Vibration on the High Seas

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Vibration on marine vessels is a very important subject. Not only can excessive vibration produce the same problems as can be found on stationary equipment, but damage to the water tight integrity of the hull can occur with catastrophic consequences. Also, marine structures tend to be more complicated than stationary systems.

Vibration on marine vessels presents some interesting problems. Not only is machinery mounted on marine vessels subjected to the same types of problems as would be encountered by other industries, but in addition they have their own unique problems. For one thing, they can be influenced by hydrodynamic affects from the water in which the hull is immersed. Also, foundations for equipment mounted on marine vessels are generally more compliant than the foundations of stationary equipment. Part of the reason for this is to make the vessel light and economical, but also the vessel itself will distort due to influences of the surrounding water. One other potential source of problems, not unique to but more often encountered on marine vessels than in other industries, is a greater emphasis on isolation. The usual reason for this is to reduce the amount of noise introduced into the environment. Examples of this include military vessels, where noise reduction is of paramount importance to maximize the stealth potential of the vessel, and ferry boats, where it is desirable to reduce the engine noise in the passenger compartments.

One other item related to marine vessels that should be fully appreciated is that the consequences of a failure can have far greater potential for disaster than would be the case in other industries. A high level of hull plate vibration can initiate a fatigue crack that can breach the water-tight integrity of the hull. This can result in the flooding of a compartment. The flooding of a component necessary for vessel control during a critical moment can result in a great deal of damage not only to the vessel itself but also to the environment and structures outside the vessel. In the worst case, the result can be the loss of the vessel and all hands on board.

For these reasons, addressing vibration-related problems on marine vessels has an inherently higher level of importance that it would have in other industries.

Forcing Functions

The four most important forcing functions in marine vessel vibration problems are:

- Fundamental engine speed
- Engine firing frequency (assuming that the vessel has a piston driven engine)
- Fundamental shaft speed
- Blade-passing frequency

Fundamental engine speed is simply the speed of the engine in RPM. The firing frequency is the engine speed times the number of cylinders in the engine divided by the number of rounds the engine makes for each time a cylinder fires. Cylinders can fire once every two (two cycle) or once every four (four cycle) engine rounds. The shaft speed is generally different from the engine speed. The reason for this is that the vessel power train usually includes a speed-reducing gearbox. The speed reduction ratio is usually indicated on the name plate of the reduction gear. For example, the speed reduction ratio might be 2.5:1 in which the engine speed is 2.5 times the shaft speed. The reason for the speed reduction is that slower, larger diameter propellers that have less of a tendency to cavitate are inherently more efficient and can transmit more power to the water than smaller, higher speed propellers that have more of a tendency to expend energy in the form of turbulence than in useful work. The last of the common forcing functions is the propeller blade passing frequency, which is simply the shaft speed times the number of blades on the propeller.

Another quirk of marine vessels that can introduce vibration-related problems is that the engine generally does not run at one speed. In fact, the range of running speeds can be substantial. This combined with the fact that there are four major forcing functions at each engine speed make it almost impossible not to excite a resonance somewhere on the vessel at a particular engine speed. In some cases, the effect of the vibration-related problems can be minimized by avoiding certain running speeds. However, there are cases where the vibration becomes quite severe as engine speed is increased, and the response of the crew is to run below the critical speed. This is an effective solution as long as there is no reason to run above the critical speed. But in such cases, it should be appreciated that if speed were to be increased rapidly through the critical speed range, the level of vibration would probably go down once engine speed was stabilized above the critical speed.

Case Histories

This article centers on three interesting case histories. The first was a new, large passenger and motor vehicle ferry. All new, American-made vessels, especially those that will be carrying passengers, are required by the Coast Guard to meet certain requirements. Among them are limits on machinery and hull plate vibrations; see the most current version of ANSI S2.16. A pre-acceptance vibration survey was performed around the main engines and at selected locations elsewhere on the vessel. Throughout the vessel, a great deal of vibration was found at the propeller blade-passing frequency. At certain locations on the hull, in particular the area between the propellers, the vibration amplitude was high enough that there were concerns related to the hull integrity. The level of the vibration did not appear to be significantly affected by engine speed. Basically, it was high at virtually all engine speeds above an idle.

High levels of vibration are generally caused by one of two conditions, either there is a system resonance or the strength of the forcing function is high. In the case of a resonant condition, even a weak forcing function can generate a high level of vibration. However, high levels of vibration due to a resonance will occur over a small frequency range. In this case, a high level of vibration was found over a large frequency range. With this being the case, it was concluded that the strength of the forcing function was quite strong.

A review of the vessel design was conducted. One interesting finding was that the hull clearance was relatively tight for the size of the propellers. At this point, a brief discussion of the affects on water flow stream on propeller vibration is in order. On single-engine vessels, the propeller shaft generally emerges from the hull through the keel. Often, there is part of the keel below the propeller that protects the propeller and supports the bottom of the rudder. On vessels with two power trains, however, the propeller shaft never comes out of a keel-like structure. It usually exits the hull and is usually supported on "V" struts that are completely unprotected and some distance from the hull (see Figure 1). The reason for the two significantly different propeller configurations is related to hydrodynamic characteristics. On single-propeller vessels, the water flow on both sides of the propeller is about the same. When the first two-power-train vessels were built, the propellers were mounted in a fashion similar to two parallel keel-like structures coming out of the hull. However, these vessels would develop a great deal of vibration at blade-passing frequency. The reason was subsequently determined to be that the water flow characteristics around the propellers were not uniform. In particular, the flow speed in the area between the keels was significantly slower than it was outside the keels. As a result, every time a propeller blade would hit the slow flow area between the keels, a pulse would be generated. This condition was addressed by mounting the propellers in the now familiar configuration on V struts and far enough from the hull that gradients in water stream flow rates would be a minimal.

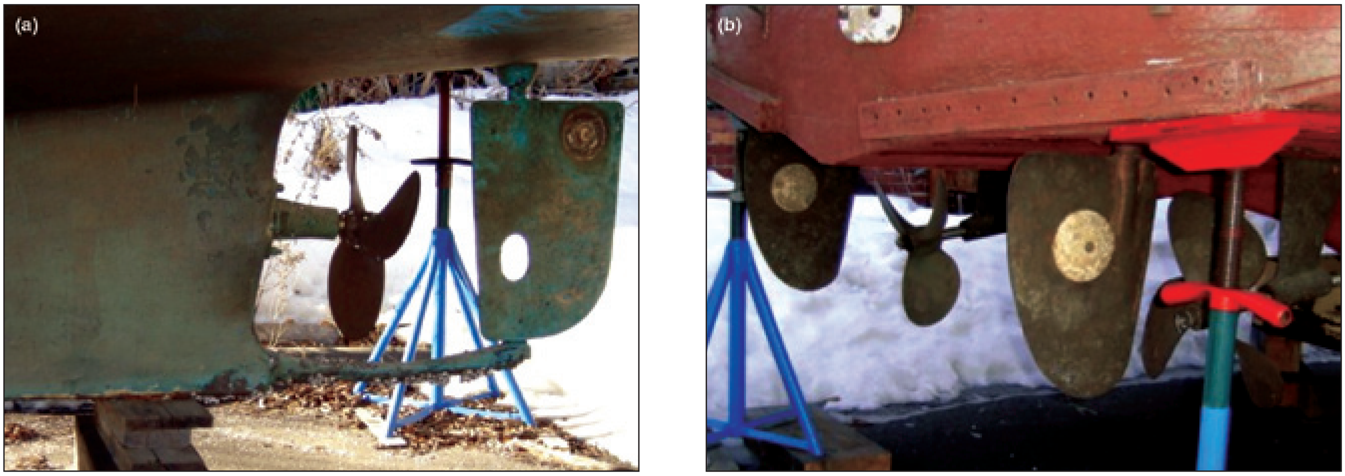

Figure 1. Propeller shafts on single- and twin-engine vessels. Note that on the single engine (a), the propeller shaft comes out of the keel and is relatively well protected by the keel. On the twin engine vessel (b), the shafts come out from the hull and are supported by struts. In this configuration, the propellers and shafts are not well protected.

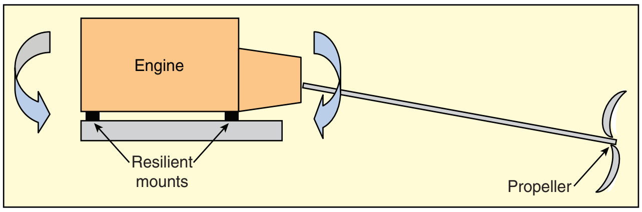

Figure 2. Diagram of a marine engine that would go into a torsional resonance about the Z axis (the axis perpendicular to the page) at a shaft speed of approximately 400 RPM. The problem was resolved by removing the resilient mounts.

In the subject vessel, the propeller shafts were mounted on V struts, but spatial constraints limited the distance the propellers could be mounted from the hull.

Another item that aggravated the condition was related to propeller rotation. On most vessels with two power trains, the propellers rotate in opposite directions or they are said to be "counter rotating." If they were not counter rotating, steering limitations would be introduced.

The propellers can counter rotate in two fashions. Relative to the space between the propellers, they can rotate up or down. It was noted by the marine architect that if the propellers rotate up, the vessel will pivot or twist in its own length better, and if the counter rotation is down, the vessel will "crab" or move sideways better. Neither condition is universally better nor worse than the other; it is just a matter of what the customer wants in the handling characteristics of his vessel. In the subject vessel, it was initially specified that the counter rotation would be up. The problem with this configuration was that strong pressure pulses would impinge on the hull immediately above the propellers. If the propellers had been located a significant distance from the hull, the strength of these pulses would have been more dissipated and probably not an issue, but because the propellers were so close to the hull, the pressure pulses were very strong and generated a great deal of vibration.

In this case, it was possible to address the condition by reversing the rotation of the power trains. Now, the counter rotation was down. There was still an upward pressure pulse toward the outboard side of the propellers, but the hull was just that much farther away from the source of the pressure pulses and curved so that the pulses impinged upon it from a somewhat oblique angle. The level of vibration was roughly an order of magnitude lower. The customer did not get exactly the handling characteristic that he wanted, but the vessel had a much lower level of vibration and was much safer.

The second case history was another ferry boat. In this vessel, attempts had been made to reduce the level of fugitive noise in the passenger compartment by setting the engines on resilient mounts as shown in Figure 2. As a result, the level of fugitive noise was reduced, but a high level of vibration would develop in the port engine as the vessel approached full speed. Interestingly, in the starboard engine, a virtually identical installation, no unusual vibration was reported at this speed.

Upon subsequent investigation, it was learned that the fugitive frequency was shaft speed, approximately 400 RPM in this case. The engine was vibrating in a "bucking" or torsional mode about the Z axis. The X axis is parallel to the shaft, Y is vertical, and Z is horizontal perpendicular to the shaft. As the front end of the engine would go up, the back would go down and vice versa.

It was surmised that the high level of vibration was the result of a resonant condition in the engine and resilient mounting system that was excited by shaft speed. A resonant frequency impact test indicated a resonance at a somewhat different frequency. The likely reason for the discrepancy was that under dynamic conditions, the thrust load affected the system stiffness and therefore the frequency at which the resonance would manifest itself.

Another interesting finding was made by manipulating the stiffness of the mounts. It was believed that the level of vibration could be addressed by changing the stiffness of the mounts. This was demonstrated as follows. First, the vessel was brought up to the fugitive speed. The engine developed the characteristic bucking mode vibration. At this point, wooden wedges were inserted between the engine/reverse gear and the bed frame at the location of each of the four resilient mounts. At this point, the level of vibration went down immediately.

The starboard engine not vibrating was also addressed. It was demonstrated that under certain operating conditions, this engine also would develop the characteristic vibration. In particular, it was demonstrated that when the vessel would run close to full speed in reverse, the starboard engine would develop the characteristic vibration. Apparently, there was some variation in the stiffness of the two sets of motor mounts.

It was recommended to the customer that the resilient mounts be eliminated or that stiffer resilient mounts be obtained.

The final case history involved a small fishing boat. The vessel was a lobster fishing boat approximately 40 feet long. It was a new boat with a hull fabricated from wood. It was an elegant vessel with teak decks and mahogany trim. The owner complained of excessive vibration.

The initial vibration analysis centered on the power train. It was subsequently determined that the initial investigation was too focused on the power train. Although some significant findings were made, the primary vibration problem was really not even identified until one stepped back and took a look at the entire system.

After it was determined that the primary problem did not appear to be directly related to the power train, the hull was investigated. Vibration data obtained from the gunwales and deck revealed a generally high level of vibration. The level of this vibration was higher and not so high at certain operating speeds, but it was generally high at all speeds above an idle. In fact, the level of vibration was high enough that there were concerns related to the

Figure 3. Propeller shaft and keel of fishing boat. Note the "half-moon shaped" blocks above and below the cutlass bearing. After these blocks had been installed, the hull and deck vibration went down dramatically.

long-term integrity of the hull. It was determined that the fugitive frequency would bear a relationship with engine speed, but it was very interesting that the fugitive frequency did not correspond to any of the four primary suspect forcing frequencies produced by marine power trains.

It was not until another fisherman brought to light his own observations that the root cause of the vibration was determined. In particular, he had a similar vessel; however, the keel on his vessel was slightly different. In both vessels, the propeller shaft emerged from the hull through the cutlass bearing that was attached to the end of the keel. However, on the subject vessel, there was a semicircular cut-out in the end of the keel both above and below the cutlass bearing . The cut-outs were not on the other vessel, and the other vessel did not have the vibration problem. These cut-outs made the hull look streamlined, but they were likely responsible for vortexes being shed immediately in front of the propeller. The pulsations generated by the propeller blades striking the vortexes was the likely forcing function of the fugitive vibration. The condition was addressed by installing filler blocks as shown in Figure 3 in the semicircular cut outs. After the filler blocks were installed, no significant vibration was observed in the hull or deck.

One other less important but still significant finding was that the exhaust pipe had a resonance that was excited at certain operating speeds. The forcing function of this vibration was engine-firing frequency. It was recommended that an expansion joint and more hangers be installed in the exhaust pipe system.

Conclusions

In conclusion, excessive vibration on marine vessels is a real problem. Not only do they pose a threat to the service life of machine elements as they do in other industries, but because they can also affect the seaworthiness of the vessel, they generally have a much higher level of importance than do similar problems at land-based facilities. The four most common forcing functions are; engine speed, engine firing frequency, shaft speed, and propeller blade-passing frequency. However, vibration problems can develop at other frequencies.

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