Torsional Vibration Linked to Water Pumping System Failure

By Troy Feese

A municipality purchased several units to pump water on an emergency basis for fire fighting. These units are located around the downtown area and can provide water through portable pipes and hoses in case a major catastrophe cuts off the primary water supply to fire hydrants. Each unit consists of a V-12 diesel engine driving a five stage vertical centrifugal pump through a right angle gearbox with a 1:1 ratio. The 1600 hp engine has an operating speed range of 1200 to 1800 rpm. The engine flywheel connects to the gearbox through a drive shaft that has universal joints on each end.

This article describes how failures of the water pumping system were linked to torsional vibration. It also shows how a solution was developed using computer analyses. Field tests were performed to verify that the solution was adequate to prevent additional failures.

The Problem

The system experienced failures of the input gear and cooling fan. Several of the bolts that held the gear to the input shaft broke after only 13 hours of operation. It was speculated that this failure was due to excessive torsional vibration or improper fit that may have caused the transmitted torque to be unevenly distributed among the bolts. The cooling fan on top of the gearbox also experience several failures. The first time the fan blades broke, it was thought to be related to possible problems with the material or manufacturing process. The fan is constructed by pressing the general shape out of the sheet metal, and then the blades are twisted to the proper pitch angle. If a small crack formed at the base of the fan blades, a high stress riser would be created. However, this type of fan has been used successfully at other installations. These fan blade failures could have been caused by high torsional vibration.

Although it was possible to use additional bolts to hold the gear more securely to the input shaft, there was concern that if torsional vibration levels were too severe, then some other portion of the system would fail resulting in more damage. Therefore, a detailed torsional analysis was performed. The wet pump impeller inertial (25% greater than dry) was used to account for the water. The dynamic torque produced by the engine was calculated from the cylinder pressures and inertia forces acting on each of the six throws. Appropriate stress concentration factors were applied to the gear and pump shaft sections. The damping in the system was evaluated to include the engine viscous damper properties as well as the effects of the bearings, packing and pumped fluid.

The torsional analysis indicated that the engine produces significant dynamic torque at 2.5x, 3.5x, 4.5x and 6x running speed. The interference diagram in Figure 1 show the calculated torsional natural frequencies and harmonic speed lines associated with the engine. The intersection points indicate torsional critical speeds. The two circled points in Figure 1 show where the 4.5x and 3.5x engine harmonics intersect the fifth torsional mode - at approximately 1400 and 1800 rpm respectively. The fifth torsional mode was of concern since the shape showed twisting in the input

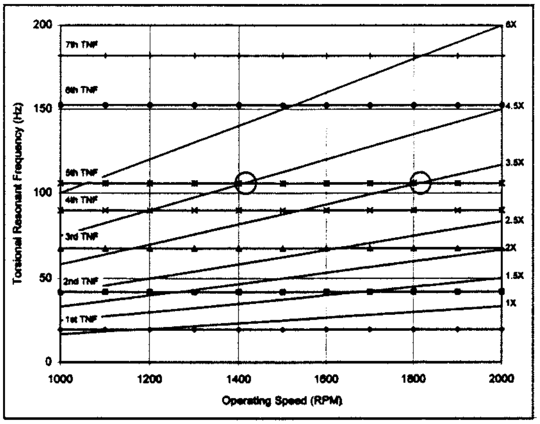

Figure 1. Interference diagram

gear shaft and oscillation at the cooling fan. Also, the engine damper is not as effective for this mode. Steady-state forced calculations were performed to predict the level of torsional vibration versus engine speed. The alternating shear shaft were above the endurance limit of the shaft material. The force analysis also showed that the cooling fan would experience high torsional oscillation.

Torsional Analysis Yields Solution

Based on the torsional analysis results, the system needed to be modified to reduce the excessive torsional vibration and stress levels. A parametric study was performed. This showed that using a "torsionally soft" coupling between the engine and gearbox would help isolate the engine harmonics from the rest of the system. A coupling with a rubber element in shear was selected that would have a low torsional stiffness (less than 300,000 in-lb/rad) and provide additional damping to the system. Since this coupling bolts directly to the engine flywheel and supports the drive shaft, the system could be easily retrofitted in the field. The analysis indicated that with the rubber coupling the torsional vibration and stress levels in the gear and pump would be significantly reduced compared to the original system.

Field measurements of the system were performed before and after the rubber coupling was installed to verify that the torsional vibration would be reduced enough to prevent additional failures. Strain gage measurements could not be made on the input gear shaft due to limited accessibility inside the gearbox. However, the torsional analysis showed a correlation between the predicted dynamic torque in the drive shaft and the alternating shear stress in the input gear shaft. Therefore, strain gages were attached to a uniform section of the drive shaft, and the signal was transmitted using all FM telemetry system. The torsional oscillation of the cooling fan were measured using an HBM torsiograph.

The vibration data were gathered over a two minute period as the engine speed was increased from 1200 to 1800 rpm. During the tests the pump was operated with recirculated water. Speed rasters of the dynamic torque measured in the drive shaft for both configurations are shown in Figures 2a and 2b. The most significant engine harmonics from the speed rasters and the overall dynamic torque (all harmonics combined) are plotted versus engine speed in Figures 3a and 3b. For the original system, the overall dynamic torque in the drive shaft was as much as 56% of the transmitted torque. However, with the rubber coupling installed the overall dynamic torque was reduced to 16% of the transmitted torque. The measured torque data compared favorably with the predicted results from the computer analyses. For example, in Figure 2a the 4.5x engine harmonic passed through a resonance near 1400 rpm, and the amplitude of the 3.5x harmonic increased as the engine speed approached 1800 rpm. The stress levels in the input gear shaft would be reduced by approximately the same amount as the dynamic torque in the drive shaft. The torsional oscillation at the cooling fan was also reduced. Based on the test results, the rubber coupling was recommended as a permanent solution. No failures have been reported since the coupling was installed.■

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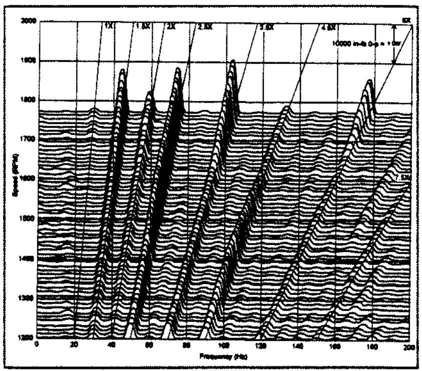

Figure 2a. Original system – dynamic torque in drive shaft

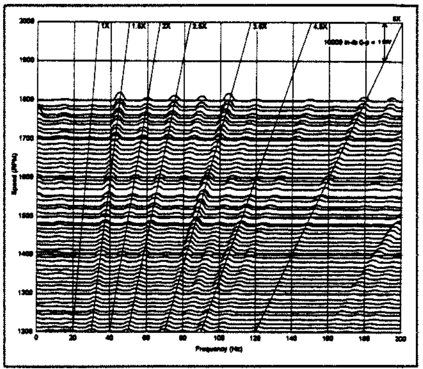

Figure 2b. Modified system with rubber coupling – dynamic torque in drive shaft

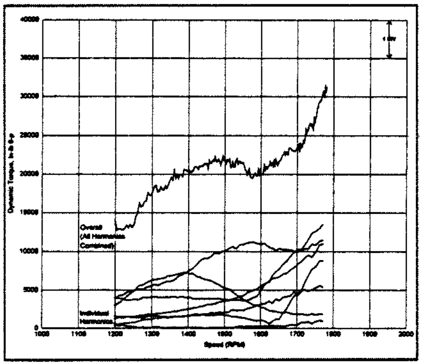

Figure 3a. Original system – dynamic torque in drive shaft

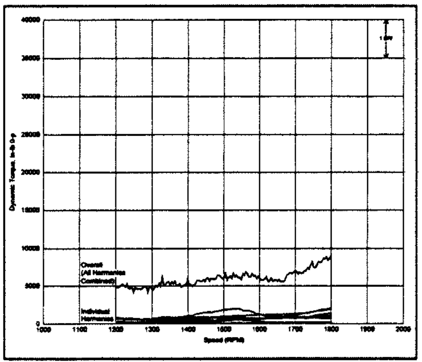

Figure 3b. Modified system with rubber coupling – dynamic torque in drive shaft