Blade Tip Rotordynamic Effects

In a seminal paper, Alford (1965) identified several rotordynamic effects arising from the flow in the clearance region between the tip of an axial flow turbomachine blade and the static housing. However, the so-called "Alford effects" are only some of the members of a class of rotordynamic phenomena that can arise from the fluid-induced effects of a finite number of blades, and, in this section, we shall first examine the more general class of phenomena.

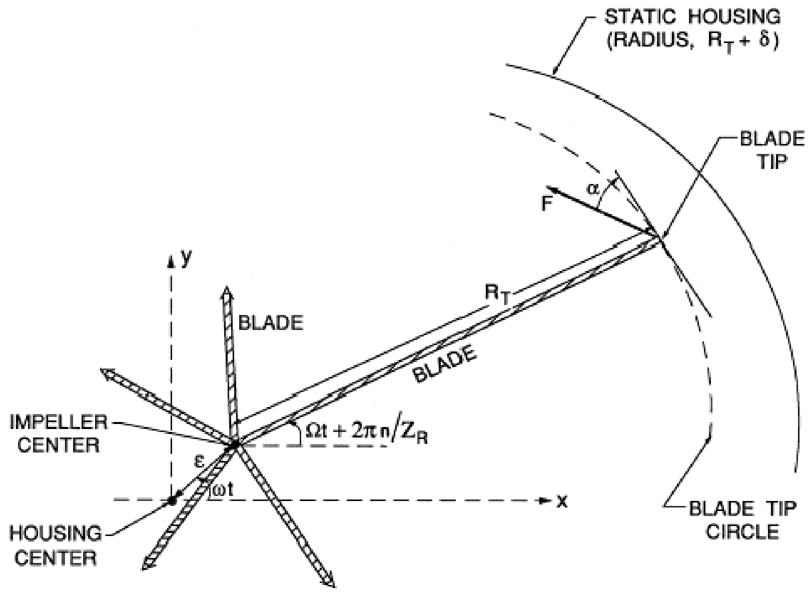

Figure 1: Schematic of the position of an axial flow turbomachine blade tip relative to a static housing as a result of the combination of rotational and whirl motion (details shown for only one of the Z_R blade tips).

Consider the typical geometry of an unshrouded impeller of radius R_T and Z_R blades enclosed by a cylindrical housing so that the mean clearance between the blade tips and the housing is δ (figure 1). If the impeller is rotating at a frequency, Ω, and whirling at a frequency, ω, with an amplitude, ϵ, then the vector positions of the blade tips at time, t, will be given by

$$x + jy = z = R_T e^{j(\Omega t + 2\pi n/Z_R)} + \epsilon e^{j\omega t} \quad \text{for} \quad n = 1 \text{ to } Z_R \tag{Mci1}$$

where the center of the housing is the origin of the (x, y) coordinate system. It follows that the clearance at each blade tip is $R_T + \delta - |z|$ which, to first order in ϵ, is δ^* where

$$\delta^* = \delta - \epsilon \cos\theta_n \quad , \quad n = 1 \text{ to } Z_R \tag{Mci2}$$

and where, for convenience, $\theta_n = \Omega t - \omega t + 2\pi n/Z_R$.

Next, the most general form of the force, F^*, acting on the tip of the blade is

$$F^* = F e^{j(\frac{\pi}{2}+\alpha)} e^{j(\Omega t + 2\pi n/Z_R)} \tag{Mci3}$$

where the functional forms of the force magnitude, F, and its inclination relative to the blade, α (see figure 1), can, for the moment, remain unspecified. The total rotordynamic forces, F_n^* and F_t^*, acting on the impeller are then obtained by appropriate summation of the individual tip forces, F^*, followed by conversion to the rotating frame. Nondimensionalizing the result, one then finds

$$F_n + jF_t = \frac{\left[\sum_{n=1}^{Z_R} j e^{j\alpha} e^{j\theta_n} F \right]_{\text{AVERAGE}}}{\pi \rho \Omega^2 R_T L \epsilon} \tag{Mci4}$$

where the quantity in square brackets is averaged over a large time. This general result may then be used, with various postulated relations for F and α, to investigate the resulting rotordynamic effects.

One choice of the form of F and α corresponds to the Alford effect. Alford (1965) surmised that the fluid force acting normal to each blade ($\alpha = 0$ or π) would vary according to the instantaneous tip clearance of that blade. Specifically, he argued that an increase in the clearance, $\epsilon \cos\theta_n$, would produce a proportionate decrease in the normal force, or

$$F = F_0 + \mathcal{K}\epsilon \cos\theta_n \tag{Mci5}$$

where F_0 is the mean, time-averaged force normal to each blade and $\mathcal{K}$ is the factor of proportionality. Moreover, for a pump $\alpha = \pi$, and for a turbine $\alpha = 0$. Substituting these values into equation (Mci4), one obtains

$$F_n = 0 \quad ; \quad F_t = \mp \mathcal{K} Z_R / 2\pi\rho\Omega^2 R_T L \tag{Mci6}$$

where the upper sign refers to the pump case and the lower to the turbine case. It follows that the Alford effect in pumps is stabilizing for positive whirl, and destabilizing for negative whirl. In a turbine the reverse is true, and the destabilizing forces for positive whirl can be quite important in the rotordynamics of some turbines.

As a second, but more theoretical example, consider the added mass effect that occurs when a blade tip approaches the casing and squeezes fluid out from the intervening gap. Such a flow would manifest a force on the blade proportional to the acceleration $d^2\delta^*/dt^2$, so that

$$\alpha = \pi/2 \quad ; \quad F = -\mathcal{K}\frac{d^2\delta^*}{dt^2} \tag{Mci7}$$

where $\mathcal{K}$ is some different proportionality factor. It follows from equation (Mci4) that, in this case,

$$F_n = \frac{\mathcal{K}}{2\pi\rho R_T L}\left(1 - \frac{\omega}{\Omega}\right)^2 \quad ; \quad F_t = 0 \tag{Mci8}$$

This positive normal force is a Bernoulli effect, and has the same basic form as the Bernoulli effect for the whirl of a plane cylinder (see section (Nld)).

Other tip clearance flow effects, such as those due to viscous or frictional effects, can be investigated using the general result in equation (Mci4), as well as appropriate choices for α and F.