Pump ED 101

Resonant Frequency & Critical Speed

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If you think hydraulic theory can be a tricky subject you should take a look at that contemporary branch of physics known as string theory. It attempts to explain all of the fundamental physical theories, including relativity and quantum mechanics, as a single theory. At its core is the hypothesis that space, time, and matter are composed of tiny string-like particles that vibrate at resonant frequencies. If it can be proven, we will end up with a single unified theory that explains everything! Now, you are probably wondering what the heck this has to do with pumps. It turns out that resonant frequency is the common thread (or maybe string in this case).

Resonance in a mechanical system is defined as "a vibration of high amplitude that is caused by a relatively small stimulus of the same period as the natural vibration period of the system". In other words, it is the vibration that results when any object, composed of an elastic material, is subjected to its "natural" vibrational frequency. The stimulus that causes this natural vibration can be mechanical or electromagnetic.

One of the most familiar examples of resonance is the old video of a wine glass that vibrates due to the pitch (frequency) of the singer's voice. When the singer holds a note that is the natural frequency of the thin glass, it begins to vibrate and eventually shatters. If you would like to see a modern day version, check out "Resonant Frequency Demonstration" on my web site. In it, the University of Michigan Physics Demonstration Lab replaces the singer with a variable frequency generator and uses a strobe light to visually slow down the pulsations of the glass. It shows the onset of resonance and demonstrates how continuing resonance can be quite destructive.

So, why is resonance and resonant frequency important in pump applications? It turns out that one of the stimuli that can cause resonance is rotational motion and, the centrifugal pump is all about rotational motion. In fact, today it is more often about the changes in rotational motion due to variable speed pumping and the, so called, critical speeds that can initiate those resonate frequencies.

The branch of mechanics known as rotordynamics defines critical speed as the angular velocity that excites the natural frequency of some rotating object. In the case of a pump shaft, it is the measured rotational speed where natural vibration occurs. It would not be unusual to expect that the radial deflection caused by the weight of an overhung impeller might lead to vibration in a horizontal pump, even if that impeller was perfectly balanced. But, a similar vibration can occur when that same pump is operated in a vertical position even though there is no radial deflection due to impeller weight. The vibration that arises in a well balanced rotor, at a particular rotational speed, is caused by small differences in the rotor density and minor machining variations. This results in a miniscule movement of the center of mass away from the center of the axis of rotation. As speed increases, the elastic forces of the metal and the radial forces caused by rotation become unbalanced and vibration occurs. This vibration increases shaft deflection and can result in component wear (seals, wear rings, & bearings) and even shaft breakage. If speed continues to increase, this natural frequency disappears and vibration will cease but, at some even higher speed, yet another natural frequency will be encountered. The lowest rotational speed at which this natural vibration occurs is called the first critical speed.

Resonance is not often a concern when short, rigid shaft pumps are operated at their design speed. Even if a natural frequency resides between zero and full speed, it is passed very quickly during starting. The wide spread use of VFD’s, however, have led many to consider the effect of resonant frequency and critical speed on pump operation. Today, it is not unusual to see a variable speed, engineering specification that requires the pump to operate a certain percentage below its first critical speed. Calculating the first critical speed could be a difficult task but, fortunately, a more common measurement can lead us to a solution.

The first critical speed of a pump shaft is linked directly to its static deflection and static deflection depends upon the weight of the rotor, its overhang length and its diameter. Actually deflection can be quite a bit more complicated because elasticity, inertia, bearing support and varying shaft diameter must also be considered. Fortunately we do not have to perform those calculations because they have already been determined by the pump designer. All we have to do is obtain the maximum static deflection from the manufacturer and substitute it into the simple equation below.

$$N_C = 187.7 / \sqrt{f}$$

N_C is the first critical speed in RPM, f is deflection in inches and 187.7 is a constant. If a pump manufacturer measures static deflection in millimeters, substitute 946 for 187.7.

Most pump manufacturers try to limit shaft deflection to about 0.005’ to 0.006” in order to reduce seal wear and maintain an efficient wear ring clearance. At a maximum deflection of 0.006” our equation calculates a first critical speed of about 2420 RPM. Obviously, pump motors with four or more poles (1800 RPM and below) operate well below this number so first critical speed is not an issue. In order for the first critical speed to become a concern at four pole speed, shaft deflection would have to be greater than 0.010”.

A pump with a shaft deflection of 0.006” but driven by a two pole motor (3600 RPM) will operate well above its first critical speed. As I mentioned earlier, this is not a concern in constant speed applications because the shaft passes through its critical speed very quickly. Even a VFD soft start is usually not an issue because the time spent in that speed range is still very short. It can, however, be an issue if the critical speed is within the speed range required by the application. Fortunately, most VFD’s can be programmed to bypass individual frequencies. For example, if the critical speed occurs between 41 and 43 Hz, the VFD will skip these frequencies and use 40 or 44 Hz instead. The shaft will still pass through the critical speed but the VFD will not allow it to remain there.

It is also worth noting, that the equation used for the calculation of critical speed is for a rotor that is running in air. When running in a liquid, certain hydrodynamic forces arise around the shaft and impeller that can provide additional stability. Known as the Lomakin effect, these forces can reduce deflection and thus increase the first critical speed well beyond its calculated value.

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