

Vibration and Propeller Design Considerations for a Jumbo Mark II class Washington State Ferry

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In May of 2003 the Washington State Ferries decided to explore changing the propeller configuration on their Jumbo Mark II class ferries to alleviate a vibration problem that had plagued this class of ferry since its inception. The engineers at the WSF had tried several things over the years to reduce the vibration and some reduction had been achieved. However, the root problem continued to persist and Azima DLI was contracted to conduct a study and collect data to determine if the switch from a 4 blade to a 5 blade propeller design could, indeed, alleviate the vibration problem. The following is a look at the background, the experimental set-up, the data collected, the analysis and the conclusions that were examined as part of that study.



The study was done to characterize the Jumbo Mark II class boats, specifically the Wenatchee, which has noticeable vibrations throughout the ship at different running speeds and rudder positions. The vibrations had been addressed over time with minor structural modifications and operational guidelines. Even with these practices and modifications in place, however, the vibration was still noticeable, causing passenger discomfort as well as the possible accelerated wear of certain ship's systems.

The Jumbo Mark II boats are 460' in length with a 90' beam. They are designed to carry 218 vehicles and 2500 passengers and are the largest ferries in the WSF fleet. The propulsion system consists of diesel generators powering inductive AC motors with a maximum output of 13,200 horsepower. A single propeller and single balanced rudder on both ends provide load/unload/transport in both directions. To avoid confusion, the terms 'bow' and 'stern' are avoided and instead the terms 'pulling end' and 'pushing end' are used.

In measurements conducted to characterize the vibration of the ship's hull, racking was observed between the passenger deck and the sun deck suggesting a mast interaction with the hull. Subsequent measurements were included one of the two masts and the study examined here encompasses both the upper hull as well as the mast interactions.

DATA COLLECTION

12 triaxial accelerometers located at various hull locations were connected via two, 12 channel ICP power unit/amplifiers to a Sony DAT (Digital Audio Tape) recorder. On accelerometers 1, 2 and 3, only the vertical and athwartships channels were recorded (blue and red arrows). On accelerometers 4, 5 and 6, only the athwartships channels were recorded (red arrows) and on the accelerometers 7, 8 and 9, only the vertical channels were recorded (blue arrows). On the mast accelerometers, 13, 14 and 15, all three axes were recorded (red, blue and green arrows). Simultaneous tachometer readings were recorded from both the pushing and the pulling end propeller shafts as well. See Figure 1.

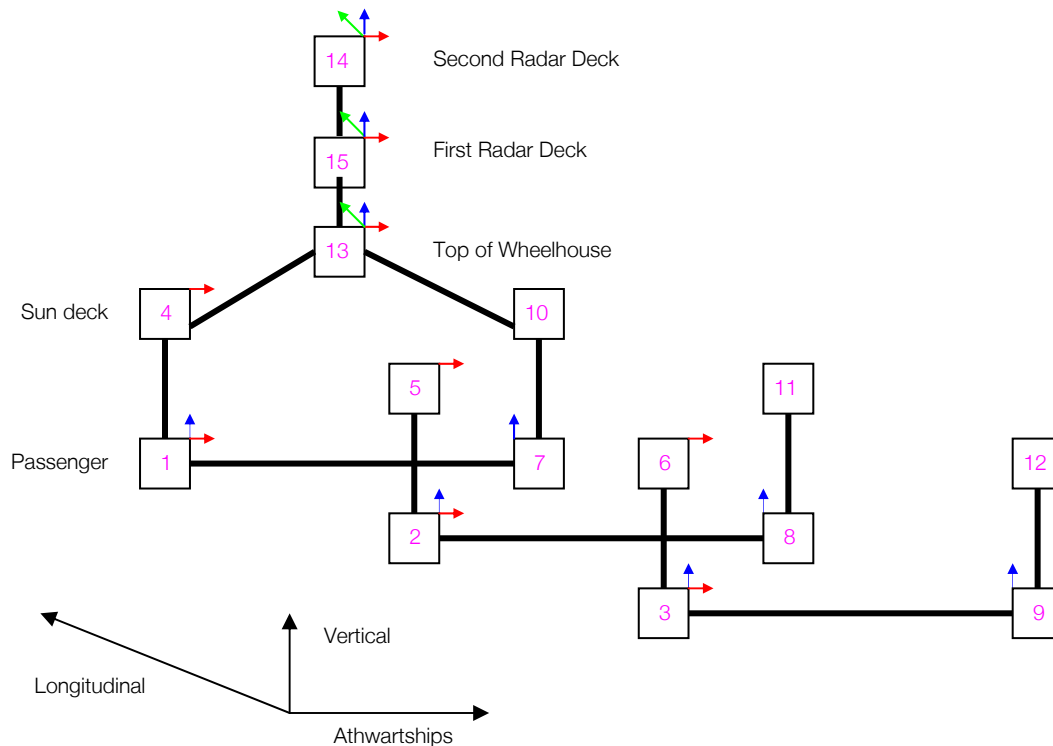


Figure 1

With the data from the above locations, and the assumption that all the locations are connected by rigid, continuous members (later verified against actual data), the following extrapolations were made to provide 12 biaxial positions and 3 triaxial positions for animation:

Vertical

Locations 1, 2, 3, 7, 8, 9 = Locations 4, 5, 6, 10, 11, 12, respectively

Athwartships

Locations 1, 2, 3, 4, 5, 6 = Locations 7, 8, 9, 10, 11, 12, respectively

In order to fully characterize the hull response, a matrix of operating scenarios were tested incorporating the following conditions:

- 1) Westbound (to Bainbridge), eastbound (to Seattle)
- 2) pushing propeller run-up, pulling propeller run-up
- 3) heavy ship, light ship
- 4) turning, straight

ANALYZING THE DATA

The data show that there is a hull resonance between 10.5 and 13.5 Hz (excited by the propeller blade rate at 158 to 203 SRPM) as can be seen in figure 2. Animations show the vibration to be dominantly second mode torsional on the pushing end and dominantly first mode vertical bending on the pulling end as explained below. Both modes were excited by the propeller blade rate at 192-195 Shaft RPM (SRPM) or (12.8-13.0 Hz) for the case illustrated in Figure 3.

Having characterized the hull response over the above matrix of operating conditions, we limited the mast study to data collected at 172 SRPM (11.5 Hz) while traveling both eastbound and westbound. This provided us with data while the hull was in a resonant condition (as determined by the hull response data) and with the mast at the pushing end as well as the pulling end of the vessel.

Animations of the mast and hull reveal that the mast moves in an elliptical motion that follows the dominant movement of the deck beneath it. They also reveal that the connection of the mast to the deck is weaker than the mast itself and that the mast is below its resonant state when the hull is vibrating at 11.5 Hz (172 SRPM).

When the mast is located on the pushing end of the vessel, the elliptical movement has a greater athwartships component when compared to the longitudinal component. See Figures 3 and 4. The deck's movement on the pushing end has a dominant second mode torsional movement and a smaller first mode vertical bending movement. These two modes were identified in the hull characterization and can be seen in figure 3. The second mode torsional movement is identified by the midship points moving in torsion and 180 degrees out of phase with the torsional movement of both the pulling and pushing end points. The first mode vertical bending movement is identified by the midship points moving vertically 180 degrees out of phase with the vertical movement of both the pulling and pushing end points. Another mast characteristic that can be observed is the difference in relative movement between the deck and the mast base and between the mast points themselves. The movement between the mast base and the deck is greater than the movement of the mast points relative to one another. This shows the connection of the mast to the deck is weaker than the mast itself. In this case, where the mast is located at the pushing end of the vessel, deformation of the mast base and deformation between the mast points themselves is greater than when the mast is located at the pulling end of the vessel and receiving less energy from the pushing propeller.

When the mast is located on the pulling end of the vessel, the elliptical movement has a greater longitudinal component when compared to the athwartships component. See Figures 5 and 6. The deck's movement, on the pulling end in this case, has a dominant first mode vertical bending movement and a smaller second mode torsional movement (different from the pushing end). These two modes were identified in the hull characterization and can be seen in figure 3. The process of identifying the 2 modes from the relative point locations in figure 3 is described above. Deformation of the mast base and deformation between the mast points themselves is less than when the mast is located at the pushing end of the vessel and receiving more energy from the pushing propeller. However, a greater magnitude of deflection between the mast base and the deck than between the mast points themselves is still evident.

The fact that the movement of the mast follows the movement of the deck indicates that the mast is not in a resonant state as a stand-alone structure and that the fundamental natural frequency of the mast is above 11.5 Hz (172 SRPM).

While researching the locations to mount accelerometers on the mast, the ship's drawings were consulted and a visual survey of the interior of the mast was conducted. From this cursory investigation, it appeared the construction of the mast consists of an elliptical skin welded to the sun deck and pilot house and stiffened with vertical angle stringers. Stiffening primarily the base and hull connections of this structure would reduce localized vibration in the wheelhouse. It would probably not have much effect on changing the response of the superstructure. It should also be noted that stiffening the mast would move it's natural frequency even further above the resonant condition of the hull (10.5 to 13.5 Hz). With all other variables held constant, the natural frequency of a structure changes by the

square root of the change in stiffness. For example, stiffening a structure by 4X shifts the natural frequency higher by 2X. This principle is important to consider when designing to avoid new propeller excited resonances.

Westbound Run up Data

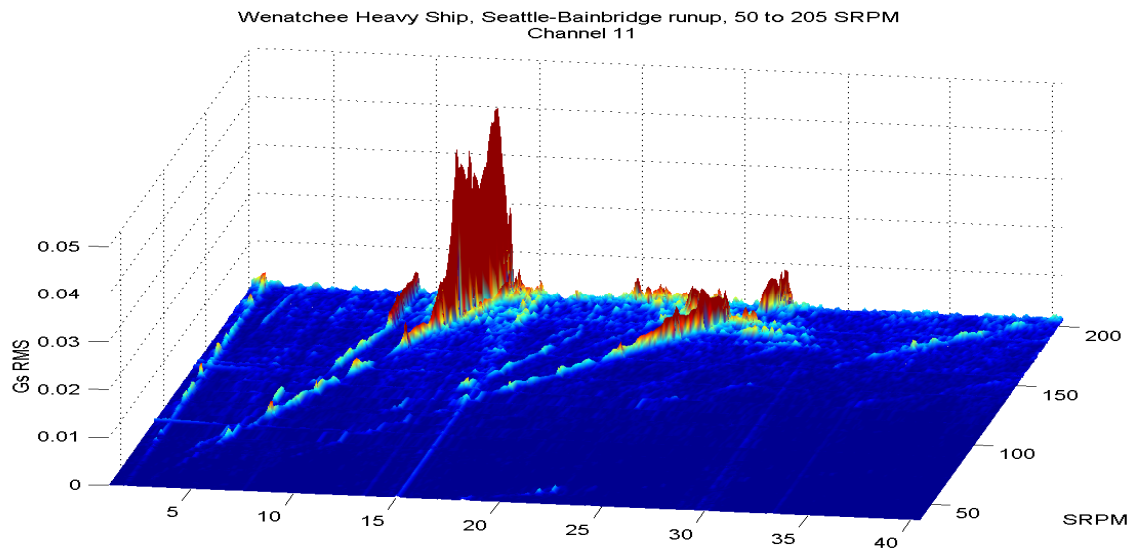


Figure 2

Westbound Animation Still of Hull Response

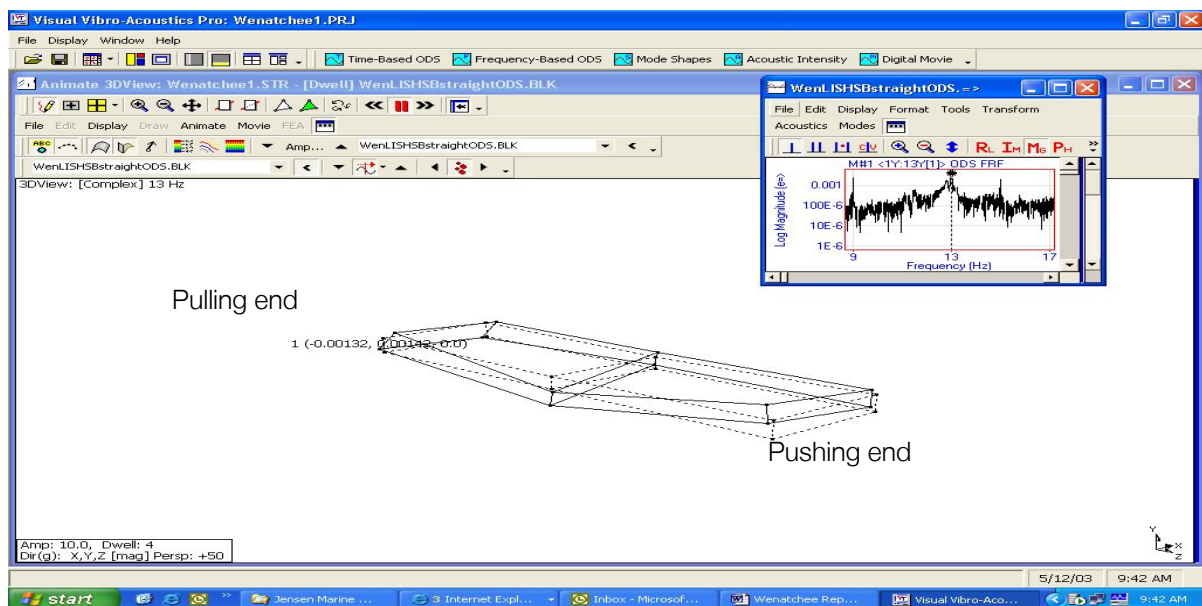


Figure 3

Eastbound Mast and Hull Animation Stills - note: red lines denote west, pushing end

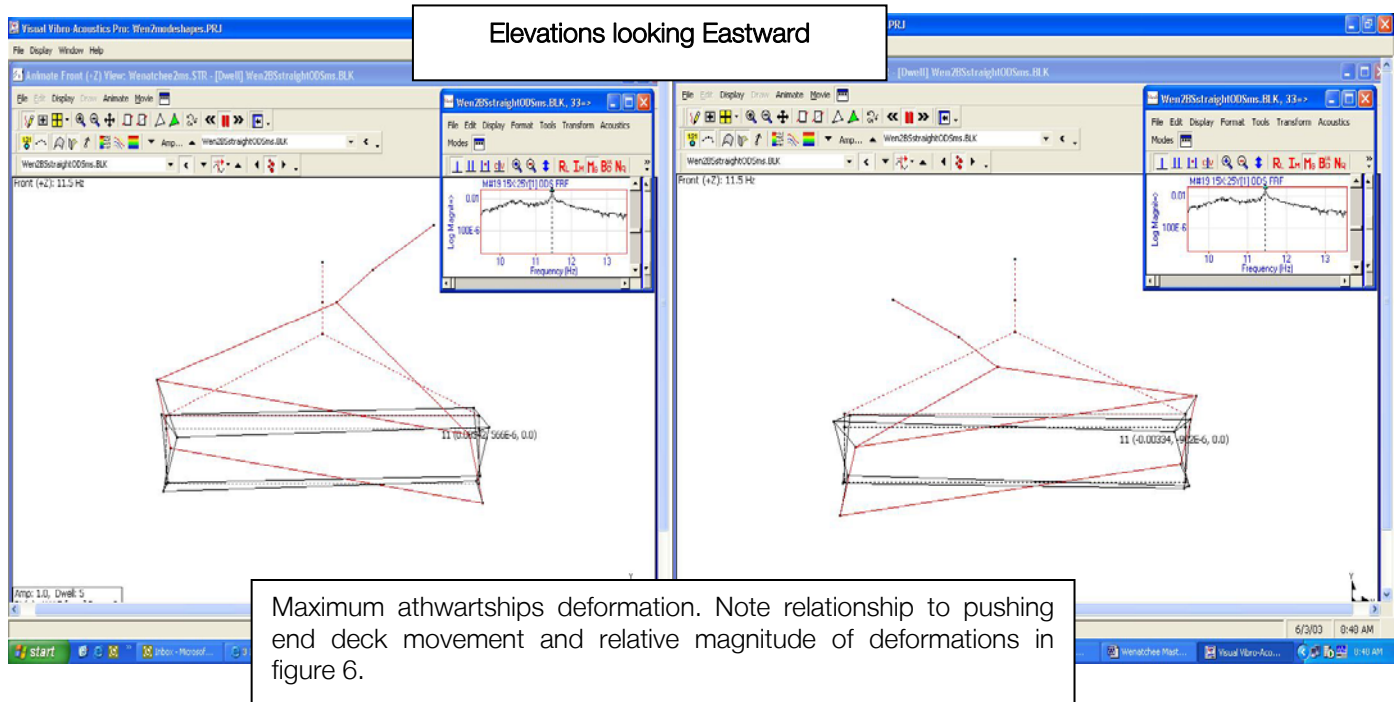


Figure 4

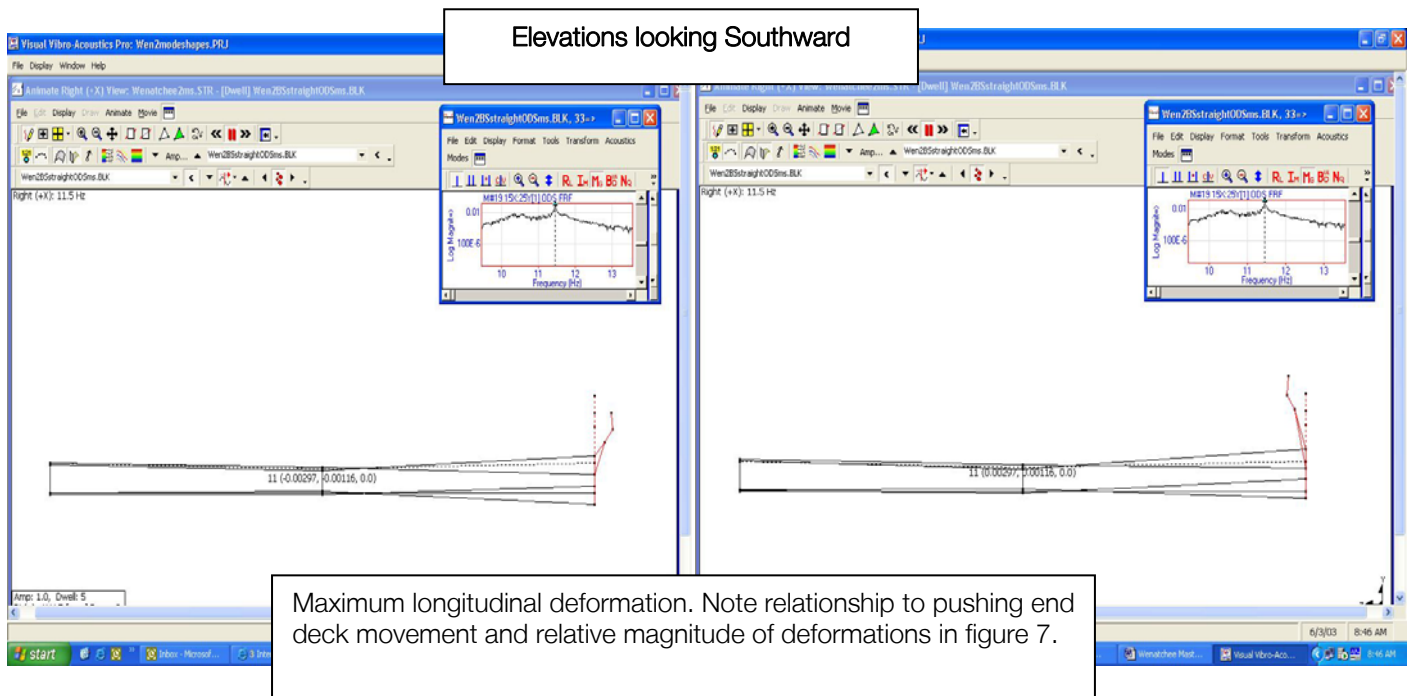


Figure 5

Westbound Mast and Hull Animation Stills – note: red lines denote west, pulling end

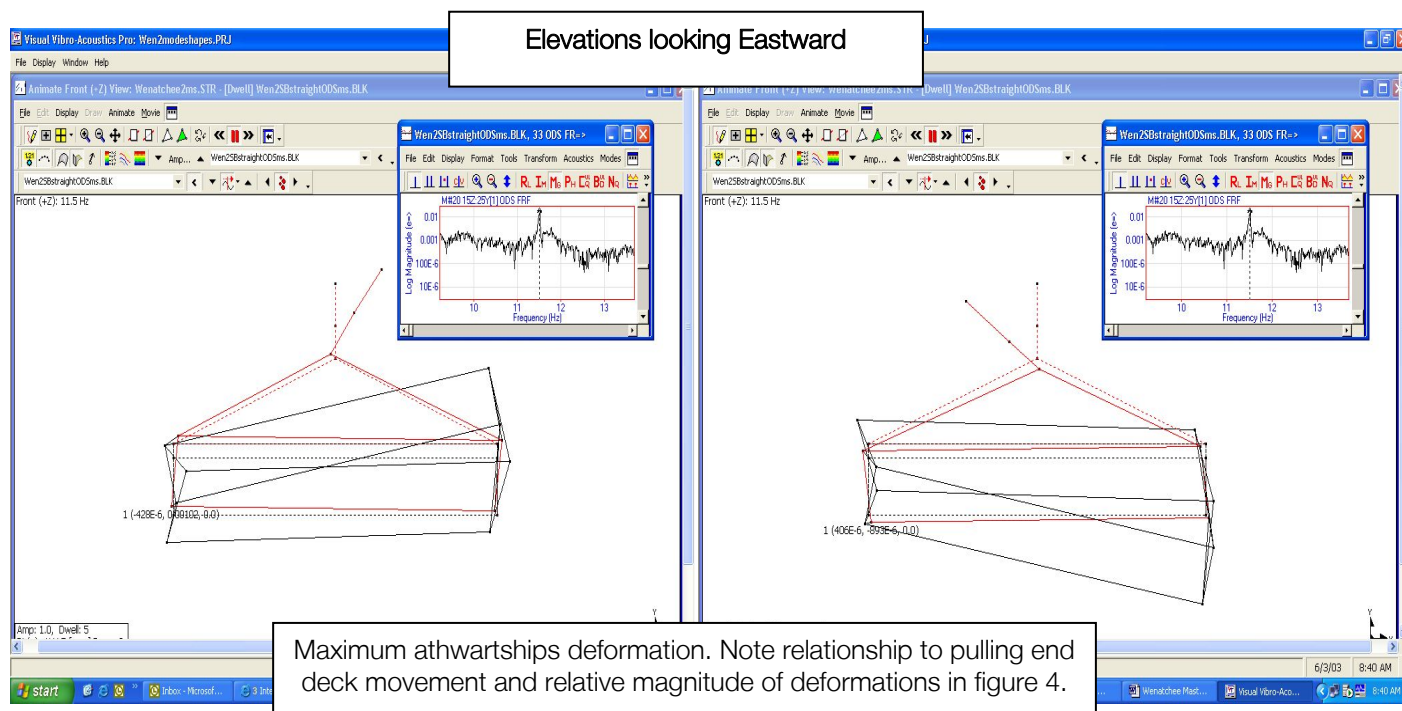


Figure 6

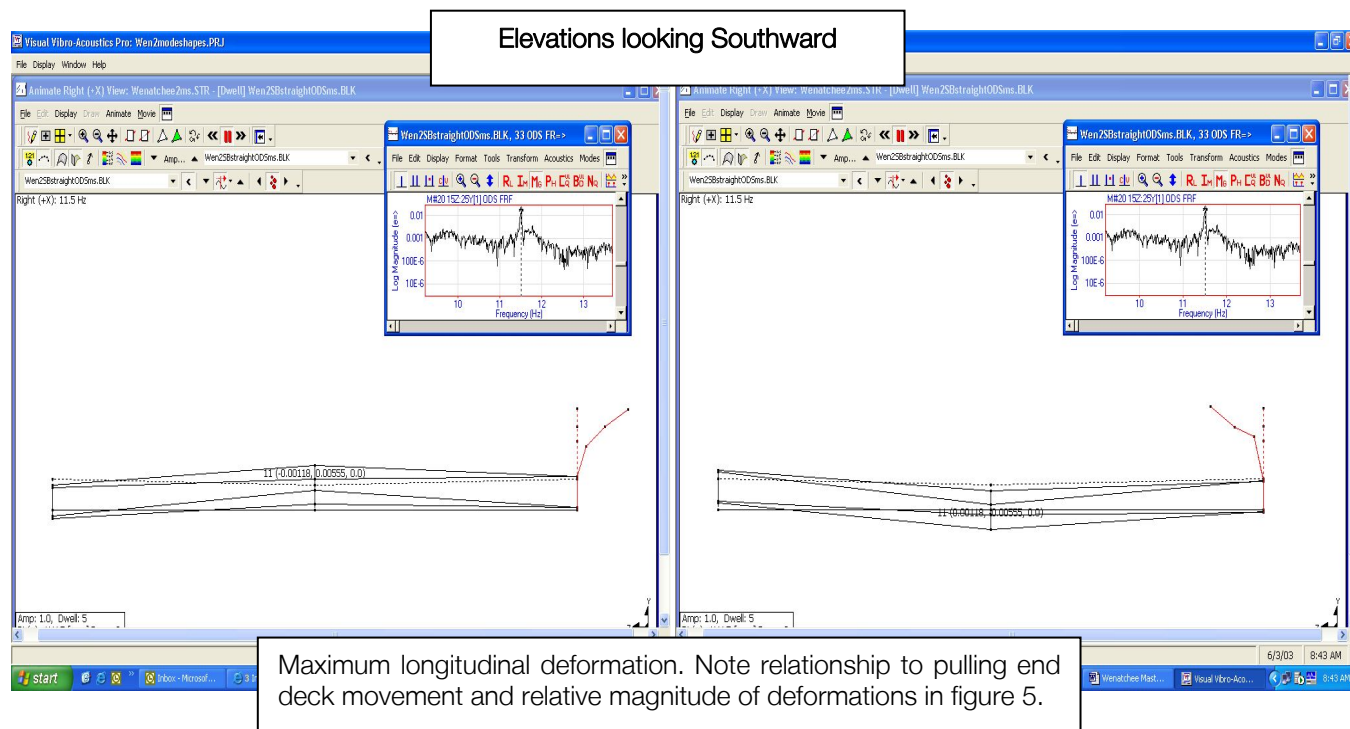


Figure 7

Rudder movements done outside of any hull resonance zone will cause the hull vibration to react linearly. Rudder movements done inside a hull resonance zone will cause the hull to react non-linearly and could result in a vibration response of severe magnitude. As an example, in the normal turns measured around Tyee Shoal arriving and departing Bainbridge, Winslow Harbor, shaft speeds are around 135 SRPM, which is below the hull resonance. The increased vibrations felt are caused by the increase in forced energy due to rudder location relative to the propeller wash, not due to a non-linear hull vibration response.

Since changing the rudder design is not really an option, the speeds at which large rudder movements will be made must be kept out of the hull resonance zones. For example, if you went to a 5 bladed propeller with the same pitch as the 4 bladed propeller, you would increase the blade rate frequency by 20% for the same speed through the water. This would take you just above the resonance band while cruising at 170 SPRM but it would put you in the bottom of the resonance band while making your turns out of Winslow harbor at 135 SRPM; with the added forced input of the rudder blocking the propeller wash.

Luckily, the Jumbo Mark IIs are powered by inductive AC motors which provide relatively constant power over a large speed range. This allows the propeller designers leeway when tailoring the pitch, shaft RPM, and speed through the water to avoid certain hull interactions.

As of the writing of this article, WSF has decided not to change the propeller configuration on the Jumbo Mark II class ferries. This decision stems from the fact that the forced vibration created by rudder movements will not be eliminated by changing the propeller configuration and the resonant vibrations can be avoided limiting the top speed. The understanding of the forced and resonant hull response of this ferry class will be used in the design and construction of the next generation of WSF boats.

Special thanks to Vince Crane and Clark Dodge both of Washington State Ferries.