Blade Flutter

Up to this point, all of the instabilities have been essentially hydrodynamic and would occur with a completely rigid structure. However, it needs to be observed that structural flexibility could modify any of the phenomena described. Furthermore, if a hydrodynamic instability frequency happens to coincide with the frequency of a major mode of vibration of the structure, the result will be a much more dangerous vibration problem. Though the hydroelastic behavior of single hydrofoils has been fairly well established (see the review by Abramson 1969), it would be virtually impossible to classify all of the possible fluid-structure interactions in a turbomachine given the number of possible hydrodynamic instabilities and the complexity of the typical pump structure. Rather, we shall confine attention to one of the simpler interactions and briefly discuss blade flutter. Though the rotor-stator interaction effects outlined above are more likely to cause serious blade vibration problems in turbomachines, it is also true that a blade may flutter and fail even in the absence of such excitation.

It is well known (see, for example, Fung 1955) that the incompressible, unstalled flow around a single airfoil will not exhibit flutter when permitted only one degree of freedom of flutter motion. Thus, classic aircraft wing flutter requires the coupling of two degrees of flutter motion, normally the bending and torsional modes of the cantilevered wing. Turbomachinery flutter is quite different from classic aircraft wing flutter and usually involves the excitation of a single structural mode. Several different phenomena can lead to single degree of freedom flutter when it would not otherwise occur in incompressible, unseparated (unstalled) flow. First, there are the effects of compressibility that can lead to phenomena such as supersonic flutter and choke flutter. These have been the subject of much research (see, for example, the reviews of Mikolajczak *et al* (1975), Platzer (1978), Sisto (1977), McCroskey (1977)), but are not of direct concern in the context of liquid turbomachinery, though the compressibility introduced by cavitation might provide some useful analogies. Of greater importance in the context of liquid turbomachinery is the phenomenon of stall flutter (see, for example, Sisto 1953, Fung 1955). A blade which is stalled during all or part of a cycle of oscillation can exhibit single degree of freedom flutter, and this type of flutter has been recognized as a problem in turbomachinery for many years (Platzer 1978, Sisto 1977). Unfortunately, there has been relatively little analytical work on stall flutter and any modern theory must at least consider the characteristics of dynamic stall (see McCroskey 1977). Like all single degree of freedom flutter problems, including those in turbomachines, the critical incident speed for the onset of stall flutter, U_C, is normally given by a particular value of a reduced speed, $U_{CR} = 2U_C/c\omega_F$, where c is the chord length and ω_F is the frequency of flutter or the natural frequency of the participating structural vibration mode. The inverse of U_{CR} is the reduced frequency, k_{CR}, or Strouhal number. Fung (1955) points out that the reduced frequency for stall flutter with a single foil is a function of the difference, θ, between the mean angle of incidence of the flow and the static angle of stall. A crude guide would be $k_{CR} = 0.3 + 4.5\theta$, $0.1 < k_{CR} < 0.8$. The second term in the expression for k_{CR} reflects the decrease in the critical speed with increasing incidence.

Of course, in a turbomachine or cascade, the vibration of one blade will generate forces on the neighboring blades (see, for example, Whitehead 1960), and these interactions can cause significant differences in the flutter analyses and critical speeds; often they have a large unfavorable effect on the flutter characteristics (McCroskey 1977). One must allow for various phase angles between neighboring blades, and examine waves which travel both forward and backward relative to the rotation of the rotor. A complete analysis of the vibrational modes of the rotor (or stator) must be combined with an unsteady fluid flow analysis (see, for example, Verdon 1985) in order to accurately predict the flutter boundaries in a turbomachine. Of course, most of the literature deals with structures that are typical of compressors and turbines. The lowest modes of vibration in a pump, on the other hand, can be very different in character from those in a compressor or turbine. Usually the blades have a much smaller aspect ratio so that the lowest modes involve localized vibration of the leading or trailing edges of the blades. Consequently, any potential flutter is likely to cause failure of portions of these leading or trailing edges.

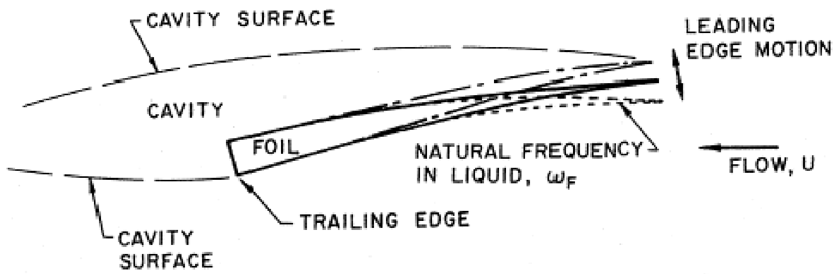

Figure 1: Sketch of the leading edge flutter of a cavitating hydrofoil or pump blade.

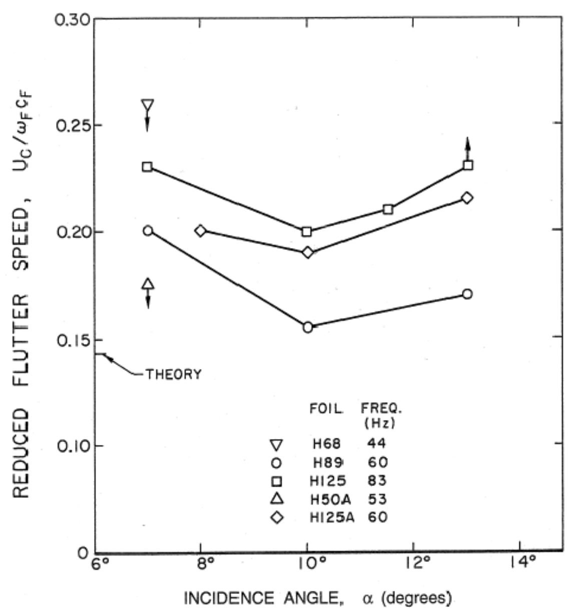

Figure 2: Dimensionless critical flutter speeds for single supercavitating hydrofoils at various angles of incidence, α, and very long cavities ($>$ 5 chord lengths) (from Brennen, Oey, and Babcock 1980).

The other major factor is the effect of cavitation. The changes which developed cavitation cause in the lift and drag characteristics of a single foil, also cause a fundamental change in the flutter characteristics with the result that a single cavitating foil can flutter (Abramson 1969). Thus a cavitating foil is unlike a noncavitating, nonseparated foil but qualitatively similar to a stalled foil whose flow it more closely resembles. Abramson (1969) provides a useful review of both the experiments and the analyses of flutter of rigid cavitating foils. However, as we previously remarked, the most likely form of flutter in a pump will not involve global blade motion but flexure of the leading or trailing edges. Since cavitation occurs at the leading edges, and since these are often made thin in order to optimize the hydraulic performance, leading edge flutter seems the most likely concern (figure 1). Data on this phenomenon was obtained by Brennen, Oey, and Babcock (1980), and is presented in figure 2. The critical incident fluid velocity, U_C, is nondimensionalized using ω_F, the lowest natural frequency of oscillation of the leading edge immersed in water, and a dimension, c_F, that corresponds to the typical chordwise length of the foil from the leading edge to the first node of the first mode of vibration. The data shows that $U_C/c_F\omega_F$ is almost independent of the incidence angle, and is consistent for a wide range of natural frequencies. Brennen *et al.* also utilize the unsteady lift and moment coefficients calculated by Parkin (1962) to generate a theoretical estimate of $U_C/c_F\omega_F$ of 0.14. From figure 2 this seems to constitute an upper design limit on the reduced critical speed. Also note that the value of 0.14 is much smaller than the values of $1-3$ quoted earlier for the stall flutter of a noncavitating foil. This difference emphasizes the enhanced flutter possibilities caused by cavitation. Brennen *et al.* also tested their foils under noncavitating conditions but found no sign of flutter even when the tunnel velocity was much larger than the cavitating flutter speed.

One footnote on the connection between the flutter characteristics of figure 2 and the partial cavitation oscillation of section (Mbfj) is worth adding. The data of figure 2 was obtained with long attached cavities, covering the entire suction surface of the foil as indicated in figure 1. At larger cavitation numbers, when the cavity length was decreased to about two chord lengths, the critical speed decreased markedly, and the leading edge flutter phenomenon began to metamorphose into the partial cavitation oscillation described in section (Mbfj).