Rotor-Stator Interaction: Forces

When one rotor (or stator) blade passes through the wake of an upstream stator (or rotor) blade, it will clearly experience a fluctuation in the fluid forces that act upon it. In this section, the nature and magnitude of these rotor-stator interaction forces will be explored. Experience has shown that these unsteady forces are a strong function of the gap between the locus of the trailing edge of the upstream blade and the locus of the leading edge of the downstream blade. This distance will be termed the interblade spacing, and will be denoted by c_b.

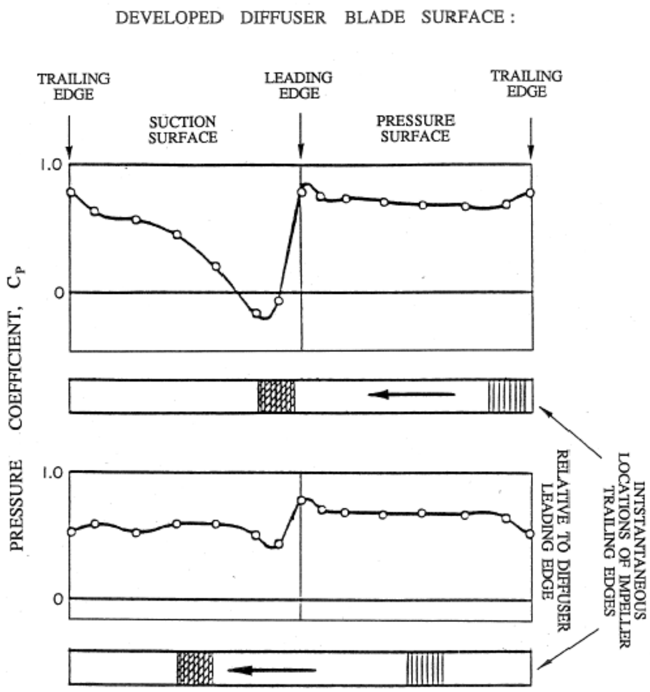

Figure 1: Pressure distributions on a diffuser blade at two different instants during the passage of an impeller blade. Data for an interblade spacing of 1.5% and $\phi_2 = 0.12$ (from Arndt *et al.* 1989).

Most axial compressors and turbines operate with fairly large interblade spacings, greater than 10% of the blade chord. As a result, the unsteady flows and forces measured under these circumstances (Gallus 1979, Gallus *et al.* 1980, Dring *et al.* 1982, Iino and Kasai 1985) are substantially smaller than those measured for radial machines (such as centrifugal pumps) in which the interblade spacing between the impeller and diffuser blades may be only a few percent of the impeller radius. Indeed, structural failure of the leading edge of centrifugal diffuser blades is not uncommon in the industry, and is typically solved by increasing the interblade spacing, though at the cost of reduced hydraulic performance.

Several early investigations of rotor-stator interaction forces were carried out using single foils in a wind tunnel (for example, Lefcort 1965). However, Gallus *et al.* (1980) appear to have been the first to measure the unsteady flows and forces due to rotor-stator interaction in an axial flow compressor. They attempt to collate their measurements with the theoretical analyses of Kemp and Sears (1955), Meyer (1958), Horlock (1968) and others. The measurements were conducted with large interblade spacing to axial chord ratios of about 50%, and involved documentation of the blade wakes. The impingement of these wakes on the following row of blades causes pressure fluctuations that are largest on the forward suction surface and small near the trailing edge of those blades. These pressure fluctuations lead to a fluctuation in the lift coefficient of ±0.06. Moreover, Gallus *et al.* (1980) show that the forces vary roughly inversely with the interblade spacing to axial chord ratio. Extrapolation would suggest that the unsteady and steady components of the lift might be roughly the same if this ratio were decreased to 5%. This estimate is confirmed by the measurements of Arndt *et al.*, described below. Before concluding this discussion of rotor-stator interaction forces in axial flow machines, we note that Dring *et al.* (1982) have examined the flows and forces for an interblade spacing to axial chord ratio of 0.35 and obtained results similar to those of Gallus *et al.*.

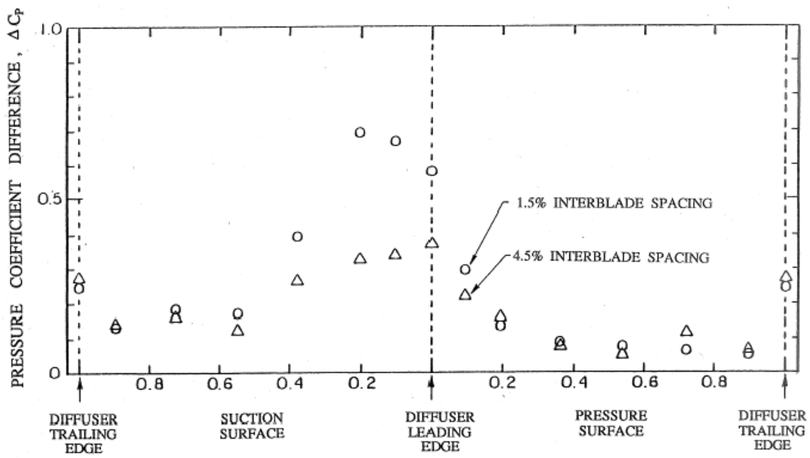

Figure 2: Magnitude of the fluctuation in the coefficient of pressure on a diffuser blade during the passage of an impeller blade as a function of location on the diffuser blade surface for two interblade spacings (from Arndt *et al.* 1989).

Recently, Arndt *et al.* (1989, 1990) (see also Brennen *et al.* 1988) have made measurements of the unsteady pressures and forces that occur in a radial flow machine when an impeller blade passes a diffuser blade. Figure 1 presents instantaneous pressure distributions (ensemble-averaged over many revolutions) for two particular relative positions of the impeller and diffuser blades. In the upper graph the trailing edge of the impeller blade has just passed the leading edge of the diffuser blade, causing a large perturbation in the pressure on the suction surface of the diffuser blade. Indeed, in this example, the pressure over a small region has fallen below the impeller inlet pressure ($C_p < 0$). The lower graph is the pressure distribution at a later time when the impeller blade is about half-way to the next diffuser blade. The perturbation in the diffuser blade pressure distribution has largely dissipated. Closer examination of the data suggests that the perturbation takes the form of a wave of negative pressure traveling along the suction surface of the diffuser blade and being attenuated as it propagates. This and other observations suggest that the cause is a vortex shed from the leading edge of the diffuser blade by the passage of the trailing edge of the impeller. This vortex is then convected along the suction surface of the diffuser blade.

The difference between the maximum and minimum pressure coefficient, ΔC_p, experienced at each position on the surface of a diffuser blade is plotted as a function of position in figure 2. Data is shown for two interblade spacings, $c_b = 0.015 R_{T2}$ and $0.045 R_{T2}$. This figure reiterates the fact that the pressure perturbations are largest on the suction surface just downstream of the leading edge. It also demonstrates that the pressure perturbations for the 1.5% interblade spacing are about double those for the 4.5% interblade spacing. Figure 2 was obtained at a particular flow coefficient of $\phi_2 = 0.12$; however, the same phenomena were encountered in the range $0.05 < \phi_2 < 0.15$, and the magnitude of the pressure perturbation showed an increase of about 50% between $\phi_2 = 0.05$ and $\phi_2 = 0.15$.

Given both the magnitude and phase of the instantaneous pressures on the surface of a diffuser blade, the result may be integrated to obtain the instantaneous lift, L, on the diffuser blade. Here the lift coefficient is defined as $C_L = L/\frac{1}{2}\rho\Omega^2 R_{T2}^2 cb$ where L is the force on the blade perpendicular to the mean chord, c is the chord, and b is the span of the diffuser blade. Time histories of C_L are plotted in figure 3 for three

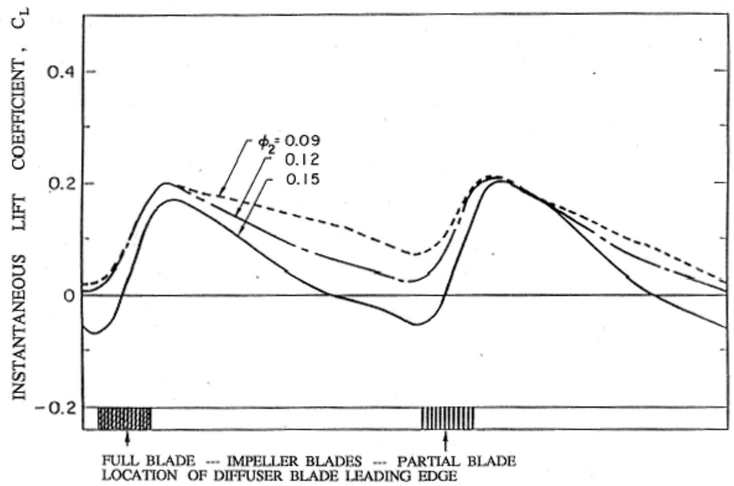

Figure 3: Variation in the instantaneous lift coefficient for a diffuser blade. The position of the diffuser blade leading edge relative to the impeller blade trailing edge is also shown. The data is for an interblade spacing of 4.5% (from Arndt *et al.* 1989).

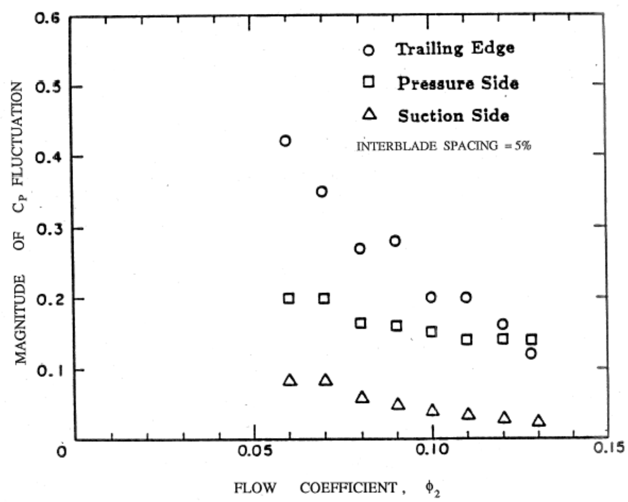

Figure 4: Magnitude of the fluctuations in the pressure coefficient at three locations near the trailing edge of an impeller blade during the passage of a diffuser blade (from Arndt *et al.* 1990).

different flow coefficients and an interblade spacing of 4.5%. Since the impeller blades consisted of main blades separated by partial blades, two ensemble-averaged cycles are shown for C_L though the differences between the passage of a full blade and a partial blade are small. Notice that even for the larger 4.5% interblade spacing, the instantaneous lift can be as much as three times the mean lift. Consequently, a structural design criterion based on the mean lift on the blades would be seriously flawed. Indeed, in this case it is clear that the principal structural consideration should be the unsteady lift, not the steady lift.

Arndt *et al.* (1990) also examined the unsteady pressures on the upstream impeller blades for a variety of diffusers. Again, large pressure fluctuations were encountered as a result of rotor-stator interaction. Typical results are shown in figure 4 where the magnitude of the pressure fluctuations is presented as a function of flow coefficient for three different locations on the surface of an impeller blade: (i) on the flat of the trailing edge, (ii) on the suction surface at $r/R_{T2} = 0.937$, and (iii) on the pressure surface at $r/R_{T2} = 0.987$. The data are for a 5% interblade spacing and all data points represent ensemble averages. The magnitudes of the fluctuations are of the same order as the pressure fluctuations on the diffuser blades, indicating that the unsteady loads on the *upstream* blade in rotor-stator interaction can also be substantial. Note, however, that contrary to the trend with the diffuser blades, the magnitude of the pressure fluctuations *decrease* with increasing flow coefficient. Finally, note that the magnitude of the pressure fluctuations are as large as the total head rise across the pump. This raises the possibility of transient cavitation being caused by rotor-stator interaction.

Considering the magnitude of these rotor-stator interaction effects, it is surprising that there is such a limited quantity of data available on the unsteady forces.