Rotating Steel Shafts

Re-print of article published October 2011

Abstract

Rotating steel shafts are used throughout the materials handling, mining and port industries wherever power transmission or the mounting of rotating components in a mechanical system is required. Shaft failure can be potentially disastrous and can lead to large repair costs and long down times. As a result owners, operators and designers of such components need to be aware of the issues involved in the design of rotating steel shafts and some general principles of good shaft design.

1. Introduction

Typically, the main issues considered when designing shafts are:

- Ensuring the shaft will not fail in fatigue over the design lifetime
- Ensuring the shaft has sufficient static strength for maximum loadings
- Ensuring the deflection of the shaft is not excessive for any mounted components
- Ensuring the natural frequency, or "critical speed", of a rotating shaft is well above any operating frequencies
- Designing the shaft so that it is easily inspectable

2. Design for Fatigue

AS1403 is the current Australian standard used in the design of rotating steel shafts. There are a number of similar international standards including the German standard DIN743 and the FEM Rules. The rationale behind AS1403 is to design the shaft for an infinite fatigue life under the applied operating loads, utilizing an appropriate safety factor.

The methodology described in AS1403 is to size the diameter of the shaft by ensuring that the stress calculated from the combined axial, bending and torsional loading is less than the fatigue limit of the steel used in the shaft. The stress at each axial location on the shaft is increased using design factors for stress raising features and a size factor depending on the diameter. Stress raising factors account for features such as keyways, notches, interference fits etc. which can significantly increase the local stresses in the shaft.

The number of stress raising features should be minimized wherever possible, and they should be located away from highly stressed regions of the shaft. The use of large, smooth radii at changes in section will also minimize local stresses. The size factor allows for the reduced strength of shafts that is observed as the diameter is increased.

Overall the standard is quite useful and is similar to international methods in its approach; however it does differ from these international codes in some important areas, including:

- AS1403 makes no differentiation between the stress concentration factors associated with bending or torsional stress. Rather it quotes a single concentration factor for the overall combined stress. The stress concentration factor for bending or torsion can be significantly different depending on the feature. For example, for a press fitted component, the stress concentration factor in torsion has been shown to be around 65% of that in bending.
- AS1403 makes no allowance for stress relieving features incorporated into the shaft. Some examples of stress relieving features are shown in Figure 1. These have been shown experimentally to reduce fatigue stresses by up to 60%.
- AS1403 does not include the effect of the surface finish on the fatigue strength of the shaft.

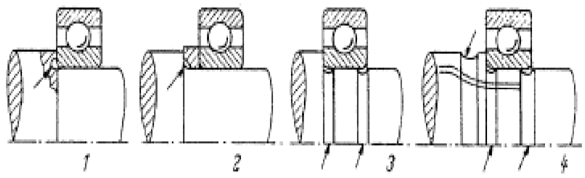

Figure 1. Examples of Stress Relieving Features
For a shaft step with a bearing seat:
1. Rounded engraved groove at step.
2. Rounding out with a spacer ring.
3. Rounded out discharge notches.
4. Additional discharge notches.

- The single "size factor" quoted in AS1403 is made up of the "metallurgical factor" and "geometry factor" that is used in other methods. The metallurgical factor accounts for the reduction in the strength of quenched and tempered steels as the diameter increases, mainly due to uneven cooling of the shaft during fabrication. The geometry factor accounts for changes in the stress gradients that occur in the shaft as the diameter increases. The relative importance of these effects varies depending on the shaft diameter, and as a result these factors have been separated in a number of other standards.
- AS1403 may be misleading in its treatment of shrink fitted components. In Figure 2, a stress concentration factor is quoted for three different nominal fits. However, the stress concentration due to a fitted component has more to do with the contact pressure between the shaft and fitted component, not the fit used. The standard would also seem to suggest that with increasingly tight fits and contact pressures, the stress concentration will increase. However tests have shown that with increasing

contact pressure, the stress concentration tends to asymptote at a constant value. The likelihood and severity of fretting of the shaft surface, which can be another indicator of fatigue damage, will in fact decrease. Thus, great care should be taken when considering the effect of shrink fitted components and wherever possible the manufacturers recommendations for stress concentration due to locking devices etc. should be used. This is allowed for in AS1403.

- These differences often tend to make the standard conservative for design, however it is important to keep these issues in mind especially when trying to get an optimal shaft design for a situation.

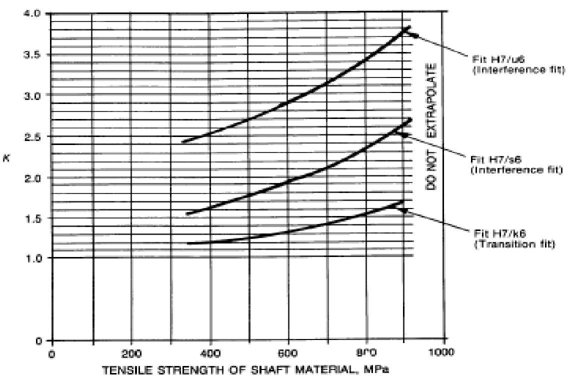

Figure 2. Stress raising factor K for fitted component without key or spline (AS1403)

3. Design for Strength

Often there are very high rare or "once off" loads that may be applied to the shaft during its lifetime that are not a major fatigue concern due to the low number of cycles associated with these loads. Example loads include: high start-up/stall torques from a motor and extreme load cases such as collisions. For these cases the design should be governed by the allowable stress method presented in AS3990. The use of higher strength steels may be necessary if the design is driven by strength concerns.

4. Design for Deflection

Deflection can be the limiting factor of design, as it is important to ensure that shafts are designed such that their deflections are within acceptable limits. Excessive deflections of shafts can affect gear performance, cause rapid wear/damage to non-self-aligning bearings and result in excessive noise and vibration. Typically the deflection of the shaft should not exceed the length/2000 at any gears or 8 mins of angular deflection at any bearings. Deflection of shafts is calculated using traditional beam deflection formulas, and as a result is dependent on the inertia, length and material used in the shaft. To minimize deflections it is important to ensure that shafts are a stiff as possible which can be achieved by ensuring that a shaft is as short as possible, or by increasing the size of the shaft. Most steels have similar elastic moduli, thus changing the material will have very little effect on reducing deflections.

5. Design for Critical Speed

The natural frequency (critical speed) of a shaft should be much higher than the operational frequency of the shaft. This is to avoid resonance of the shaft which can result in excessive vibration causing rapid wear of any mounted components, excessive noise, deflection and fatigue of the shaft. The natural frequency of the shaft is given by the equation:

Natural Frequency = $\sqrt{(\text{Stiffness/Mass})}$

The critical speed is dependent on the stiffness and mass of the shaft. Thus the design considerations for critical speed are very similar to that for deflection in that ideally the shaft should have a high stiffness to mass ratio, resulting in a high natural frequency.

6. Design for Inspection

There are several material properties that are of importance when considering shaft specification. One of these is the toughness of the steel. If a fracture mechanics approach is used the steel toughness is used to determine the maximum tolerable crack size for different locations in the shaft and also the rate of a fatigue crack growing in the shaft. Other fracture mechanics approaches provide information on the largest crack/flaw size that will not propagate a fatigue crack. All of this information is useful in determining the inspection interval of the shaft. It is an important aspect of the shaft design that the regions of higher stress range, where fatigue cracks are most likely to initiate, are able to be inspected to find the small flaws than can initiate a fatigue crack and that the shaft design results in a tolerable flaw size that can be detected.

7. General Shaft Design Principles

In summary, the following issues are useful to remember when designing or assessing the design of a rotating steel shaft:

- Generally, the shaft diameter should be minimized. This will reduce fabrication costs and avoid reductions in the strength of the shaft due to metallurgical effects.
- Carefully consider the component mounting method used when designing the shaft – these can significantly affect the stresses in the shaft.
- Keep necessary stress raising features away from highly stressed areas on the shaft. Also use large, smooth radii at all corners and changes in section as this will minimize the effect of local stress concentrations and help keep the size of the shaft down.
- Be aware of the beneficial effect that stress relieving features, such as relief notches, can have on the stresses in a shaft.

- Be aware that AS1403 may be misleading in the area of shrink fitted components, and it is often a good idea to use the manufacturer’s recommendations for the stress concentration due to locking elements etc. when designing a shaft.
- Keep shafts as short as possible. This will increase the stiffness of the shaft, reducing the deflection of the shaft while increasing the natural frequency (critical speed) of the shaft, allowing higher operating frequencies.
- The choice of steel used in the shaft is important for strength and fatigue, however when the design is driven by deflection or critical speed concerns, the type of steel used is less important as most steels have similar elastic moduli. The fracture toughness of the steel can also be important in specifying inspection intervals.
- It is important to design the shaft, and location of shaft mounted components, such that the shaft is easily inspectable.

For any enquires regarding this document, please email: admin@aspec.com.au.