Fundamentals of Jet Propulsion with Applications

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On the cover is the PW 4000 Series – 112-inch fan (courtesy of Pratt & Whitney)

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the tip and with significant blade twist from hub to tip. Typical total pressure ratios for fans are 1.3 to 1.5 per stage. However, the fundamental thermodynamics, fluid mechanics, and design methodology are the same for the fan and two compressors. Thus, for the remainder of this chapter no distinctions are made in the analysis of the three stage types.

If one were to unwrap the blades around the periphery of the compressor and consider its geometry to be planar two-dimensional when viewed from the top, a series of "cascades" would be seen as shown in Figure 6.6.a. The fluid first enters the inlet guide vanes. Next, it enters the first rotating passage. In Figure 6.6.a, the rotor blades are shown to be moving with linear velocity U, which is found from $R\omega$, where ω is the angular speed and R is the mean radius of the passage. The blades and vanes are in fact airfoils, and the pressure (+ +) and suction surfaces (− −) can be defined as shown in the figure. After passing through the cascade of rotor blades, the fluid enters the cascade of stator vanes. The fluid is turned by these stationary vanes and readied to enter the second stage, beginning with the second rotor blades, ideally incidence free. In general, the second stage has a slightly different design than the first stage (all of the stages are different). The process is repeated for each stage. In Figure 6.6.a, compressor component stations 0 through 3 are defined. It is very important not to confuse these with engine station designations.

An important parameter in compressor design is the solidity, which is defined as C/s, where s is the blade spacing, or pitch, and C is the chord. The solidity is the inverse of the pitch-to-chord ratio s/C. Both parameters are defined in Figure 6.6.a. If the solidity becomes too large, frictional effects, which decrease the efficiency and total pressure ratio, become large because the boundary layers dominate the passage flow. However, if the solidity becomes too small, sufficient flow guidance is not attained (this phenomenon is termed "slip") and the flow thus does not adequately follow the blade shape. Separation can also become a major problem. For the low-solidity case due to slip, less power is added to the flow than desired; as a result, the compressor does not operate at the necessary pressure ratio. Because of accompanying separation (and losses), the maximum efficiency is not realized. Thus, a compromise is needed. In Section 6.11 a method is presented to optimize the single-stage aerodynamic performance or maximize the efficiency. Typical values of solidity for a compressor are approximately 1. The selection of solidity is partially responsible for the resulting number of blades in a cascade. For example, for the Pratt & Whitney JT9D turbofan, 46 blades are used on the fan rotor stage, and the number of blades on the compressor stages ranges from 60 to 154. For comparison, the exit guide vanes for the fan (which has an extremely large chord) have only nine blades.

It is very important that the number of stator vanes and rotor blades for a stage or nearby stages be different. If they were equal, a resonance due to fluid dynamic blade interactions could be generated, resulting in large blade, disk, and shaft vibrations accompanied by noise. This would reduce the life of the blades and compromise engine safety. Often, and if possible, blade or vane numbers are selected as prime numbers, but they are always chosen such that common multiple resonances are not excited. Cumpsty (1977) reviews this topic in detail.

Another important parameter for blade performance is the ratio of the distance to the maximum camber to the chord length of the blade a. This distance is also shown in Figure 6.6.a. This parameter strongly influences the lift and drag characteristics of blades, which in turn have marked effects on the efficiency and pressure ratio of a stage.

If one examines the cross-sectional flow areas in the passages between the blades (area normal to the mean flow direction), it will be seen that the areas increase from the inlet to the exit of the rotor, as shown in Fig 6.6.b, and also increase from the inlet to the exit of the stator. Thus, both the rotor and stator blade rows act like diffuser sections.