_1 = \beta_2 = \alpha_3,\ \beta_1 = \alpha_2 = \beta_3$)
- Flow is two dimensional
- Axial velocity is constant ($u_1=u_2=u_3$)
- Losses are characterized by the stage polytropic efficiency, e
- Mean radius is constant ($r_m=(r_h+r_t)/2$)
- Gas is calorifically perfect

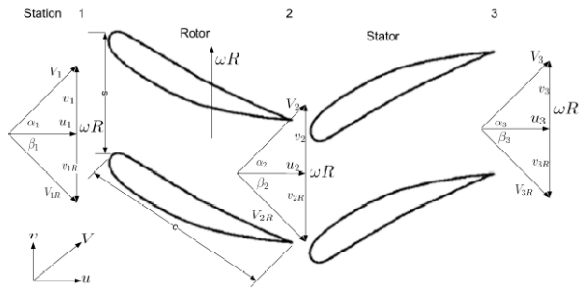

Figure 3. Velocity triangles for compressor stage.

Note that the assumption of constant axial velocity greatly simplifies the analysis because every velocity triangle in Fig. has the same base dimension. This approach is also consistent with the current design practice [4]. In order to achieve constant axial velocity cross sectional area is altered according to Eq. 1.

$$\dot{m} = \rho_1 u_1 A_1 = \rho_2 u_2 A_2 = \rho_3 u_3 A_3 \quad (1)$$

Assuming uniform total properties at the station then the cross sectional flow area can be calculated using the so called mass flow parameter (MFP) by Eq. 2. Mass flow parameter is defined as per Eq 3. It is particularly useful for calculating flow areas or in finding any single flow quantity, provided that the other four quantities are known at that station [5].

$$A_i = \frac{\dot{m}\sqrt{T_{ti}}}{P_{ti}(cos\alpha_i)MFP(M_i)} \quad (2)$$

$$MFP = \frac{\dot{m}\sqrt{T_{ti}}}{P_t A} = M\sqrt{\frac{\gamma}{R}}(1+\frac{\gamma-1}{2}M^2)^{\frac{\gamma+1}{2(1-\gamma)}} \quad (3)$$

Since the stages are repeating $\beta_2 = \alpha_1$ from velocity triangles.

$$v_{2R} = v_1 = wr - v_2 \quad (4)$$

$$v_1 + v_2 = wr \quad (5)$$

In this case the diffusion factor is the same for both the rotor and the stator. If one solves for α_2 from Eq. 6

$$D = \left(1 - \frac{cos\alpha_2}{cos\alpha_1}\right) + \left(\frac{tan\alpha_2 - tan\alpha_1}{2\sigma}\right)cos\alpha_2 \quad (6)$$

Therefore for a given value of α_1, σ and D there is only one corresponding α_2 value [5], which can be solved from Eq. 7.

$$cos\alpha_2 = \frac{2\sigma(1-D)\Gamma + \sqrt{\Gamma^2 + 1 - 4\sigma^2(1-D)^2}}{\Gamma^2+1} \quad (7)$$

where,

$$\Gamma = \frac{2\sigma + sin\alpha_1}{cos\alpha_1} \quad (8)$$

Temperature rise accross the stage can be calculated from the total enthalpy change, which in turn can be calculated from the velocity triangles as per Eq. 9. Note that since the gas is calorifically perfect and there is no chemical reaction, then $\Delta h = c_p \Delta T$.

$$\Delta T_t = T_{t3} - T_{t1} = \frac{V_2^2 - V_1^2}{c_p} = \frac{V_1^2}{c_p} = \left(\frac{cos^2\alpha_1}{cos^2\alpha_2} - 1\right) \quad (9)$$

Consequently total enthalpy ratio accross the stage is calculated according to Eq. 10.

$$\tau = \frac{T_{t3}}{T_{t1}} = \frac{(\gamma-1)M_1^2}{1+(\gamma-1)M_1^2/2}\left(\frac{cos^2\alpha_1}{cos^2\alpha_2} - 1\right) + 1 \quad (10)$$

Knowing the total temperature ratio τ and stage polytropic efficiency e stage pressure ratio π can be calculated with Eq. 11.

$$\pi = \frac{P_{t3}}{P_{t1}} = (\tau_s)^{\gamma e_c/(\gamma-1)} \quad (11)$$

Another important quantity of interest to the designer is the disk speed wR to the inlet speed V_1ratio. With the aid of velocity triangles and some trigonometry this can be calculated as follows (Eq. 12).

$$\frac{wr}{V_1} = cos\alpha_1(tan\alpha_1 + tan\alpha_2) \quad (12)$$

Consequently for a specified value of the diffusion factor, solidity and stage polytropic efficiency one can plot the whole family of solutions for a repeating row repeating stage compressor stage as a function the flow inlet angle α_1 [5]. The results are provided in Fig.4. Note that, this figure holds the key for the repeating-rowrepeating stage design procedure.

For a design to be realistic one must take into account radial variations. In order to do a constant amount of work on the fluid passing through a stage less turning of the fluid is required with increasing radius due to the Euler pump equation [6]. Furthermore, static pressure has to increase to keep the radial equilibrium of the swirling flow. Consequently, airfoil and flow properties should vary in the radial direction.

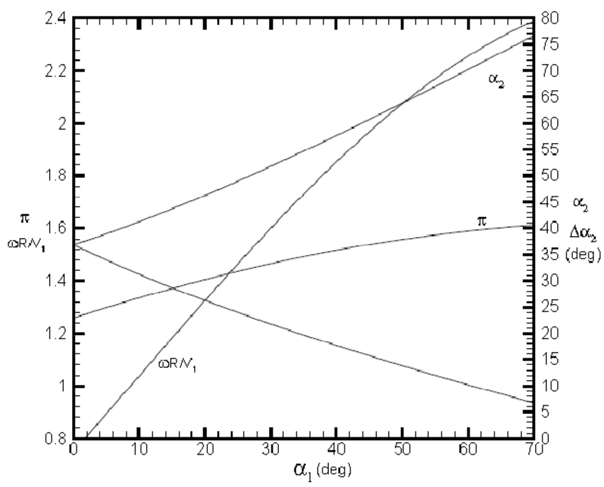

Figure 4. Repating Compressor Stage (D = 0.55, σ = 1.0, e = 0.90).

In this paper, a case where the stagnation enthalpy is constant along the radius is taken into consideration. One such velocity distribution is the free vortex swirl distribution. For free vortex swirl distribution the swirl velocity is given by Eq. 13.

$$v_1 = a\frac{r_m}{r} - br_m r \quad \& \quad v_2 = a + -br_m r \quad (13)$$

Note that for a repeating stage design as is the case here $v_1 = v_3$ and the degree of reaction is provided by Eq. 14.

$$°R = 1 - \frac{a}{wr_m}\left(\frac{r_m}{r}\right)^2 \quad (14)$$

where the constant a is given by,

$$a = wr_m(1 - °R_m) \quad (15)$$

Inlet guide vanes (IGV) are commonly used prior to the first compressor stage. They have a dual purpose; first one is to adjust to Mach number of the flow, the second one is to divert the flow angle for the very first compressor stage. Assuming that the flow is isentropic between the free stream (0) and the exit of inlet guide vanes (1), the following relation can be written (Eq.16).

$$A_0 MFP(M_0) = (cos\alpha_1)A_1 MFP(M_1) \quad (16)$$

Table 1 shows typical design values for axial compressors of aeroengines. These values nevertheless represent the state-of-the-art and hence are used as guidelines throughout the design procedure.

Table 1. Typical values of compressor parameters [5].

Parameter	Typical value
Flow coefficient	0.6
D-Factor	0.45
Axial Mach number	0.5
Degree of reaction	0.5
Reynolds number based on chord	5×10^5
Tip relative Mach number (1st rotor)	1.3-1.4
Stage average solidity	1.4
Stage average aspect ratio	1
Polytropic efficiency	0.9
Hub rotational speed	300 m/s
Tip rotational speed	400 m/s
Loading coefficient	0.35
DCA blade Mach range	0.8-1.2
NACA-65 series Mach range	<0.8
Blade leading radius	%5 of tmax
Compressor pressure ratio per spool	up to 20
Aspect ratio, fan	~3
Aspect ratio, compressor	~2
Taper ratio	0.8

3. DESIGN METHOD

The fan design process is started with examining the fan of the baseline model F-100, which serves as the powerplant to the F-16 fighter aircarft [7]. With the information gained from baseline model and the parametric cycle analysis, the new parameters are determined for design point. After the design point determination, the number of stages is determined with the help of information of baseline model and other low bypass ratio turbofan engines. Computations are carried out in OCTAVE environment. Finally, a solid model is drawn for the three-stage fan.

3.1. Design Point Determination

The design process is accomplished with the selection of the fan design point and the determination of the number of fan stages. Off-design point complications were not addressed. Thereafter, stage parameters D, M_0, σ, e and the aerodynamic definition of each stage are chosen according to design guidelines and the current technology level.Diffusion factor D is a measure of difficulty for modelling the cascade and airfoil flows in compressor. To determine a realistic value, the present technology level is considered. With the state-of-the-art aerodynamic understanding designing for diffusion factors up to 0.6 are quite possible. Thus it is logical to select D to be 0.56 for the first design iteration. The other design point values are $M_0 = 0.64$,$\sigma = 1$ and $e = 0.89$.

3.2. Determination of the Number of Stages

The number of stage has a number of effects on the engine performance, especially on the pressure ratio required for mixing and the temperature rise. Determination of the number of stage is performed within the light of the parametric cycle analysis, baseline model and the existing engine models. The most of the existing low bypass ratio turbofan engines such as F-119 and EJ-200 utilize three stages in their low pressure compressors and the selected baseline model F-100 turbofan engine has also a three stage fan [8]. Furthermore, the parametric analysis shows that the selection of fan pressure ratio to be 3.8 would be more logical in order to achieve required performance. If the fan pressure ratio is determined to be 3.8, this ratio can be easily accomplished with the three stage fan. As a result, fan pressure ratio is selected to be 3.8 for our design.

3.3. Aerodynamic Design

It is fortunate that, compressor stage design is not as though as a turbine stage design. This is because the Mach number of the flow decreases as it passes through stages of compression and therefore compressibility effects are reduced and also the probability of shock is avoided. Furthermore due to the reduced blade height at later stages (due to area contraction) the difference between hub and tip speeds also diminished aiding the designer. Most of the compressors utilize NACA 65-series airfoils that give adequate stall margin in subsonic conditions. In multistage compressors, airfoils are designed to avoid several stall situations. To illustrate, the front face of the compressor tends to positive stall while the aft stage has a tendency to negative stall that is the main reason why airfoils are important in a compressor.

For the current design NACA 65A010 blade profile is used for all stages. This profile is shown in Fig. 5, additionally airfoil coordinates are provided in Table 2. Leading edge radius is 0.654% of the chord length. Furthermore, the tip profile has 3% thickness and the hub profile has 10% thickness for the first stage. Since both the hub and the tip linear speeds are reduced from the front to the aft of the fan (due to area contraction), the tip profile has 4% thickness and the hub profile has 9% thickness for stage 2. Similar to the second stage, the tip and the hub profiles have 5 and 8% thicknesses respectively for the third stage. The hub profiles have also wider cambers due to the lower linear speed rather than tip profiles in our design. The hub, tip and mid-span profiles for the first stage are provided seen in Fig.6. The profiles are stacked on top of each other and hence a quasi three dimensional blade shape is obtained.

Table 2. Airfoil coordinates.

x	y	dy/dx
0	0	n/a
0.5	0.7753	0.7243
0.75	0.9368	0.5866
1.25	1.1923	0.4471
2.5	1.6303	0.2809
5	2.1872	0.1953
7.5	2.6525	0.1721
10	3.0429	0.1432
15	3.6607	0.1069
20	4.1288	0.0812
25	4.4834	0.0608
30	4.7413	0.0427
35	4.9114	0.0256
40	4.9938	0.0075
45	4.9816	-0.0126
50	4.8618	-0.0353
55	4.6306	-0.0572
60	4.301	-0.0739
65	3.8966	-0.0876
70	3.4298	-0.0994
75	2.9104	-0.1081
80	2.3518	-0.1149
85	1.7714	-0.1158
90	1.1893	-0.1188
95	0.6033	-0.1089
100	0	-6.0658

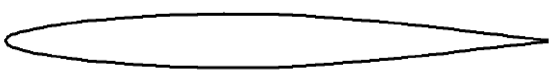

Figure 5. NACA 65A010 Blade Profile.

While determining metal angles γ, we chose zero incidence angles for all stages across, which is nothing but the common design practice, and exit deviations are compensated as per the Carter rule (Eq. 17). Blade angles are provided in Table 5. More detailed calculations would require blade-to-blade solutions of coupled Euler and boundary layer equations in order to check for exit deviations and to also verify polytropic efficiencies as well as assumptions on the diffusion factor [9], however we have not followed such a detailed procedure for a preliminary design.

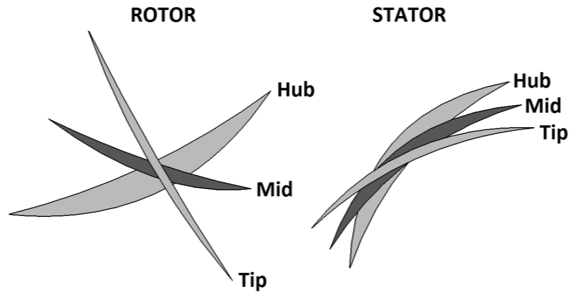

Figure 6. Hub, Tip and Midspan Profiles of the First Stage.

$$\delta_c = \frac{\gamma_1 - \gamma_2}{4\sigma} \tag{17}$$

Solidity σ being known number of blades is easily found by dividing the circumference at the mean radius to the blade spacing s and rounding up to the next integer.

Table 3. Summary of fan design.

Stage	0	1	2	3
M_1	0.64	0.867	0.68	0.595
π_s	1	1.6651	1.5497	1.4681
$P_{t1},\ kPa$	101.3	101.3	168.7	261.4
$T_{t1},\ K$	293.2	293.2	345.3	397.4
$r_h,\ mm$	200.7	239.6	291.4	323.5
$r_t,\ mm$	630.1	591.2	539.4	507.2
$A_1,\ m^2$	1.121	1.095	0.751	0.546

Table 4. Number of blades for each row.

Stage	0	1	2	3
		Rotor		
c/h	-	0.4	0.4	0.4
Blades	-	18	25	34
Chord, mm	-	15.42	10.72	7.86
		Stator		
c/h	0.3	0.4	0.4	0.4
Blades	21	21	30	39
Chord, mm	12.73	12.79	9.14	6.84

A schematic cross-section of the fan is provided in Fig.7. As seen in the figure three stages follow an inlet guide vane. Three dimensional rotor and stator parts of the fan are drawn with the aid of a solid modeling program. Hub and case were also added to the three dimensional solid models. The whole fan assembly can be seen in Fig 8. Similarly the stator and rotor assemblies are individually shown in Fig. 9.

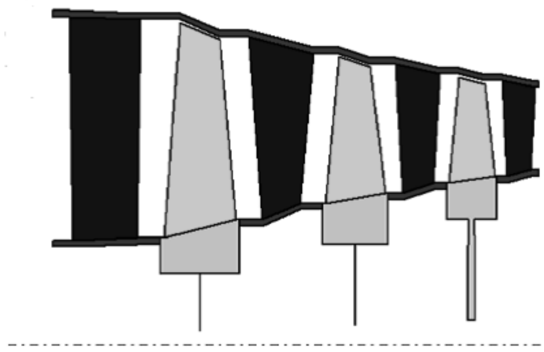

Figure 7. Fan cross section.

Table 5. Blade Angles.

Stage		Hub		Mean		Tip	
		Rotor	Stator	Rotor	Stator	Rotor	Stator
IGV	Inlet	0.0		0.0		0.0	
	Exit	58.8		38.7		29.2	
1	Inlet	9.9	67.0	-53.6	53.6	-68.3	43.6
	Exit	60.7	33.8	-20.8	20.8	-57.1	13.5
2	Inlet	-21.9	62.7	-53.6	53.6	-65.2	46.3
	Exit	44.3	29.5	-20.8	20.8	-51.1	15.1
3	Inlet	-34.6	60.2	-53.6	53.6	-62.8	48.0
	Exit	27.9	27.0	-20.8	20.8	-46.1	16.2

4. CONCLUSION

In conclusion a quasi three dimensional fan design has been accomplished using a repeating row repeating stage design procedure. Note that in an axial compressor the actual flow field is quite elaborate. In this design procedure recall that secondary flows, leakages are not incorporated into design directly. However, they are somehow accounted for in the choice of polytropic efficiency. Polytropic efficiency is an indicator of the technology level. Therefore, these effects can be lumped into this parameter, for the sake of performing preliminary calculations. This preliminary compressor design can then be utilized as a baseline for some quite sophisticated three dimensional inverse aerodynamic design procedures in order to optimize the aerodynamic shape. Therefore such a preliminary design procedure can reduce the overall turnover time for design iteration. After these efforts a test rig would ultimately be necessary to obtain the full operating characteristics experimentally and to check the validity of certain assumptions made during the preliminary design phase.

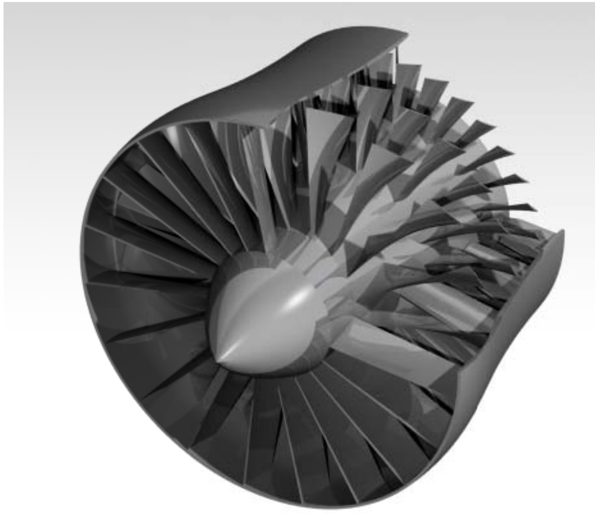

Figure 8. Cutaway view of the fan assembly.

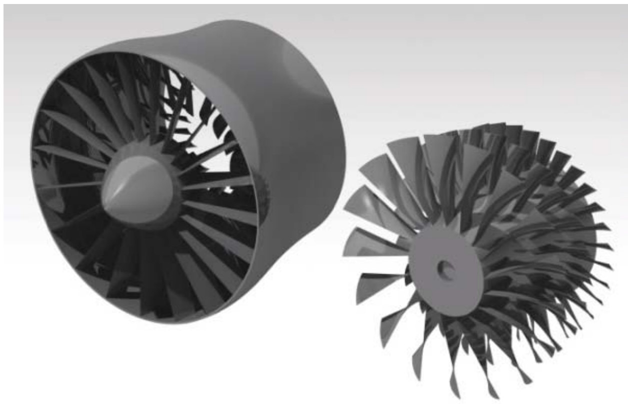

Figure 9. Stator and rotor assemblies.

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VITAE

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