Figure 1: proximity probes measuring shaft orbit.

Lateral Mode

The importance of shafting vibration analyses

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There are three modes of vibration that must be considered for marine propulsion shafting: lateral (whirling), longitudinal (axial), and torsional vibration. Each mode has its own unique characteristics, causes, and resolutions. Excessive lateral vibrations can be extremely destructive and dangerous for personnel onboard a vessel. Our focus here will be on lateral vibration, which is associated with the shaft rate-excited vertical and horizontal displacement of the shafting while in operation. A common comparison is the vibration of a guitar string being plucked—as you adjust your fingers closer along the frets, shortening the length of the vibrating string, the natural frequency increases.

Incidents of lateral vibration occur in all parts of daily life, but only those that are noticeable or excessive bring unwanted attention to engineers and designers. For example, the London Millennium Bridge, which opened in June 2000, was closed 2 days later due to displacements of 50 to 70 mm experienced by pedestrians. As it turned out, the lateral force induced to the bridge at the frequency of the pedestrian footsteps was similar to some of the lateral vibration modes (approximately 0.5 to 1.0 Hz). The issue was resolved by adding a mixture of stiffening, viscous dampers, and tuned mass dampers. (For more information on the incident, see “Lateral Vibration of Pedestrian Bridges,” by Yasmin H. Rehmanjee, Massachusetts Institute of Technology, 2001.) Fortunately, in this case, the motion only caused public concern and there was no risk of structural damage.

There is no shortage of experiences across the marine and turbo-machinery fields where catastrophic failures have occurred. The costs and down

Lateral Mode *continued*

Figure 3: probe tip wiped by excessive shaft displacement.

time associated with damage to large machinery installations is a concern; however, many lost their lives in factories and power plants before this phenomenon was well understood.

Analysis and measurement

For new construction vessels, classification societies require a lateral vibration analysis to be performed, and measurement of vibrations during sea trials if a natural frequency is within +/- 20% of the operating range. Generally, for slow-speed diesel engine powered vessels, the system design characteristics (shaft speed around 75-125 RPM) are such that excessive lateral vibrations do not occur. As the operating shaft speed increases, the potential for coincidence with a natural mode increases and more extensive analyses may be needed to fully understand the system response. These may include finite element analysis of bearing foundation stiffness, unbalance/forced response analysis, and time series simulations.

A typical case of excessive lateral vibrations is a shafting system with an unloaded support bearing, resulting in the span between supporting bearings increasing significantly. Unloading can occur due to relative wear of outboard sterntube or strut bearings, or lightly loaded bearings becoming unloaded due to changes in vessel loading condition. The system natural frequency may also be significantly affected by the bearing foundation support stiffness. Unloaded bearings (increasing span between bearings) and decreasing support stiffness (overly flexible foundations) decrease the system natural frequency of lateral vibration. For example, the natural frequency of a notional 250 mm diameter, 10 m long shaft increases from 7.8 Hz to 29.7 Hz with addition of a mid-span bearing, significantly affecting the system response.

Recent cases of excessive lateral vibration of marine propulsion shafting indicate the importance of understanding the parameters influencing the vibration, and further assessing the potential affects. When a vessel undergoes a re-fit, significant changes to the system vibration (and static alignment) characteristics can occur. The engineering analyses may not identify these issues until testing, at which point significant costs and time are required to correct, not to mention any damage or potential injuries that may occur. Let's examine two sample cases of recent lateral vibration issues and their resolution.

Case 1: offshore supply vessel

Excessive vibrations were reported by crews on a series of a 230-ft. offshore supply vessels. Machinery components had experienced failures, including gearbox bearings, and in one case the propeller shaft broke near the propeller. These vessels have twin-screw controllable pitch propellers driven by 3,000 HP 900 RPM diesel engines, through a reduction gearbox with a rated propeller shaft speed of 163 RPM. The propulsion shaft was about 36 ft. long and supported by two water lubricated outboard bearings. First, a theoretical alignment and lateral vibration analysis was conducted to understand the system characteristics and expected behavior.

To further investigate, all three modes of shafting vibration were measured with proximity probes being used to describe the shaft orbit in the vertical plane. Figure 1 shows a typical arrangement for measurement of lateral vibration using proximity probes located immediately forward of the seal near the forward sterntube bearing. It was found that lateral vibrations were excessive while maneuvering and also when operating in the dynamic positioning mode. Figure 2 illustrates the measured range of shaft orbits of two vessels of the same class during turns to starboard, one of which had the forward sterntube bearing loaded and the other with it unloaded.

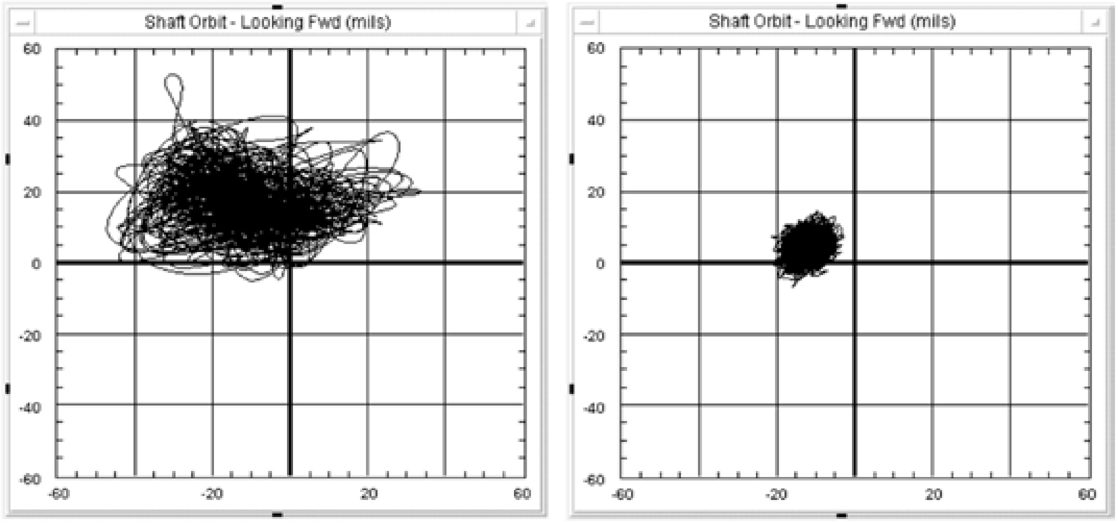
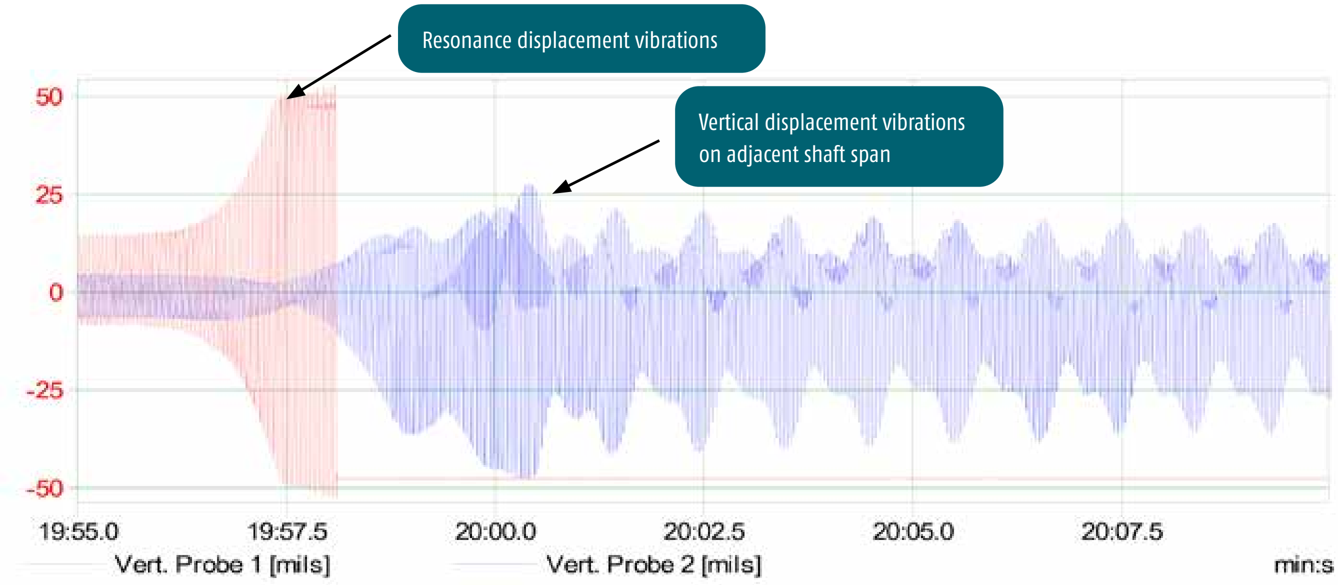


Figure 2: shaft orbit, forward sterntube bearing unloaded and loaded.

Excessive vibrations had been experienced since delivery of the vessels, and the port propeller shaft broke off at the propeller flange on one vessel. The vibrations were attributed to excessive shaft whirling as a result of a misalignment of the propulsion shaftline, such that the sterntube bearing was unloaded. The shaftlines were re-aligned. Shaft vibration measurements conducted on two vessels confirmed that the

Lateral Mode *continued*

Figure 4: time domain plot of measured resonant vertical shaft vibrations.



re-alignment eliminated excessive shaft whirling vibrations. No machinery damage or excessive vibrations were reported on these ships since the re-alignment work was completed. However, excessive structural vibrations continued to occur on one vessel even though the forward sterntube bearing was loaded after realignment, resulting in cracks in the structure around the nozzle and on the deck coverings.

On this vessel, it was found that excessive lateral (whirling) shaft vibrations were present above 700 engine RPM during all operations. An examination of the ship structural arrangement indicated that the struts, nozzles, and rudders were not adequately supported. This lack of support was considered the cause of the excessive shaft vibrations. Fortunately, the shaft speed could be limited to 700 RPM without significantly impacting the requirements of the vessel's performance. The ship vibrations were reported to be no longer present under this operating condition, and considerable fuel savings were realized.

Case 2: double-ended ferry

In the case of a double-ended ferry being constructed based mostly on a previous proven design, excessive lateral vibrations occurred. There is incentive to take advantage of the latest technology, fuel efficiency, and cost savings (lighter engines) when re-powering and updating designs. The propulsion machinery original arrangement consisted of two propulsion trains, one for each end of the vessel. Each propulsion train was comprised of a five-blade cycloidal propulsion unit driven by a diesel engine through a torsional coupling, a turbo (fluid) coupling, and a gear tooth coupling. The ferry was originally designed and built with 900 RPM engines. The line shafting was approximately 72 ft. long, 5 in. in diameter, and supported by 7 roller bearings. The new vessel had a 1,600 RPM engine driving a similar shafting arrangement between the cycloidal thruster and engine. The gearing in the thruster was revised to maintain similar propeller design RPM.

The design phase calculations indicated that resonant lateral shafting vibrations may occur, as the first natural frequency was near the operating RPM that could cause resonance. However, recommendations were only to measure the vibration during trials to determine if they were acceptable, rather than a re-design of the shafting system to ensure the first natural frequency was significantly higher than the maximum shaft speed.

During dock trials, significant excessive lateral vibrations at 1,100 RPM were found. The system was emergency stopped. The maximum vertical displacement of the shaft was approximately 7 mm based upon a damaged proximity probe, as shown in figure 3. The associated time domain plots are shown in figure 4, where shaft vertical vibrations were increasing exponentially, indicating resonance vibrations.

An independent lateral vibration analysis was conducted, which determined the natural frequency to be within the operating range, approximately 19.5 Hz (1,170 RPM), similar to the original design calculations. To avoid resonance by increasing separation margin between the operating shaft speed (excitations) and the natural frequency, the following options were investigated: one, decrease operating shaft speed; two, increase shaft diameter; and three, decrease bearing spans.

A least cost modification was found, which included the addition of five support bearings and re-design of a shaft coupling at the propulsor end. These changes increased the theoretical natural frequency

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to 37 Hz (2,220 RPM), well above the 1,600 RPM operating shaft speed. Sea trials were successful, with no excessive vibrations.

Decreasing shaft spans to increase the lateral natural frequency by adding bearings has the disadvantage of increasing the shafting system stiffness and reducing the static bearing loads. This increases the risks of having unloaded bearings and "skidding" of the rollers.

Therefore, proper alignment, which is critical to successful operation, is more difficult and requires accurate measurements. A variety of alignment methods were used, most importantly the strain gauge technique.

An important consideration for owners and shipyards is to ensure those enlisted to conduct theoretical analysis, design review, and measurements are also those experienced with analysis and successful troubleshooting of similar systems. For example, marine propulsion shafting alignment is very different from typical engine/motor to pump alignments performed with optical methods. If personnel are not experienced in all aspects of marine propulsion shafting system design, performance, alignment, and vibration, both theoretical and practical, then there is a higher risk of serious operations issues arising.

Fortunately (and unfortunately), just when you think you have seen it all in the marine industry, a new and different problem occurs. This keeps engineers learning and growing through their careers. We pass these lessons down to future generations, not only for cost and efficiency, but also especially for safe operations. **MT**

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