Unsteady Flows

Many of the phenomena listed in section (Mbfa) require some knowledge of the unsteady flows corresponding to the steady cascade flows discussed in sections (Mbcb) and (Mbce). In the case of non-cavitating axial cascades, a large volume of literature has been generated in the context of gas turbine engines, and there exist a number of extensive reviews including those by Woods (1961), McCroskey (1977), Mikolajczak *et al.* (1975) and Platzer (1978). Much of the analytical work utilizes linear cascade theory, for example, Kemp and Sears (1955), Woods (1955), Schorr and Reddy (1971), and Kemp and Ohashi (1975). Some of this has been applied to the analysis of unsteady flows in pumps and extended to cover the case of radial or mixed flow machines. For example, Tsukamoto and Ohashi (1982) utilized these methods to model the start-up transients in centifugal pumps and Tsujimoto *et al.* (1986) extended the analysis to evaluate the unsteady torque in mixed flow machines.

However, most of the available methods are restricted to lightly loaded cascades and impellers at low angles of incidence. Other, more complex, theories (for example, Adamczyk 1975) are needed at larger angles of incidence and for highly cambered cascades when there is a strong coupling between the steady and unsteady flow (Platzer 1978). Moreover, most of the early theories were only applicable to globally uniform unsteady flows in which the blades all move in unison. Samoylovich (1962) appears to have been the first to consider oscillations with arbitrary interblade phase differences, the kind of analysis needed for flutter investigations (see below).

When the incidence angles are large so that the blades stall, one must resort to unsteady free streamline methods in order to model the flows (Woods 1961). Apart from the work of Sisto (1967), very little analytical work has been done on this problem which is of considerable importance in the context of turbomachinery. One of the fluid mechanical complexities is the unsteady or dynamic response of a separated flow that may lead to significant departures from the sucession of events one might construct based on a quasistatic approach. Some progress has been made in understanding the "dynamic stall" for a single foil (see, for example, Ham 1968). However, it would appear that more work is needed to understand the complex dynamic stall phenomena in turbomachines.

Unsteady free streamline analyses can be more confidentally applied to the analysis of cavitating cascades because the cavity or free streamline pressure is usually known and constant whereas the corresponding pressure for the wake flows may be varying with time in a way that is difficult to predict. Thus, for example, the unsteady response for a single supercavitating foil (Woods 1957, Martin 1962, Parkin 1962) has been compared with experimental measurements by Acosta and DeLong (1971). As an example, we present (figure 1) some data from Acosta and DeLong on the unsteady forces on a single foil undergoing heave oscillations at various reduced frequencies, $\omega^* = \omega c/2U$. The oscillating heave motion, d, is represented by

$$d = Re\left\{\tilde{d}e^{j\omega t}\right\} \quad \text{(Mbfc1)}$$

where the complex quantity, $\tilde{d}$, contains the amplitude and phase of the displacement. The resulting lift coefficient, C_L, is decomposed (using the notation of sections (Gbc)) into

$$C_L = \bar{C}_L + Re\left\{\tilde{C}_{Lh}e^{j\omega t}\right\} \quad \text{(Mbfc2)}$$

and the real and imaginary parts of $\tilde{C}_{Lh}/\omega*$ which are plotted in figure 1 represent the unsteady lift characteristics of the foil. It is particularly important to note that substantial departures from quasistatic behaviour occur for reduced frequencies as low as 0.2, though these departures are more significant in the noncavitating flow than in the cavitating flow. The lines without points in figure 1 present results for the

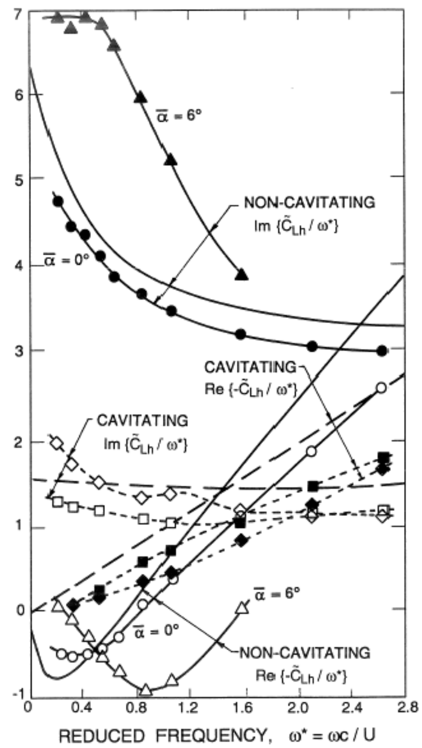

Figure 1: Fluctuating lift coefficient, $\tilde{C}_{Lh}$, for foils undergoing heave oscillations at a reduced frequency, $\omega^* = \omega c/U$. Real and imaginary parts of $\tilde{C}_{Lh}/\omega^*$ are presented for (a) non-cavitating flow at mean incidence angles of 0° and 6° (b) cavitating data for a mean incidence of 8°, for very long choked cavities (□) and for cavities 3 chords in length (◇). Adapted from Acosta and DeLong (1971).

corresponding linear theories and we observe that the agreement between the theory and the experiments is fairly good. Notice also that the $Re\{-\tilde{C}_{Lh}\}$ for noncavitating foils is negative at low frequencies but becomes positive at larger ω whereas the values in the cavitating case are all positive. Similar data for cavitating cascades would be necessary in order to analyse the potential for instability in cavitating, axial flow pumps. The author is not aware of any such data or analysis.

The information is similarly meagre for all of the corresponding dynamic characteristics of radial rather than axial cascades and, consequently, our ability to model dynamic instabilities in centrifugal pumps is very limited indeed.