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Trg M. Pavlinovica 6
HR-21000 Split, Croatia
Tel./Fax +385 21 490 154
http://www.cadea.hr

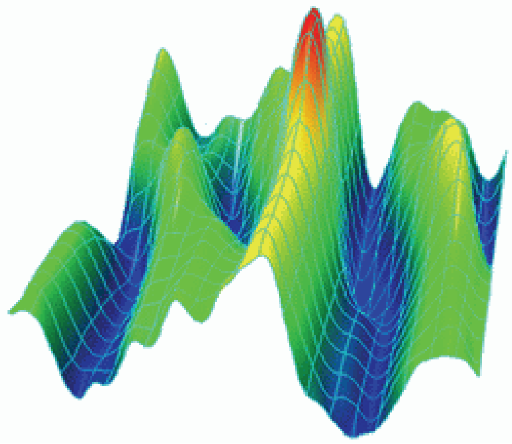
SHAFTING VIBRATION PRIMER

Gojko Magazinović, **CADEA**

This paper is partly based on the text published in the article: G. Magazinovic, "On Torsional Vibrations of the Propulsion Plant Shafting", Ukorak s vremenom (1998)18, 11-14 (in Croatian). Copyright © 1998, Marine Engineers Association, All rights reserved

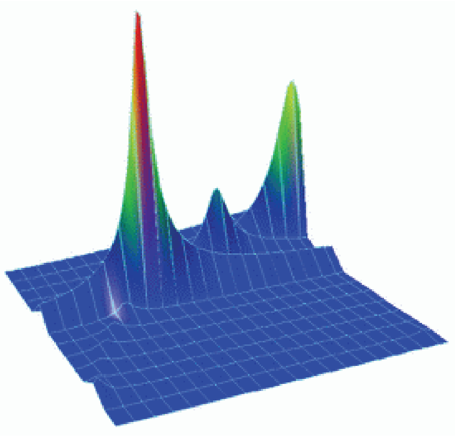
Introduction

All onboard machines, devices and structures are more or less subjected to the influence of vibrations. The vibration movement, or vibrations, is a special type of object movement in which the object (machine, device or structure) oscillates around some neutral position (equilibrium state).



There are various sources of vibrations, as well as various kinds of vibration movement. The consequences of a vibration movement vary greatly, from mere inconvenience for a human body, to the fatigue and stress that arise in the parts of machines, devices or structures. Unacceptably high vibration levels may become the source of pain for the humans and the cause of malfunction or even the collapse of machines, devices and structures.

When propulsion shafting vibrations are involved, there are three distinct types of vibration movement, each with specific sources, characteristics and consequences. These tree kinds of shafting vibrations are torsional, axial and lateral vibrations.



Shafting torsional vibrations

Shafting torsional vibrations are characterized by variable speeds of shafting rotation.

Shafting torsional vibrations are characterized by variable speeds of shafting rotation. In contrast to other detectable types of vibration, like axial or lateral vibrations, shafting torsional vibrations are *"invisible."* However, this kind of shafting vibration may become, under certain circumstances, the cause of serious damages, including shafting fractures.

The origin

Torsional vibrations are the characteristic of nearly all rotational machines and devices. However, torsional vibrations of internal combustion engines and their shafting are especially significant. These vibrations appear as the result of the variable revolution of rotating parts, invisible to the human eye.

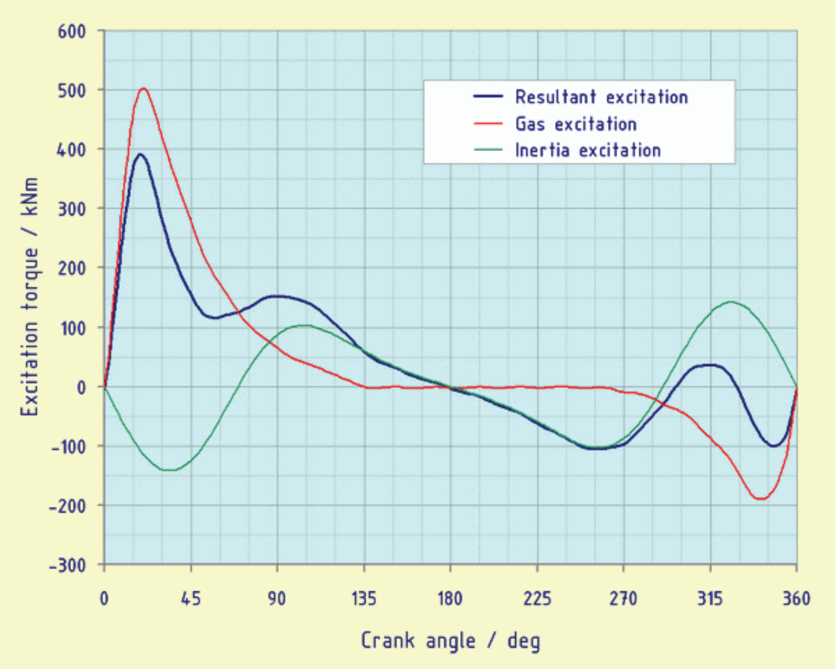


Figure 1. Excitation torque generated in cylinder of a typical low-speed diesel engine during crankshaft's full revolution (360 degrees). The resultant excitation combines the influences of the gas pressure and the crank mechanism inertial forces.

Torsional vibrations are the consequence of a number of processes. The most common are:

The main sources:
- gas pressure;
- crank mechanism; and
- propeller.

- variable gas pressure in the cylinder of an engine;
- inertial forces of a crank mechanism; and
- fluctuation of sea water flow around the propeller.

The excitation of torsional vibrations is significantly determined by the piston's stroke and the mean effective pressure. The ongoing increase of these characteristics is the cause of increased vibration excitation in the recent propulsion plants.

Shaft load includes a variable torque component, as well as a static torque component.

Figure 1. shows the variation of the excitation torque on the crank pin of a typical low-speed, two-stroke diesel engine. The crankshaft load Includes, besides the variable torque component, a static torque component that depends on the power transmitted and the engine speed.

The total engine excitation is the result of simultaneous action of all cylinders.

Since propulsion engines are composed of a number of cylinders, the total torque is the result of the simultaneous actions of all cylinders, taking into account the phase angle between them due to the firing order, as seen in Figure 2.

During a misfiring operation, a strong counter torque occurs.

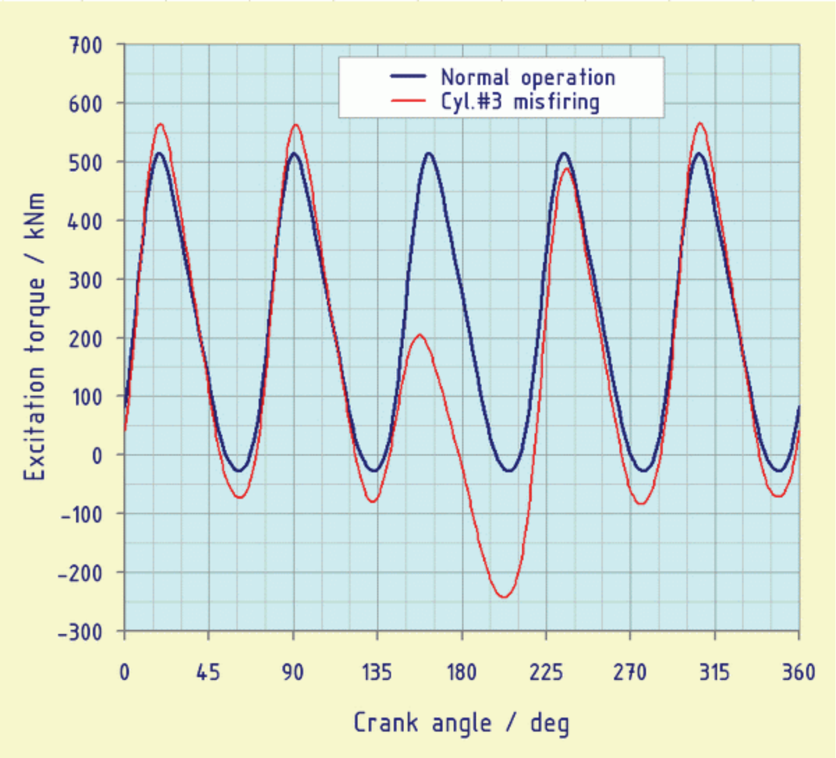


Figure 2. Cumulative excitation torque generated in a typical five-cylinder, low-speed diesel engine during crankshaft's full revolution (360 degrees). The blue line represents the case when all cylinders work properly (normal operation). The red line represents the case when cylinder No. 3 lacks ignition (misfiring operation).

The variable torque initiates vibration of the propulsion plant components.

The variable torque, generated in the engine's cylinder, is transmitted through the shafting up to the propeller. This torque initiates the vibration movement of the propulsion plant components.

The response of a system

Mechanical systems, as a whole, possess some vibration properties denoted as *natural frequencies* and corresponding *modes of vibration*.

Resonance: the event when excitation frequency is equal to the system's natural frequency.

If the frequency of excitation, expressed as the number of impulses per second, is sufficiently different from the system's natural frequency, the system will vibrate "moderately." If, however, the frequency of excitation is equal or nearly equal to the system's natural frequency, the system will respond by strong, even severe vibrations, shown in Figure 3.

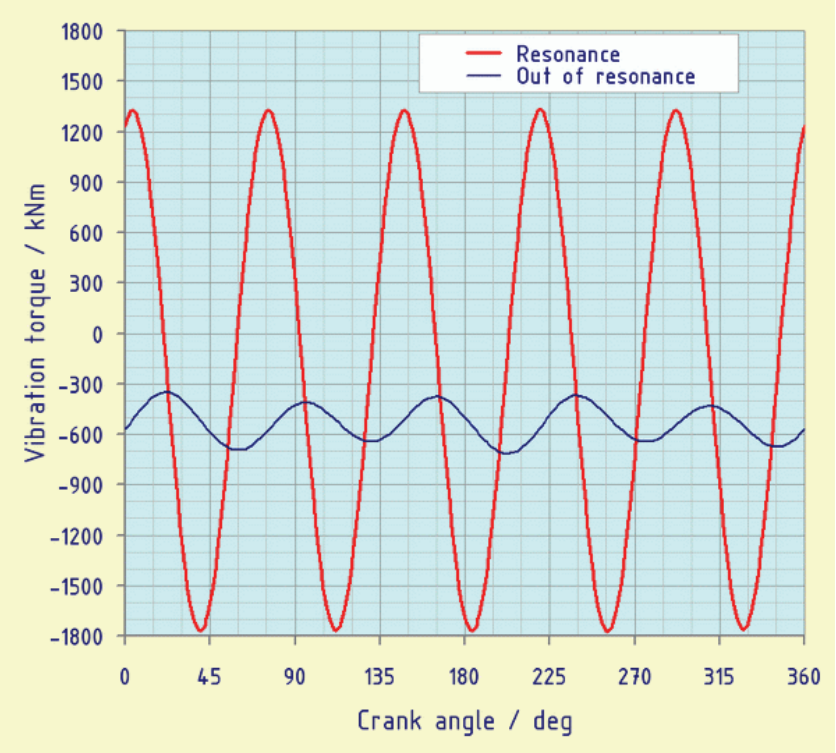


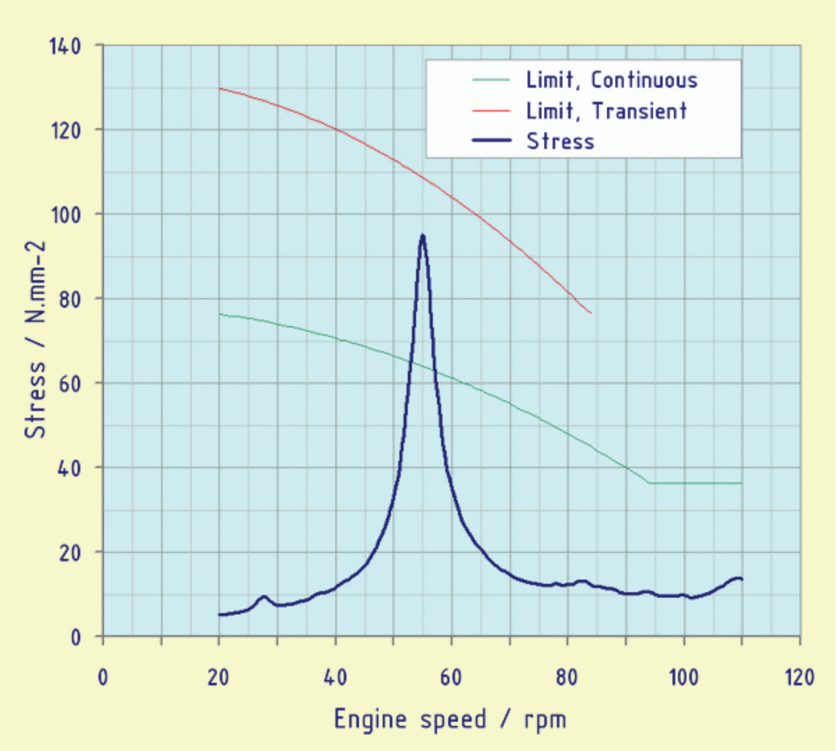
Figure 3. Typical vibration torque variation in a propeller shaft of a conventional, low-speed diesel engine propulsion plant. The blue line corresponds with the system's out-of-resonance running condition, while the red line corresponds to the system's resonance running condition.

The propulsion plant, composed of the propulsion engine, the shafting and the propeller, denotes a vibration system. This system, determined by the inertia of its components, as well as by the stiffness between them, possesses its own natural frequencies and corresponding modes of vibration.

The propulsion shafting, composed of the crankshaft, the intermediate shaft and the propeller shaft, will vibrate when excited by variable torque.

The total torsional stress is a sum of the static and the vibration stress.

The main consequence of propulsion shafting torsional vibration is the occurrence of torsional vibration stresses in the components of the system (Figure 4). The total torsional stress in each component of a shafting system is then determined as the sum of a vibration stress component and a static stress component. As mentioned earlier, the static stress component is a product of power transmission.



The static stress component is not included herein.

Figure 4. Typical torsional vibration stress response for intermediate shaft during normal operation of a conventional low-speed diesel engine propulsion plant. Stress limits for engine's continuous and transient running are also included.

Stress limits

The stress limits depend on many factors, including the engine speed.

Classification societies prescribe the amount of allowable torsional vibration stresses for engine crankshafts, intermediate shafts and propeller shafts. These stress limits are determined by the purpose, shape, material selected, dimensions and intended operation of shafting. Moreover, the stress limits are not constant; instead, they are a function of engine speed.

At the engine's low speeds, the stress limits increase, whereas at the engine's high speeds, the stress limits decrease. When the engine's speed rises, the static stress component also rises and it is necessary that the total stress level remain within acceptable limits.

For each shaft type, there exist two distinct stress limits.

For each shaft type, classification societies prescribe two values of stress limits - the lower and the higher (Figure 4).

- The lower stress limit is applicable to the entire speed range of a propulsion plant. This limit determines the maximum stress level allowed for the continuous engine operation.

The higher stress limit should not be exceeded *in any* case!

- The higher stress limit is applicable only for a fraction of the entire speed range, i.e., up to 80% of the engine's maximum continuous speed. This stress limit represents the stress level which, in any case, should not be exceeded.

If the lower stress limit is exceeded, the barred speed range is introduced.

In the events that actual vibration stresses exceed the lower stress limit, but not the higher stress limit, the so-called barred speed range is introduced.

The barred speed range must be passed through rapidly. Actually, torsional vibrations need some time to fully develop and, if the barred speed range is passed sufficiently rapidly, there is a great possibility that the full stress level will never be reached.

The barred speed range is clearly noted in red on the tachometer, as well as on notice boards. Moreover, more recent propulsion plants are equipped with special devices that ensure that this range is rapidly passed. The intermediate shaft vibratory stress variation, as shown in Figure 4, exhibits some interesting points deserving of more clarification.

- Engine speed ranges below 40 rpm and over 70 rpm are characterized by moderate, even low stress levels. Torsional vibration stress is exceptionally low in the engine speed range above 90 rpm, i.e., in the vicinity of an engine service speed that is 105 rpm. Fortunately, the static torsional stress component is the largest in this region.

- The peak vibration stress is reached at 55 rpm, when the engine output is less than 15% of the maximum continuous rating. At the same time, the static stress component amounts to approximately one third of the shaft static stress at the nominal engine speed. This is due to the resonance between the excitation torque and the system's natural frequency. Therefore, this engine speed is usually called the critical speed.

- In the engine speed range between 53 and 57 rpm, the actual vibration stress is higher than the stress limit for continuous running, and the barred speed range is introduced. For the safety reasons, the actual restricted speed range is usually imposed in a slightly wider interval.

The influence of one cylinder not firing

Each kind of firing irregularity increases vibratory stresses.

One cylinder not firing is an extreme kind of firing irregularity.

In general, any irregularity in cylinder firings usually produces enlarged vibratory stresses in the components of a propulsion plant. As shown in Figure 5, the absence of firing in one of the cylinders significantly changes the entire propulsion plant torsional vibration behavior.

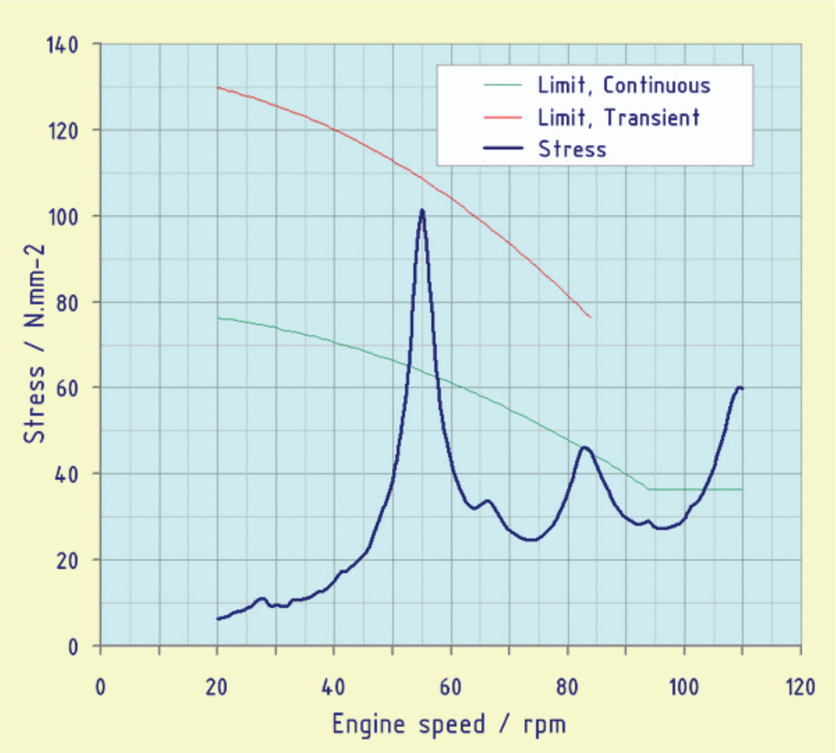


Figure 5. Typical torsional vibration stress response for intermediate shaft during one cylinder misfiring operation of a conventional, low-speed diesel engine propulsion plant. Stress limits for the engine's continuous, as well as transient running are also included.

Misfiring in any one cylinder causes the rise of resonances that are small, even negligible, during the engine's normal operation. Moreover, these resonances are usually placed in the vicinity of an engine's rated speed and thus cause an additional operation limitation. Fortunately, these operation limitations are not permanent, but only applicable until the resolution of the problem.

In the case of an intermediate shaft, as shown in Figure 5, the additional speed restrictions would be, together with the previous case, in the interval between 80 rpm and 86 rpm, as well as in the region above 102 rpm. Since no one classification society allows barred speed ranges in the region above 80% of the rated speed, the operation limitation will read:

No barred speed ranges are allowed in the region above 80% of the rated speed.

"*In the event of one cylinder misfiring the maximum engine speed is not to exceed 80 rpm.*" The note of this or a similar meaning should be included in the propulsion plant operation manual.

More on resonance

The resonance is a state of movement when the system vibrates in phase with an externally applied load.

Peaks on a diagram correspond to system resonances.

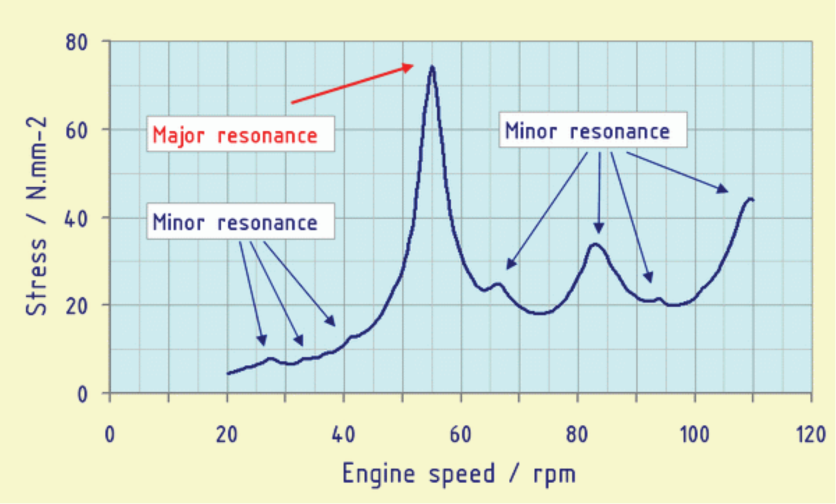


Figure 6. Resonances

The excitation torque is composed of a number of single harmonic excitations.

Each single harmonic excitation has its own frequency.

The system response is also constructed from a number of single harmonic responses.

The excitation torque is composed of a number of single harmonic excitations. Each single harmonic excitation has its own frequency, which is a multiple of the shaft rotation frequency. This multiple is called the *order*. There exists the first order excitation, the second order excitation, etc. Of course, the *i*-th order excitation produces the *i*-th order response. Finally, the system response, shown in Figure 6, is also constructed from a number of single harmonic responses.

Each single harmonic response has its own system resonance. Various peaks on the diagram in Figure 6 correspond to such system resonances.

The main resonance, usually denoted as a system main critical speed, occurs when the system vibrates in phase with the *n*-th order excitation. If the propulsion plant is powered by a two-stroke engine, *n* is equal to the number of engine cylinders. If, on the other hand, the propulsion plant is powered by a four-stroke engine, *n* is equal to the one half of the number of engine cylinders.

Counteracting shafting torsional vibrations

The most effective countermeasure is an appropriate shafting design.

It is extremely important to act as soon as possible.

Later, the possible solutions are rare and expensive.

The easiest, fastest and most cost-effective way to counteract shafting torsional vibrations is in the propulsion shafting design phase. Later, when the propulsion shafting is finished and put in operation, satisfactory solutions are rare and more expensive.

During the propulsion shafting design phase, it is possible by proper design to keep vibration responses within the allowable limits. The most usual measures are:

- selection of appropriate dimensions and materials,
- selection of appropriate turning wheel,
- selection of appropriate tuning wheel, and
- selection of engine appropriate location, if applicable.

Minor torsional vibration problems of an existing propulsion plant may be resolved by appropriate operations, i.e., by the rapid pass through the hazardous speed ranges. If this is not applicable, the only possible solutions are the propulsion shafting redesign, or mounting of a torsional vibration damper.

The torsional vibration damper is a device that should be mounted on the fore end crankshaft flanges. It absorbs some vibration energy from the system and in that way saves the propulsion shafting components from the unacceptable stress levels. However, it should be clearly realized that this solution may be prohibitively costly - the cost of a large torsional vibration damper may be in excess of 100,000 USD per piece.

Shafting axial vibrations

Shafting axial vibrations are characterized by shafting segments oscillating in a fore-and-aft direction around some neutral position. For simplified description purposes only, this motion may be compared to the movement of an accordion during play.

Shafting axial vibrations are mainly excited by the propeller's thrust variations, as well as by forces generated in the engine's crank mechanism. Namely, the excitation forces coming from the gas pressure and from the inertia of alternating masses are converted into the equivalent crank throw opening-closing forces, acting along the longitudinal, axial, direction. In some cases, due to torsional-axial coupling, excessive axial vibrations may be excited by shafting torsional vibrations.

Although shafting axial vibrations alone are rarely the cause of severe shafting damages, they are usually the cause of a vessel's hull vibration, excited by the variable force acting on the engine's trust block.

To minimize unfavorable side effects of the shafting axial vibrations, most enginebuilders of the low-speed diesel engines integrate an axial vibration damper into the engine casing. That way, the axial vibration damper becomes a standard building block of modern low-speed diesel engines.

Shafting lateral vibrations

Shafting lateral vibrations are characterized by shafting segments oscillating in a plane passing through the shaft's neutral position. For simplified description purposes only, the shaft axis may be considered the shaft neutral position.

Lateral vibrations may be considered as a special case of the more general whirling vibrations, which represent the resultant motion of two concurrent motions, each in perpendicular planes passing through the shaft neutral position.

Lateral vibrations are mainly excited by the propeller weight, propeller induced variable forces and shafting segments' weight and imbalance. The amplitudes of lateral vibrations are generally enlarged by the increased span between the line shaft bearings. However, it must be clearly understood that a small inter-bearing distance could also provoke enlarged lateral vibrations. It is especially the case with the stern tube bearings, if the forward stern tube bearing becomes unloaded.

In general, the basic design countermeasure against the unacceptable shafting lateral vibrations is to ensure that the lateral natural frequencies are positioned sufficiently far away with respect to the propeller rotation speed.

Questions & Answers

Q: Why are shafting torsional vibrations so important?

A: Propulsion shafting is one of the most important onboard systems. Therefore, it deserves special consideration during design, manufacturing, and later, operation.

Virtually all onboard structures and systems are subjected to static as well as dynamic loads. However, the importance of these two types of loads is not uniformly distributed. Some building blocks are predominantly statically loaded, whereas others are predominantly dynamically loaded. Besides, building blocks have different sensitivity to static and dynamic loads. Therefore, they need different approaches during the design, the manufacturing, and the operation stages.

Design engineers are not able to take into account all the factors acting on the structural parts or machines. However, they must consider the most important loads and processes.

When propulsion shafting is considered, as it is mostly dynamically loaded, its dynamic behavior is the major factor influencing its overall reliability and efficiency. This means that shafting vibration behavior, especially torsional vibration behavior, is the most important factor influencing shafting design.

It must be clearly realized that classification societies' formulas take into account static loads only, and therefore, these formulas are not sufficient for proper shafting designs. *Only thorough torsional vibration analysis may confirm or reject the validity of the proposed shafting design!*

Q: What is the importance of shafting axial or lateral vibrations?

A: In general, axial and/or lateral vibrations are less severe than torsional vibrations. However, this does not mean that the effects of axial and/or lateral vibrations may be neglected. Propulsion shafting is too important to be designed without considering axial and/or lateral vibration effects.

In general, classification societies require additional vibration analyses and/or measurements if they expect, based on their previous experiences, increased vibration responses.

Q: Can axial or lateral vibrations cause severe damages?

A: Definitely yes! Although axial or lateral vibrations are generally less severe than torsional vibrations, there exists evidence of severe damages caused by axial and/or lateral vibrations.

Moreover, coupled torsional and/or axial and/or lateral vibration is a case of mutual vibrations, when each type of vibration simultaneously contributes to severe damage.

Q: Does a particular engine model produce the same vibration effect independently from the configuration of the propulsion plant?

A: Definitely not! Propulsion engine is not an isolated vibration system; actual vibration system consists of an engine, shafting, propeller and other devices (e.g., gears, clutches and couplings). Only the vibration system as a whole may be considered as a system that possesses good or bad vibration behavior.

It means that the same engine model may behave completely differently in different propulsion environments, constructed of different propulsion plant components.

Q: The engine runs smoothly. Is there a possibility of severe shafting torsional vibrations, although there is no visible evidence of any vibrations?

A: Unfortunately yes! Torsional vibrations behave, to some extent, differently from other types of vibrations. For example, floor vibration may be easily detected by the people onboard. Similarly, table or device vibrations are also easily noticeable. On the other hand, shafting torsional vibration behaves differently. Namely, shafting torsional vibrations are the consequence of shafting variable speed of rotation. Since angular displacements are very small, they are invisible to all observers. Moreover, during the high shafting torsional vibrations, the propulsion engine alone may appear stable and free of any vibrations.

The fact that the shafting torsional vibrations are not visible does not mean that they do not exist!

Q: The engine runs at a low speed, say 30% SMCR. Is there a possibility that the propulsion shafting is subjected to severe torsional vibrations?

A: Yes! High vibration stresses are the consequence of resonance conditions. As described elsewhere (e.g., in the Shafting torsional vibrations pages of this primer), major resonant conditions may be met at various engine speeds, even if they are very low. In these cases, shafting may be subjected to high, even severe, vibration stresses, although the engine operates at low speed and/or low output power.

The only way to predict hazardous engine speeds is to perform shafting vibration analyses. In addition, it is a good engineering practice, if not required by the classification society in charge, to measure actual vibration responses during the sea-trials.