Rotating Stall

Rotating stall is a phenomenon which may occur in a cascade of blades when these are required to operate at a high angle of incidence close to that at which the blades will stall. In a pump this usually implies that the flow rate has been reduced to a point close to or below the maximum in the head characteristic (see, for example, data in section (Mbbe)). Emmons *et al.* (1955) first provided a coherent explanation of propagating stall. The cascade in figure 1 will represent a set of blades (a rotor or a stator) operating at a high angle of incidence. Then, if blade B were stalled, this generates a separated wake and therefore increased blockage to the flow in the passage between blades B and A. This, in turn, would tend to deflect the flow away from this blockage in the manner indicated in the figure. The result would be an increase in the angle of incidence on blade A and a decrease in the angle of incidence on blade C. Thus, blade A would tend to stall while any stall on blade C would tend to diminish. Consequently, the stall "cell" would tend to move upwards in the figure or in a direction away from the oncoming flow. Of course, the stall cell could consist of a larger number of blades with more than one exhibiting increased separation or stall. The stall cell will rotate around the axis and hence the name "rotating stall." Moreover, the speed of propagation will clearly be some fraction of the circumferential component of the relative velocity, either $v_{\theta 1}$ in the case of a stator or $w_{\theta 1}$ in the case of a rotor. Consequently, in the case of a rotor, the stall rotates in the same direction as the rotor but with 50-70% of the rotor angular velocity.

In distinguishing between rotating stall and surge, it is important to note that the disturbance depicted in figure 1 does not necessarily imply any oscillation in the total mass flow rate through the turbomachine. Rather it implies a redistribution of that flow. On the other hand, it is always possible that the perturbation caused by rotating stall could resonate with, say, one of the acoustic modes in the inlet or discharge lines, in which case significant oscillation of the mass flow rate could occur.

While rotating stall can occur in any turbomachine, it is most frequently observed and most widely studied in compressors with large numbers of blades. Excellent reviews of this literature have been published by Emmons *et al.* (1959) and more recently by Greitzer (1981). Both point to a body of work

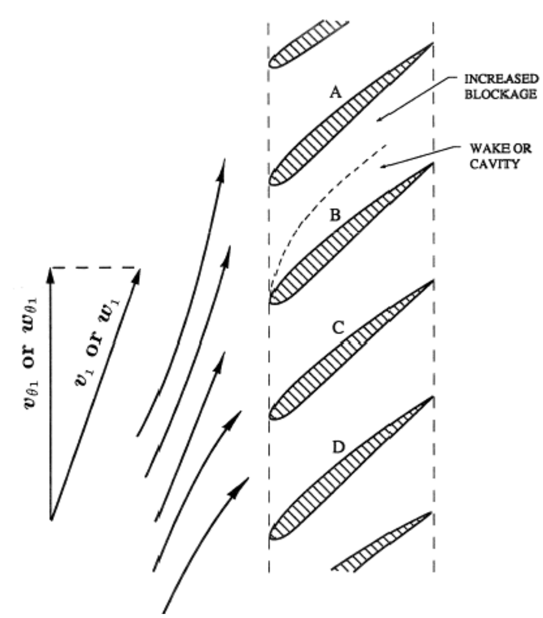

Figure 1: Schematic of a stall cell in rotating stall or rotating cavitation.

designed to predict both the onset and consequences of rotating stall. A useful approximate criterion is that rotating stall in the rotor occurs when one approaches a maximum in the total head rise as the flow coefficient decreases. This is, however, no more than a crude approximation and Greitzer (1981) quotes a number of cases in which rotating stall occurs while the slope of the performance curve is still negative. A more sophisticated criterion that is widely used is due to Leiblein (1965), and involves the diffusion factor, Df, defined previously in section (Mbcd). Experience indicates that rotating stall may begin when Df is increased to a value of about 0.6.

Though most of the observations of rotating stall have been made for axial compressors, Murai (1968) observed and investigated the phenomenon in a typical axial flow pump with 18 blades, a hub/tip radius ratio of 0.7, a tip solidity of 1.15, and a tip blade angle of 20°. His data on the rotating speed of the stall cell are reproduced in figure 2. Note that the onset of the rotating stall phenomenon occurs when the flow rate is reduced to a point below the maximum in the head characteristic. Notice also that the stall cell propagation velocities have typical values between 0.45 and 0.6 of the rotating speed. Rotating

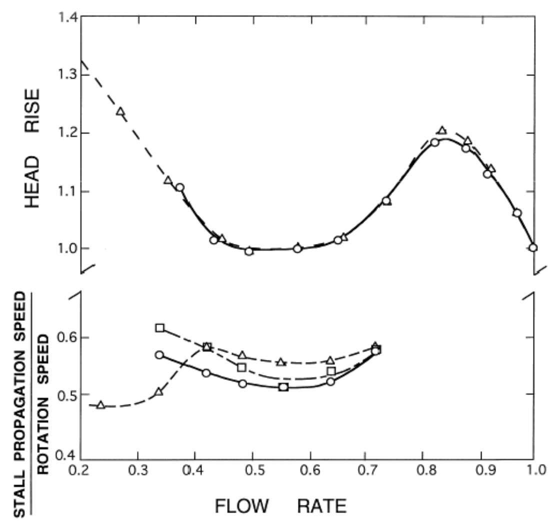

Figure 2: The head characteristic for an 18-bladed axial flow pump along with the measurements of the propagation velocity of the rotating stall cell relative to the shaft speed. Adapted from Murai (1968). Data is shown for three different inlet pressures. Flow and head scales are dimensionless.

stall has not, however, been reported in pumps with a small number of blades perhaps because Df will not approach 0.6 for typical axial pumps or inducers with a small number of blades. Most of the stability theories (for example, Emmons *et al.* 1959) are based on actuator disc models of the rotor in which it is assumed that the stall cell is much longer than the distance between the blades. Such an assumption would not be appropriate in an axial flow pump with three or four blades.

Murai (1968) also examined the effect of limited cavitation on the rotating stall phenomenon and observed that the cavitation did cause some alteration in the propagation speed as illustrated by the changes with inlet pressure seen in figure 2. It is, however, important to emphasize the difference between the phenomenon observed by Murai in which cavitation is secondary to the rotating stall and the phenomenon to be discussed below, namely rotating cavitation, which occurs at a point on the head-flow characteristic at which the slope is negative and stable, and at which rotating stall would not occur.

Turning now to centrifugal pumps, there have been a number of studies in which rotating stall has been observed either in the impeller or in the diffuser/volute. Hergt and Benner (1968) observed rotating stall in a vaned diffuser and conclude that it only occurs with some particular diffuser geometries. Lenneman and Howard (1970) examined the blade passage flow patterns associated with rotating stall and present data on the ratio, Ω_{RS}/Ω, of the propagation velocity of the stall cell to the impeller speed, Ω. They observed ratios ranging from 0.54 to 0.68 with, typically, lower values of the ratio at lower impeller speeds and at higher flow coefficients.

Perhaps the most detailed study is the recent research of Yoshida *et al.* (1991) who made the following observations on a 7-bladed centrifugal impeller operating with a variety of diffusers, with and without vanes. Rotating stall with a single cell was observed to occur in the impeller below a certain critical flow coefficient which depended on the diffuser geometry. In the absence of a diffuser, the cell speed was about $80-90\%$ of the impeller rotating speed; with diffuser vanes, this cell speed was reduced to the range $50-80\%$. When impeller rotating stall was present, they also detected the presence of some propagating disturbances with 2, 3 and 4 cells rather than one. These are probably due to nonlinearities and an interaction with blade passage excitation. Rotating stall was also observed to occur in the vaned diffuser with a speed less than 10% of the impeller speed. It was most evident when the clearance between the impeller and diffuser vanes was large. As this clearance was decreased, the diffuser rotating stall tended to disappear.

Even in the absence of blades, it is possible for a diffuser or volute to exhibit a propagating rotating "stall". Jansen (1964) and van der Braembussche (1982) first described this flow instability and indicate that the flow pattern propagates with a speed in the range of $5-25\%$ of the impeller speed. Yoshida *et al.* (1991) observed a four-cell rotating stall in their vaneless diffusers over a large range of flow coefficients and measured its velocity as about 20% of the impeller speed.

Finally, we note that rotating stall may resonate with an acoustic mode of the inlet or discharging piping to produce a serious pulsation problem. Dussourd (1968) identified such a problem in a boiler feed system in which the rotating stall frequency was in the range $0.15\Omega \rightarrow 0.25\Omega$, much lower than usual. He also made use of the frequency domain methods of section (Gbc) in modeling the dynamics of this multistage centrifugal pump system. This represents a good example of one of the many hybrid problems that can arise in systems with turbomachines.