Frequencies of Oscillation

One of the diagnostics which is often, but not always, useful in addressing a turbomachine vibration problem is to examine the dominant frequencies and to investigate how they change with rotating speed. Table 1 is intended as a rough guide to the kinds of frequencies at which the above problems occur. We have attempted to place the phenomena in rough order of increasing frequency partly in order to illustrate the fact that the frequencies can range all the way from a few Hz up to tens of kHz. Some of the phenomena scale with the impeller rotating speed, Ω. Others, such as surge, may vary somewhat with Ω but not linearly; still others, like cavitation noise, will be largely independent of Ω.

Of the frequencies listed in table 1, the blade passing frequencies need some further clarification. We will denote the numbers of blades on an adjacent rotor and stator by Z_R and Z_S, respectively. Then the fundamental blade passage frequency in so far as a single stator blade is concerned is $Z_R\Omega$ since that stator blade will experience the passage of Z_R rotor blades each revolution of the rotor. Consequently, this will represent the fundamental frequency of blade passage excitation insofar as the inlet or discharge lines or the static structure is concerned. Correspondingly, $Z_S\Omega$ is the fundamental frequency of blade passage excitation insofar as the rotor blades (or the impeller structure) are concerned. However, the excitation is not quite as simple as this for both harmonics and subharmonics of these fundamental frequencies can often be important. Note first that, while the phenomenon is periodic, it is not neccessarily sinusoidal, and therefore the excitation will contain higher harmonics, $mZ_R\Omega$ and $mZ_S\Omega$ where m is an integer. But more importantly, when the integers Z_R and Z_S have a common factor, say Z_{CF}, then, in the framework of the stator, a particular pattern of excitation is repeated at the subharmonic, $Z_R\Omega/Z_{CF}$, of the fundamental, $Z_R\Omega$. Correspondingly, in the framework of the rotor, the structure experiences subharmonic excitation at $Z_S\Omega/Z_{CF}$. These subharmonic frequencies can be more of a problem than the fundamental blade passage frequencies because the fluid and structural damping is smaller for these lower frequencies. Consequently, turbomachines are frequently designed with values of Z_R and Z_S which have no common factors, in order to eliminate subharmonic excitation. Further discussion of blade passage excitation frequencies is included in section (Mbfh).

Table 1: Typical frequency ranges of pump vibration problems.

VIBRATION CATEGORY		FREQUENCY RANGE
A2	Surge	System dependent, $3-10\ Hz$ in compressors
A2	Auto-oscillation	System dependent, $0.1-0.4\Omega$
A1	Rotor rotating stall	$0.5\Omega-0.7\Omega$
A1	Vaneless diffuser stall	$0.05\Omega-0.25\Omega$
A1	Rotating cavitation	$1.1\Omega-1.2\Omega$
A3	Partial cavitation oscillation	$< \Omega$
C1	Excessive radial force	Some fraction of Ω
C2	Rotordynamic vibration	Fraction of Ω when critical speed is approached.
A4	Blade passing excitation (or B2)	$Z_R\Omega/Z_{CF}, Z_R\Omega, mZ_R\Omega$ (in stator frame) $Z_S\Omega/Z_{CF}, Z_S\Omega, mZ_S\Omega$ (in rotor frame)
B1	Blade flutter	Natural frequencies of blade in liquid
B3	Vortex shedding	Frequency of vortex shedding
A6	Cavitation noise	$1\ kHz-20\ kHz$

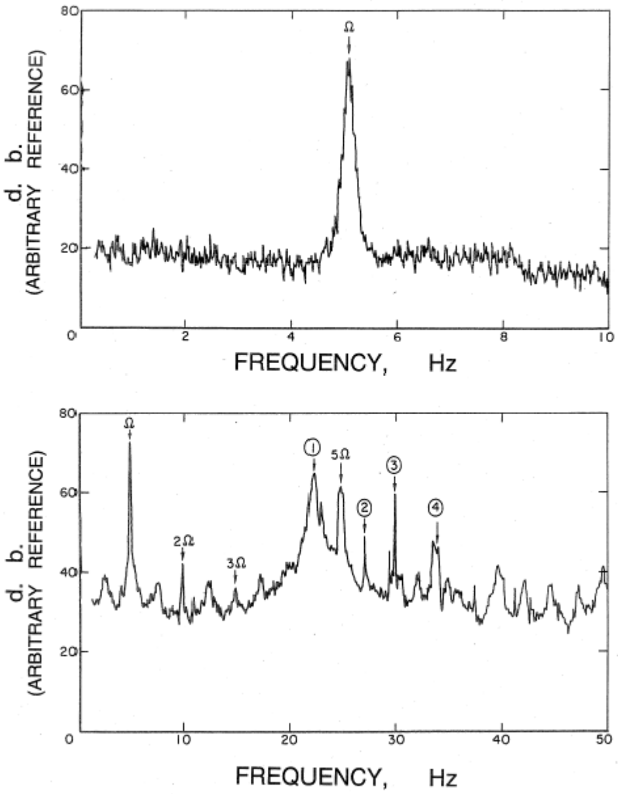

Figure 1: Typical spectra of vibration for a centrifugal pump (Impeller X/Volute A) operating at 300 *rpm* (Chamieh *et al.* 1985).

Before proceeding to a discussion of the specific vibrational problems outlined above, it may be valuable to illustrate the spectral content of the shaft vibration of a typical centrifugal pump in normal, nominally steady operation. Figure 1 presents examples of the spectra (for two frequency ranges) taken from the shaft of the five-bladed centrifugal Impeller X operating in the vaneless Volute A (no stator blades) at 300 *rpm* (5 Hz). Clearly the synchronous vibration at the shaft fundamental of 5 Hz dominates the low frequencies; this excitation may be caused by mechanical imperfections in the shaft such as an imbalance or by circumferential nonuniformities in the flow such as might be generated by the volute. It is also clear that the most dominant harmonic of shaft frequency occurs at 5Ω because there are 5 impeller blades. Note, however, that there are noticeable peaks at 2Ω and 3Ω arising from significantly nonsinusoidal excitation at the shaft frequency, Ω. The other dominant peaks labelled $1 \rightarrow 4$ represent structural resonant frequencies unaffected by shaft rotational speed.

At higher rotational speeds, more coincidence with structural frequencies occurs and the spectra contain more noise. However, interesting features can still be discerned. Figure 2 presents examples, taken from Miskovish and Brennen (1992), of the spectra for all six shaft forces and moments as measured in the rotating frame of Impeller X by the balance onto which that impeller was mounted. F_1, F_2 are the two rotating radial forces, M_1, M_2 are the corresponding bending moments, F_3 is the thrust and M_3 is the torque. In this example, the shaft speed is 3000 *rpm* ($\Omega = 100\pi \; rad/sec$) and the impeller is also being whirled at a frequency, $\omega = I\Omega/J$, where $I/J = 3/10$. Note that there is a strong peak in all the forces and moments at the shaft frequency, Ω, because of the steady radial forces caused by volute asymmetry. Rotordynamic forces would be manifest in this rotating frame at the beat frequencies $(J \pm I)\Omega/J$; note that the predominant rotordynamic effect occurs at the lower of these beat frequencies, $(J - I)\Omega/J$. The moments M_1 and M_2 are noisy because the line of action of the forces F_1 and F_2 is close to the chosen axial location of the origin of the coordinate system, the mid-point of the impeller discharge. Consequently,

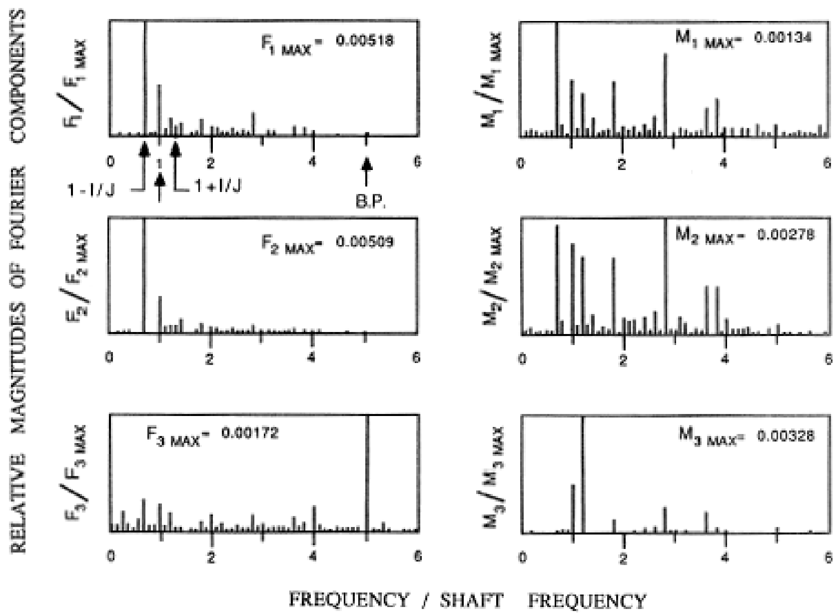

Figure 2: Typical frequency content of $F_1, F_2, F_3, M_1, M_2, M_3$ for Impeller X/Volute A for tests at $3000rpm$, $\phi = 0.092$, and $I/J = 3/10$. Note the harmonics $\Omega, (J \pm I)\Omega/J$ and the blade passing frequency, 5Ω.

the magnitudes of the moments are small. One of the more surprising features in this data is the fact that the unsteady thrust contains a significant component at the blade passing frequency, 5Ω. Miskovish and Brennen (1992) indicate that the magnitude of this unsteady thrust is about $0.2 \rightarrow 0.5\%$ of the steady thrust and that the peaks occur close to the times when blades pass the volute cutwater. While this magnitude may not seem large, it could give rise to significant axial vibration at the blade passing frequency in some applications.