# Introduction

The trend toward higher speed, high power density liquid turbomachinery has inevitably increased the potential for fluid/structure interaction problems, and the severity of those problems. Even in the absence of cavitation and its complications, these fluid structure interaction phenomena can lead to increased wear and, under the worst conditions, to structural failure. Exemplifying this trend, the Electrical Power Research Institute (Makay and Szamody 1978) has recognized that the occurrence of these problems in boiler feed pumps has contributed significantly to downtime in conventional power plants.

Unlike the cavitation issues, unsteady flow problems in liquid turbomachines do not have a long history of research. In some ways this is ironic since, as pointed out by Ek (1957) and Dean (1959), the flow within a turbomachine must necessarily be unsteady if work is to be done on or by the fluid. Yet many of the classical texts on pumps or turbines barely make mention of unsteady flow phenomena or of design considerations that might avoid such problems. In contrast to liquid turbomachinery, the literature on unsteady flow problems in gas turbomachinery is considerably more extensive, and there are a number of review papers that provide a good survey of the subject (for example, McCroskey 1977, Cumpsty 1977, Mikolajczak *et al.* 1975, Platzer 1978, Greitzer 1981). We will not attempt a review of this literature but we will try, where appropriate, to indicate areas of useful cross-reference. It is also clear that this subject incorporates a variety of problems ranging, for example, from blade flutter to fluid-induced rotordynamic instability. Because of this variety and the recent vintage of the fundamental research, no clear classification system for these problems has yet evolved and there may indeed be some phenomena that have yet to be properly identified. It follows that the classification system that we will attempt here will be tentative, and not necessarily comprehensive. Nevertheless, it seems that three different categories of flow oscillation can occur, and that there are a number phenomena within each of the three categories. We briefly list them here and return to some in the sections that follow.

[A] **Global Flow Oscillations.** A number of the identified vibration problems involve large scale oscillations of the flow. Specific examples are:

[**A1**] Rotating stall or rotating cavitation occurs when a turbomachine is required to operate at a high incidence angle close to the value at which the blades may stall. It is often the case that stall will first be manifest on a small number of adjacent blades and that this “stall cell” will propagate circumferentially at some fraction of the main impeller rotation speed. This phenomenon is called rotating stall and is usually associated with turbomachines having a substantial number of blades (such as compressors). It has, however, also been reported in centrifugal pumps. When the turbomachine cavitates the same phenomenon may still occur, perhaps in some slightly altered form. Such circumstances will be referred to as “rotating stall with cavitation.” But there is also a different phenomenon which can occur in which one or two blades manifest a greater degree of cavitation and this “cell” propagates around the rotor in a manner superficially similar to the propagation of rotating stall. This phenomenon is known as “rotating cavitation.”

[**A2**] Surge is manifest in a turbomachine that is required to operate under highly loaded circumstances where the slope of the head rise/flow rate curve is positive. It is a system instability to which the dynamics of all the components of the system (reservoirs, valves, inlet and suction lines and turbomachine) contribute. It results in pressure and flow rate oscillations throughout the system. When cavitation is present the phenomenon is termed “auto-oscillation” and can occur even when the slope of the head rise/flow rate curve is negative.

[**A3**] Partial cavitation or supercavitation can become unstable when the length of the cavity approaches the length of the blade so that the cavity collapses in the region of the trailing edge.

Such a circumstance can lead to violent oscillations in which the cavity length oscillates dramatically.

- [**A4**] Line resonance occurs when one of the blade passing frequencies in a turbomachine happens to coincide with one of the acoustic modes of the inlet or discharge line. The pressure oscillation magnitudes associated with these resonances can often cause substantial damage.
- [**A5**] It has been speculated that an axial balance resonance could occur if the turbomachine is fitted with a balance piston (designed to equalize the axial forces acting on the impeller) and if the resonant frequency of the balance piston system corresponds with the rotating speed or some blade passing frequency. Though there exist several apocryphal accounts of such resonances, the phenomenon has yet to be documented experimentally.
- [**A6**] Cavitation noise can sometimes reach a sufficient amplitude to cause resonance with structural frequencies of vibration.
- [**A7**] The above items all assume that the turbomachine is fixed in a non-accelerating reference frame. When this is not the case the dynamics of the turbomachine may play a crucial role in generating an instability that involves the vibration of that machine as a whole. Such phenomena, of which the Pogo instabilities are, perhaps, the best documented examples, are described further in section (Mbfn).

[B] **Local Flow Oscillations.** Several other vibration problems involve more localized flow oscillations and vibration of the blades:

- [**B1**] Blade flutter. As in the case of airfoils, there are circumstances under which an individual blade may begin to flutter (or diverge) as a consequence of the particular flow condition (incidence angle, velocity), the stiffness of the blade, and its method of support.
- [**B2**] Blade excitation due to rotor-stator interaction. While [B1] would occur in the absence of excitation it is also true that there are a number of possible mechanisms of excitation in a turbomachine that can cause significant blade vibration. This is particularly true for a row of stator blades operating just downstream of a row of impeller blades or vice versa. The wakes from the upstream blades can cause a serious vibration problem for the downstream blades at blade passing frequency or some multiple thereof. Non-axisymmetry in the inlet, the volute, or housing can also cause excitation of impeller blades at the impeller rotation frequency.
- [**B3**] Blade excitation due to vortex shedding or cavitation oscillations. In addition to the excitation of [B2], it is also possible that vortex shedding or the oscillations of cavitation could provide the excitation for blade vibrations.

[C] **Radial and Rotordynamic Forces.** Global forces perpendicular to the axis of rotation can generate several types of problem:

- [**C1**] Radial forces are forces perpendicular to the axis of rotation caused by circumferential nonuniformities in the inlet flow, casing, or volute. While these may be stationary in the frame of the pump housing, the loads that act on the impeller and, therefore, the bearings can be sufficient to create wear, vibration, and even failure of the bearings.
- [**C2**] Fluid-induced rotordynamic forces occur as the result of movement of the axis of rotation of the impeller-shaft system of the turbomachine. Contributions to these rotordynamic forces can arise from the seals, the flow through the impeller, leakage flows, or the flows in the bearings themselves. Sometimes these forces can cause a reduction in the critical speeds of the shaft system, and therefore an unforeseen limitation to its operating range. One of the common characteristics of a fluid-induced rotordynamic problem is that it often occurs at subsynchronous frequency.

Two of the subjects included in this list have a sufficiently voluminous literature to merit separate sections. Consequently, sections (Mca) to (Mcp) are devoted to radial and rotordynamic forces, and sections (Gba) to (Gbg) to the subject of system dynamic analysis and instabilities. The remainder of this chapter will briefly describe some of the other unsteady problems encountered in liquid turbomachines.

Before leaving the issue of classification, it is important to emphasize that many of the phenomena that cause serious vibration problems in turbomachines involve an interaction between two or more of the above mentioned items. Perhaps the most widely recognized of these resonance problems is that involving an interaction between blade passage excitation frequencies and acoustic modes of the suction or discharge lines. But the literature contains other examples. For instance, Dussourd (1968) describes flow oscillations which involve the interaction of rotating stall and acoustic line frequencies. Another example is given by Marscher (1988) who investigated a resonance between the rotordynamic motions of the shaft and the subsynchronous unsteady flows associated with flow recirculation at the inlet to a centrifugal impeller.