MARINE PROPULSION SHAFTING EXCESSIVE TORSIONAL VIBRATIONS: CASE STUDIES

D.N. Bruce Cowper P.Eng. and Zac Schramm, PE

LamaLo USA, LLP

bcowper@lamalotech.com zschramm@lamalousa.com

Abstract

Theoretical torsional vibration analysis of marine propulsion shafting systems has been shown to provide good results and assurances that the shafting design and operations can avoid excessive vibrations. Systems with low-speed diesel prime movers are well known for their barred speed ranges due to resonant torsional vibrations. Measurements are taken during sea trials to verify the barred ranges. However, for other systems which incorporate gearing, flexible couplings, cardan shafts, higher shaft speeds, and other non-conventional components, the torsional vibration characteristics can be difficult to estimate. Yet the torsional vibrations are not always measured during sea trials. Unfortunately, costly failures can occur. Direct measurement of the torsional vibratory stresses with near real-time display have proven to be reliable in identifying excessive vibrations and remedial actions to be taken. This paper provides examples of cases where excessive torsional vibrations were measured. The measurement technique, results and actions taken to prevent further failures are likewise presented.

INTRODUCTION

As the complexity, performance, and power of marine propulsion shafting systems increase, the expectation is that design analysis accurately models the systems operation. Components such as flexible couplings, cardan shafts, and gearing operating at higher speeds (> 1,000 RPM) can have torsional vibration characteristics that are difficult to estimate. Direct measurement of shaft torque has proven to be a reliable method to identify excessive vibrations and determine corrective actions. Presented here are two cases where torsional vibration measurements identified barred speed ranges that would protect the system from costly damage and provide more reliable operation.

MEASUREMENT TECHNIQUE

Instrumentation

Shaft torque was measured using strain gauges installed in a full bridge configuration mounted directly to the shaft. Strain gauge signals were conditioned and transmitted to a stationary receiver using a digital telemetry system. The properties of the shafting were used in the calculation of the calibration factor to obtain torsional strain from the strain gauge output. Shaft RPM was measured using an optical sensor and a tachometer. A GPS receiver can be used to record ship speed and heading.

Data Acquisition System

A custom program was used to store and analyse the shaft vibration data on a laptop computer. Analog voltage signals from torque and RPM sensors were digitized, typically at rates of 2000 to 5000 readings/sec/channel. Data was recorded and stored continuously throughout the trials. Measurements were displayed in near-real time on the laptop computer, so an assessment of the shaft torsional vibration severity could be made throughout the trials. This included time domain strip charts of the torsional shaft vibrations and shaft speed. A display of the average torque, shaft speed, and ship speed over the previous 10 seconds can also be shown. The measurement error in the maximum amplitude of the torsional vibration was typically less than 4% for vibration frequencies up to 200 Hz.

Data Analysis Technique

Post analysis was conducted by reading selected stored data files and analysing the data in the time domain. Fast Fourier Transforms of the time domain data were computed to verify/determine dominant frequencies of vibration. Low and high pass digital filters were applied when required to eliminate noise or isolate vibrations at specific frequencies.

CASE STUDIES OF EXCESSIVE TORSIONAL VIBRATIONS

Two case studies are presented below, which present measurement results and recommendations.

Case 1: Bulk Cargo Vessel

The vessel is 192 m long, has a cargo capacity of 19,600 tons and a rated ship speed of 11.5 knots. Two V16-cylinder, four-stroke diesel engines provide the propulsive power, each rated 2,059 kW at 900 RPM. The engine power is fed through a double-input/single-output reversible reduction gearbox to a fixed-pitch 4977 mm diameter, 4-bladed propeller. Figure 1 shows a schematic of the shafting system.

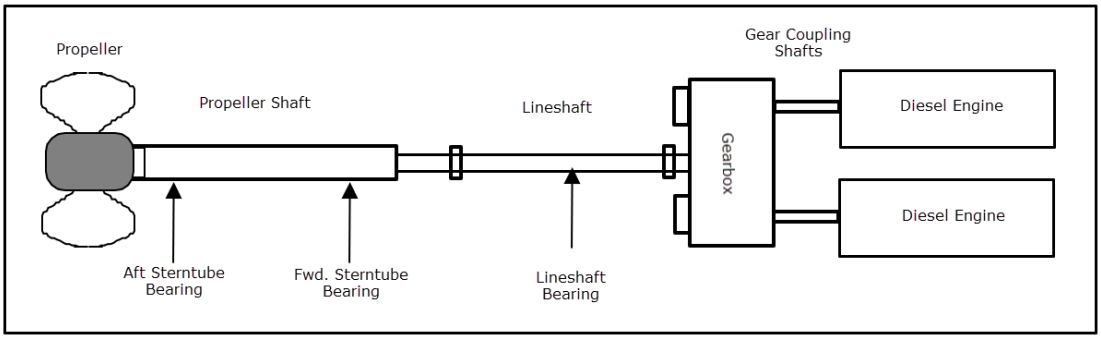

Figure 1 – Case 1: Propulsion Shafting Schematic

Numerous failures had occurred to the propulsion engines, the shaft couplings between the gearbox and main engine, and recently there had been two connecting-rod failures. To assist in the failure investigation, torque and power measurements were taken during a return voyage. The shaft torque was measured at three locations: 1 meter forward of the intermediate shaft bearing, and at about 1 meter forward of the gearbox on both the port and starboard shafts connecting the gearbox to the main engine. Figures 2 and 3 provide plots of the measured torsional vibration amplitudes against shaft speeds. Figures 4, 5 and 6 provide example time domain plots at shaft speeds prior to, during, and after resonant vibrations.

The following results were obtained from the measurement program:

- There was resonant vibration of the gearbox input shafts at 90 RPM (Ahead), and 85 RPM (Astern), corresponding to ½ Engine Order.
- There was resonant vibration of the propeller shaft at 71 RPM, which corresponded to blade-rate excitations. There was also resonant vibration of the gearbox input shafts corresponding to ½ Engine Order.
- The clutch-in torques and vibrations were acceptable. The clutch was only engaged with shaft rotation at 20 RPM or lower.

The following recommendations were made:

- A barred speed range from 85 to 95 shaft RPM be implemented.
- When slowing down the vessel the propeller shaft speed be lowered directly from 80 to 60 RPM, avoiding the 71 RPM astern resonance.
- The astern propeller shaft speed be limited to 80 RPM.
- Investigate options to change the torsional vibration characteristics such that critical shaft speeds are not in the operating range. This would include changes on the input shaft to the engine (e.g., increased diameter) and/or fitting of torsional flexible couplings.

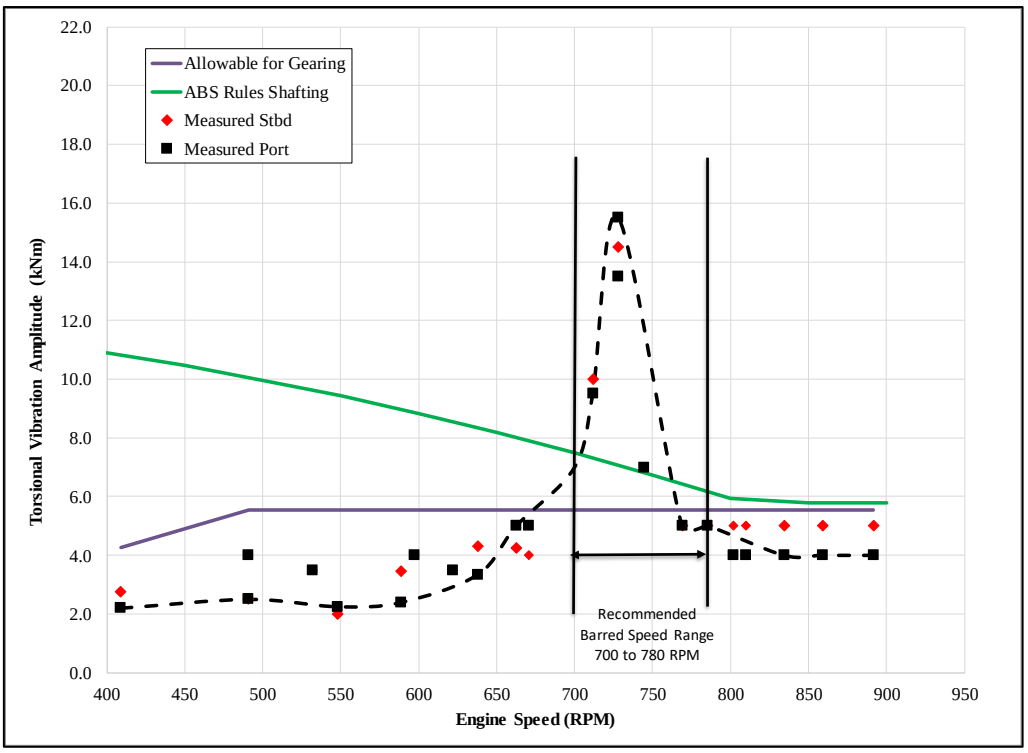

Figure 2 - Torsional Vibrations: Engine Input Shafts

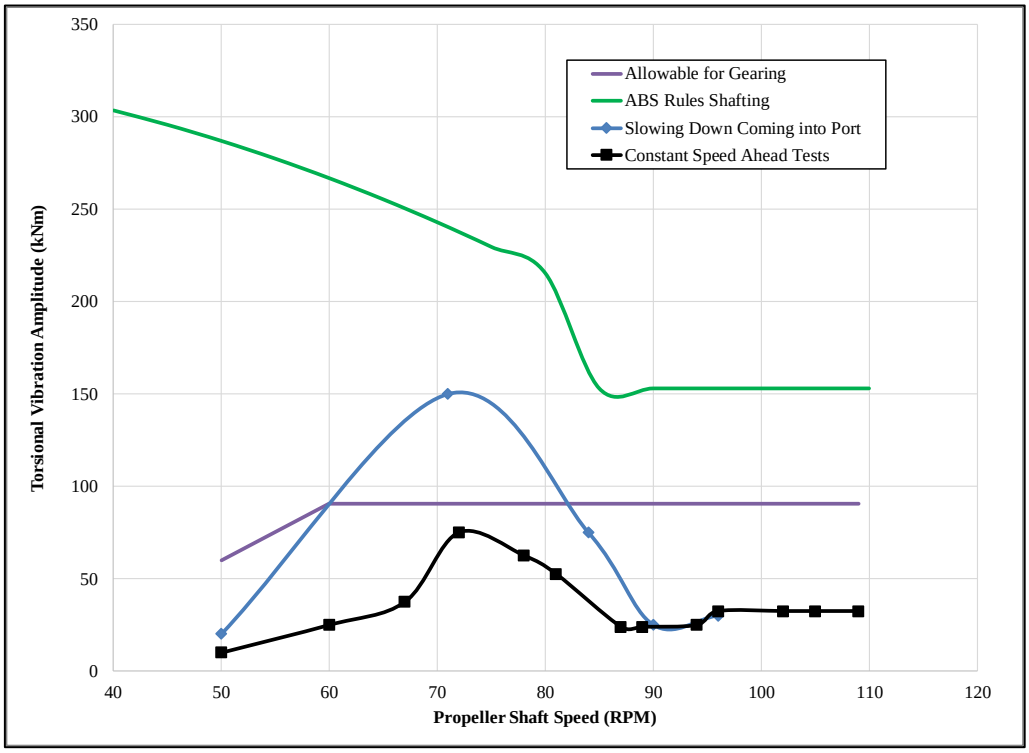

Figure 3 - Torsional Vibrations: Propeller and Line Shafts

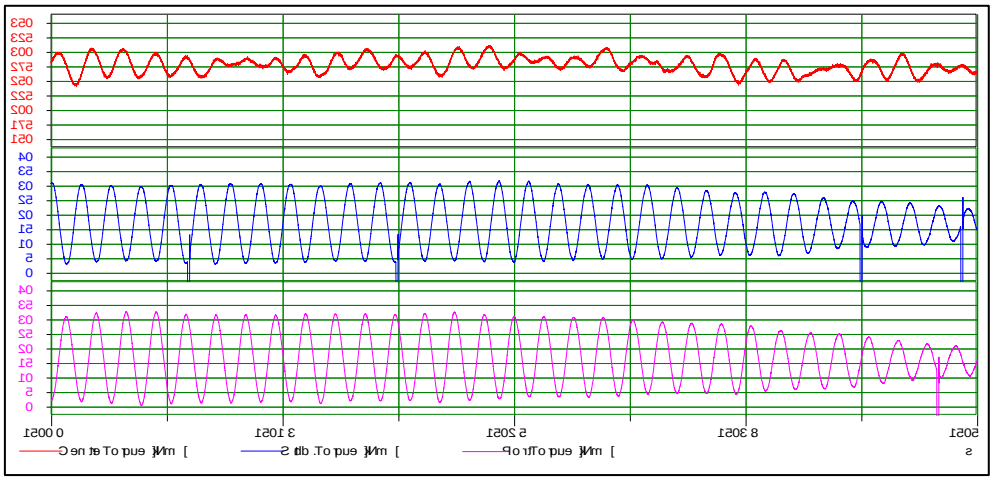

Figure 4 - Resonant Torsional Vibrations: 90 RPM

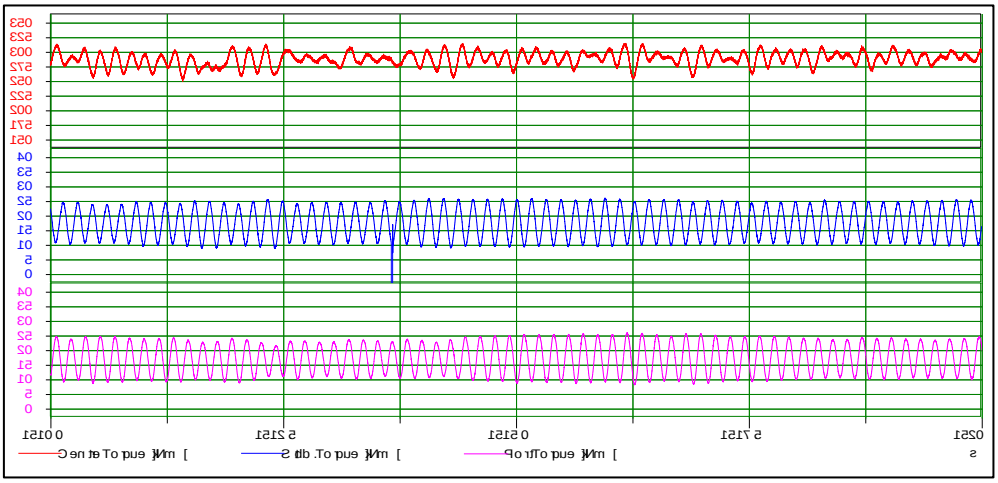

Figure 5 - Torsional Vibrations: 94 RPM

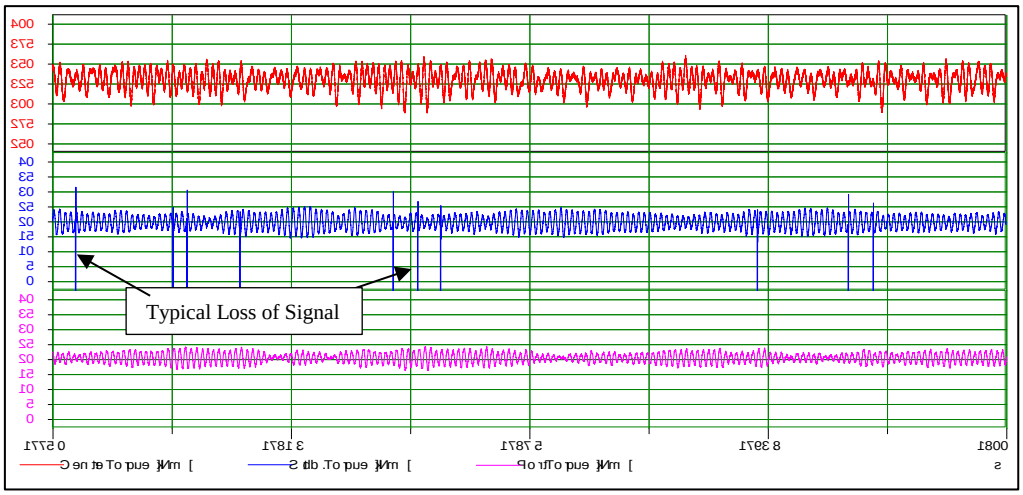

Figure 6 - Torsional Vibrations: 102 RPM

Case 2: Z-Drive Tug

The vessel has a twin-screw propulsion configuration (port and starboard). Each of the Z-Drive controllable-pitch propellers is driven directly by a 16-cylinder four-stroke diesel engine with a rating of 3052 kW at 1050 RPM. The shafting is about 10.7 m long, with a 5.1 m long “counter shaft” supported by three roller bearings, and a 5.6 m long intermediate shaft supported by four roller bearings with Cardan shafts at each end. Figure 7 provides a schematic of the shafting system.

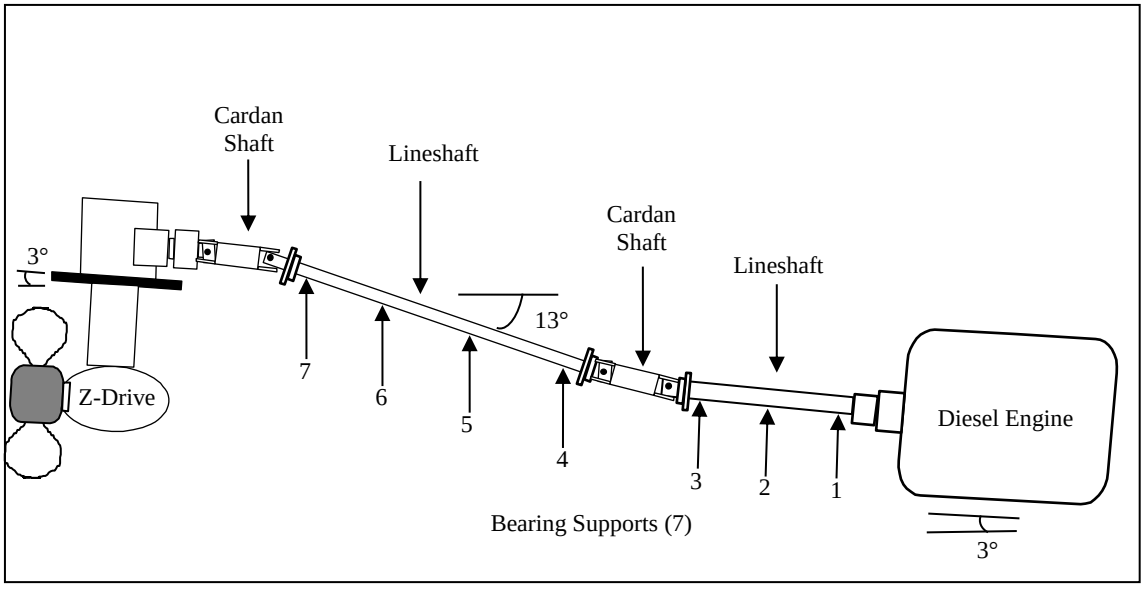

Figure 7 - Case 2: Propulsion Shafting Schematic

Torsional vibrations in the counter shaft, as well as shaft power, were measured during Bollard Pull tests. Figures 8 to 12 provide example results.

The measurements indicated that there was a resonant torsional vibration occurring at around 900 RPM. The vibration amplitude was greater than 200 % of the mean torque, which may cause gear-tooth backlash. The frequency of vibration was about 7 Hz, which corresponded to ½ Engine Order.

It was recommended that a Barred Speed Range be imposed from 870 to 950 RPM. Further measurements were recommended to better define the barred speed range, both at bollard and free running and to investigate changes to the torsional coupling stiffness to change the vibration characteristics.

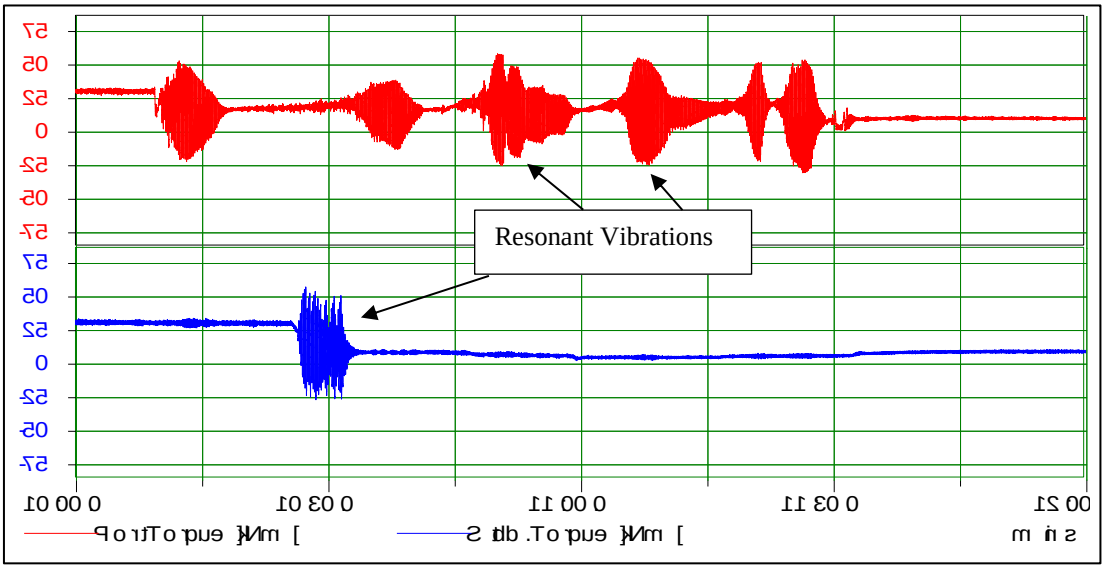

Figure 8 – Torsional Vibrations during Bollard Pull Testing

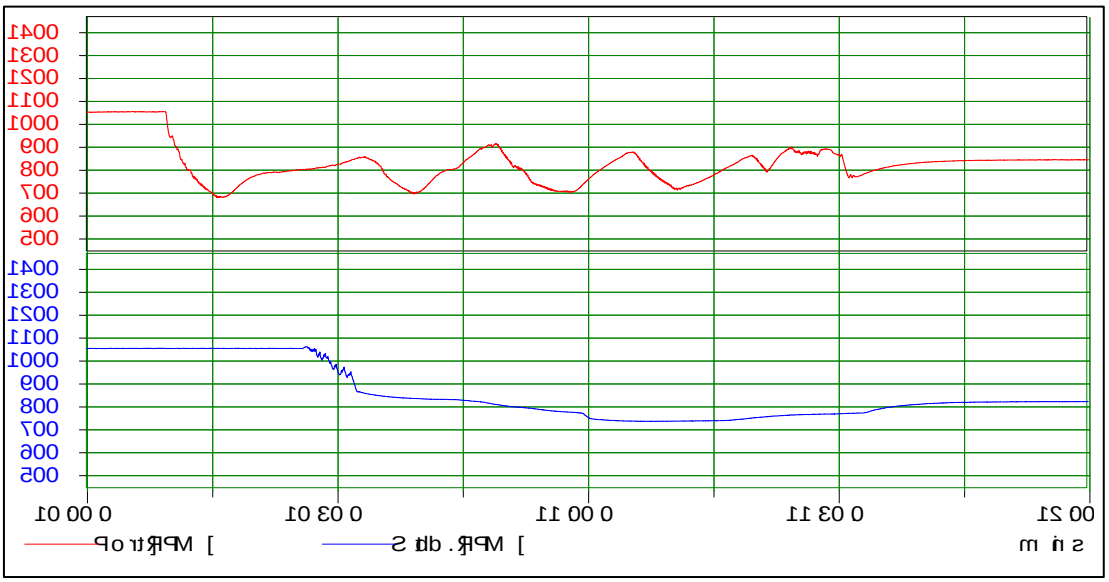

Figure 9 – Shaft RPM during Bollard Pull Testing and Resonant Vibrations

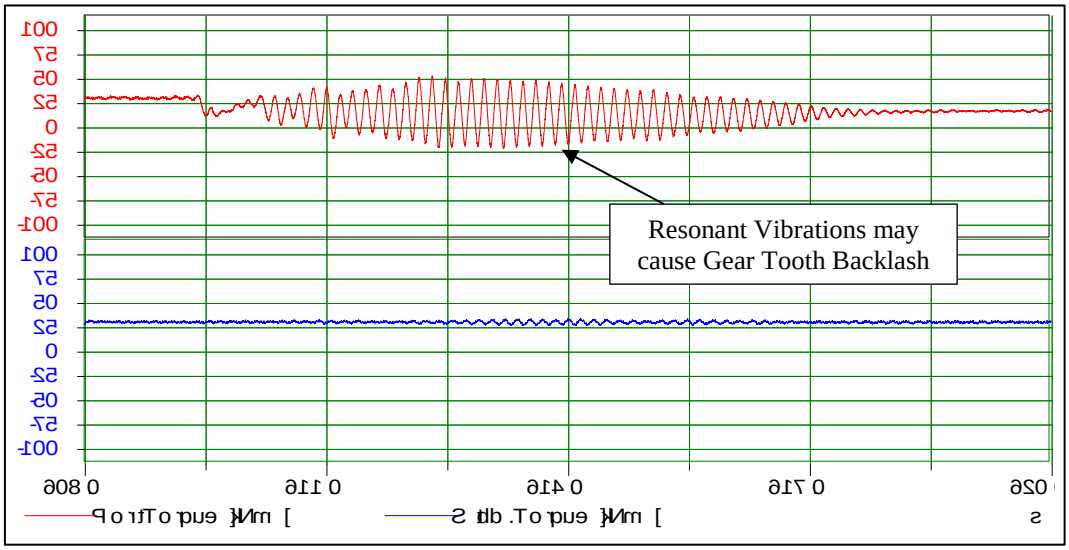

Figure 10 – Torsional Vibrations during Bollard Pull Testing

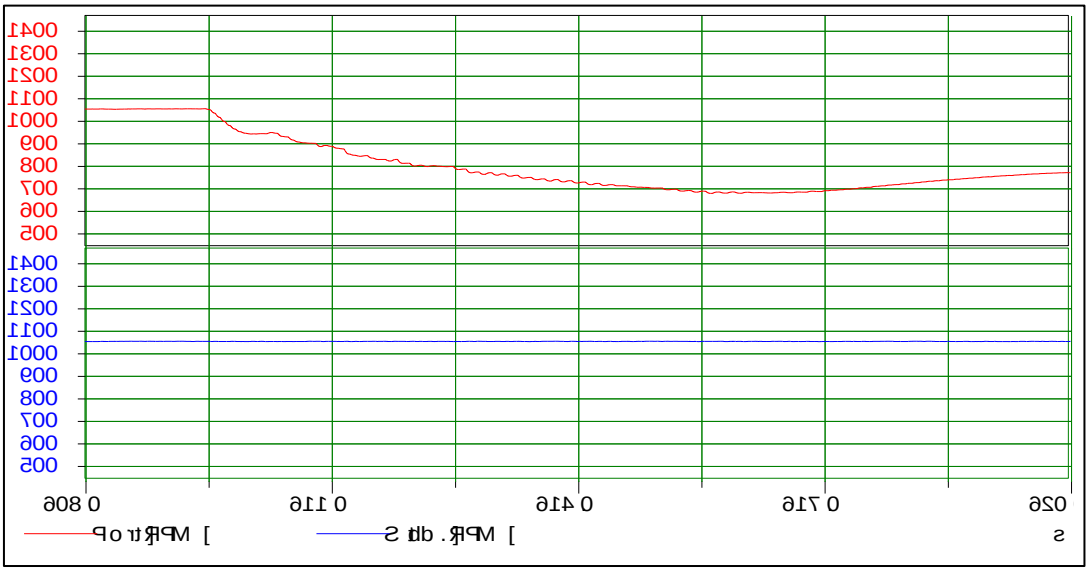

Figure 11 – Shaft RPM during Bollard Pull Testing Resonant Vibrations

CONCLUSIONS

Currently, torsional vibration measurements are compulsory at sea trials on slow speed diesel installations due to the expectation of a barred speed range. On other arrangements a theoretical torsional vibration analysis is only required to provide an estimate of vibrations. Significant differences between the theoretical and as-built vibrations can occur with more complex shafting designs, including those with cardan shafts and longer shafts between engines and gearboxes. In some cases, barred speed ranges were not anticipated but were required to ensure safe and reliable operations. Based on experience with a wide range of vessel types and sizes, real time monitoring during sea trials of the 1st of class shafting systems is appropriate under certain circumstances.