HEAVY MOVABLE STRUCTURES, INC.
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Span Drive Machinery Vibration

Hood Canal Bridge

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MARRIOTT'S RENAISSANCE HOTEL AT SEAWORLD
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Figure 1. Hood Canal Bridge 1961

Introduction

The William A Bugge Bridge, more commonly known as the Hood Canal Bridge (104/5.1 and 104/5.2), is a floating concrete pontoon bridge. The original structure was built in 1961 to carry traffic across the 330-foot deep Hood Canal. See Figure 1. The floating portion of the bridge is 7,450 feet long. The bridge carries one lane of traffic in each direction with shoulders that serve as bicycle lanes. The HCB has an elevated roadway deck that allows waves and spray to wash over the lower deck without disrupting traffic and provides access to the complete structure for maintenance personnel without entering the roadway. The environment on Hood Canal can be challenging: salt water, winds and waves, tide changes of minus four feet to plus thirteen feet. On February 13, 1979 the west draw span broke away and the west half of the bridge sank in a severe windstorm with wind gusts in excess of 120 miles per hour. See Figure 2. A new, stronger west half with improved anchors, hatches and reinforcement was designed and open to traffic in 1982. The east half was replaced in 2009 with similar features. In 2009, during the east half replacement, the mechanical/electrical system on the west half was rehabilitated to be compatible to the new east half.

Figure 2. Hood Canal Bridge after West Half Sunk

Figure 3. Submarine Passing Through a 600 Foot Opening

The bridge has two retractable draw spans that provide a total of 600-foot opening for marine traffic, as shown in Figure 3. Each draw span is operated utilizing four motors that engage the draw pontoons through rack and pinions. The bridge provides openings for recreational boaters, contractors, Navy ships and nuclear submarines. The original structures had pickle fork shape bulges that allowed the draw pontoons to retract into. During replacement of each half the bulges were removed to improve roadway alignment. Now each draw pontoon retracts under three 100-foot long hydraulically raised spans that raise a portion of the roadway approximately nine feet to allow the draw spans to be retracted beneath them.

Background

The east half replacement utilized the basic concept applied to the west half replacement in the 1980's. The same firm that provided the replacement in 1980's was again retained to "dust of the plans" and provide any lessons learned and code changes over the last 30 years to the design. It was also decided to add capacity for widening to include shoulders and possibly future widening to four lanes during this time. Since the early 1980's design, three AASHTO Movable Highway bridge standards emerged; Standard Specifications for Movable Highway Bridges 1988 and AASHTO LRFD Movable Highway Bridge Design Specifications First Edition 2000 & Second Edition 2007. For the most part all of the new Standards were already in practice.

A few notable changes in the control system were to remove the 208 volt ungrounded control system, replace the aging PLC's with more modern PLC's and change the Square D thyrister drives to Hubbell drives. The notable changes made to the mechanical system included placing the machinery on a common frame and complying with the new codes for materials.

Start-up

The initial start-up for the new east half draw span / lift decks took place at the graving dock where the pontoons were constructed in order to float the structure in place with minimal impact to the traveling public. See Figure 4. Some disadvantage to this approach was not all systems were in their final configuration and it was a fairly controlled environment, unlike Hood Canal.

Figure 4. East Half Draw Leaving the Graving Dock.

The west half rehabilitation took place on-site to the existing structure once the new east half was operational for a 300-foot opening.

During commissioning/start-up of the completed systems, audible harmonic banging was present at certain RPMs of the draw spans. The banging was more predominate on the east half then the west half, but existed on both halves. All of the components that were changed during replacement/refurbishment during the contract in 2009 were reviewed, since the west half with similar components had operated acceptably for 30 plus years. The list boiled down to the new drives, machinery configuration and the low speed couplings. All other components in the drive system were the same or similar to the 1980's west half.

It was first assumed that tuning of the drives could cause improper load sharing. The 1980's drive system on the west half was Square D thyrister drives. The thyrister drives were configured in pairs (kitty-corner). The newly installed Hubbell drives each controlled a single motor independently. The Engineer of Record and a top-notch drive tuner were retained to assess and tune the drives.

Investigation/Evaluation

The investigation began with studying the drives and the drives parameters. While oscillations of the lower gear boxes were occurring, the drive currents were constant. The drives were configured with some unknown torque limit setting during construction that was well above 150% FLT. The machinery had been designed for continuous operation at 150% FLT of 75 hp drive motors. Deflections of the lower gear boxes were measured from 0.007 to 0.008 inches during normal operations and 0.020 to 0.040 inches when exhibiting audible oscillations. See Figure 5 for machinery arrangement. All motor drives for the draw spans had their motor torques set to 150% FLT and then to 100% FLT. 100% FLT allowed for draw span separation and acceptable operation. By lowering the FLT the maximum lower gear box deflection measured was 0.020 inches.

During a full speed opening during testing all drives tripped due to a lift deck limit switch issue. This resulted in an inadvertent emergency stop condition. The motor brakes alone decelerated the span to a stop without any dynamic braking assistance from the drives. A dial micrometer installed on one of the machinery lower gear box showed excessive oscillating movement during deceleration and the oscillations were audible.

The oscillations started around 500 RPM of the motor shafts and dampened out below 200 RPM. This observation would indicate the drives and motors were not the source of the oscillations. It was determined at that time a lower gear box vibration assessment may help identify the source of the audible oscillations.

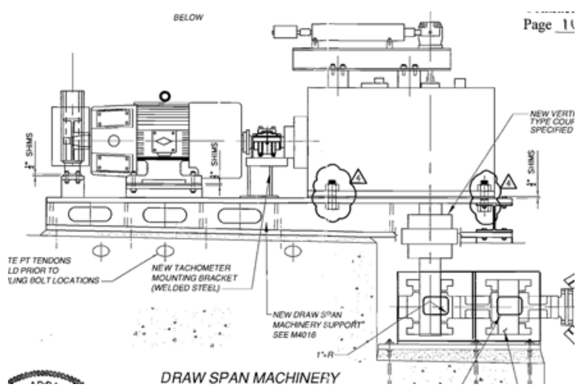

Figure 5. Elevation View of Span Drive Machinery Arrangement

With the use of accelerometers providing electrical output directly related to acceleration/deceleration, the digitally recorded output signals were double-integrated to displacement time-history waveforms for analysis. It was apparent from the plots that several frequencies were excited at different times throughout the operation. During the acceleration a predominant frequency excited at approximately 4.9 Hz, corresponding to a motor speed of 445 rpm. During deceleration a predominant frequency excited at approximately 3.67 Hz, which corresponds to a motor speed of 333 rpm. It was determined from the vibration assessment that the 3.7 Hz and 4.9 Hz were most likely represented resonant frequencies from horizontal motion of the lower gear boxes.

A shift from the vibration assessment results led to analyzing the cause/solution of the resonant frequencies in the drive machinery. Stafford Bandlow Engineering, Inc. (SBE) was hired to analyze and determine if the vibrations were driven or indeed resonant.

Vibration Analysis

SBE's preliminary vibration investigation of the issue included a review of pinion shaft strain data simultaneously recorded with motor speed and lower gear assembly deflections. See Figure 6.

Example charts from the preliminary investigation are shown in Figures 7 and 8. Figure 7 shows a recording of the pinion shaft strain and the motor speed. Figure 8 shows a close-up of oscillations in the pinion strain data.

From the recorded data it was determined that the vibration issue was due to operation near the natural frequency of the system and that the issue was driven by the open gear tooth impact frequency.

Figure 6. Lower Gear Box Assembly. The assembly is shown with instrumentation for LVDT deflection measurements and strain recordings at the pinion shaft.

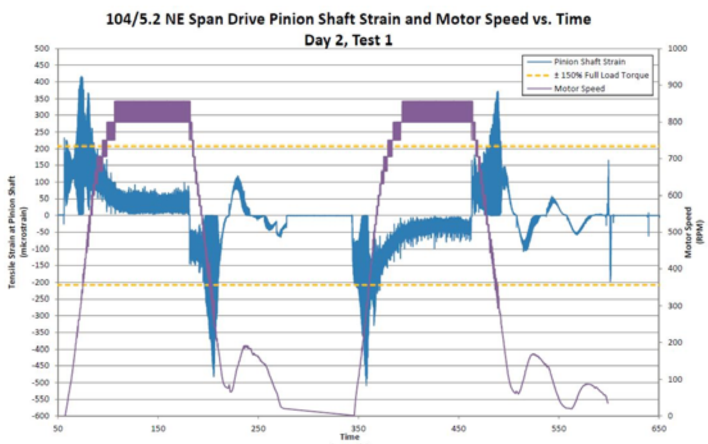

Figure 7. Chart Showing Recorded Pinion Strain and Motor Speed

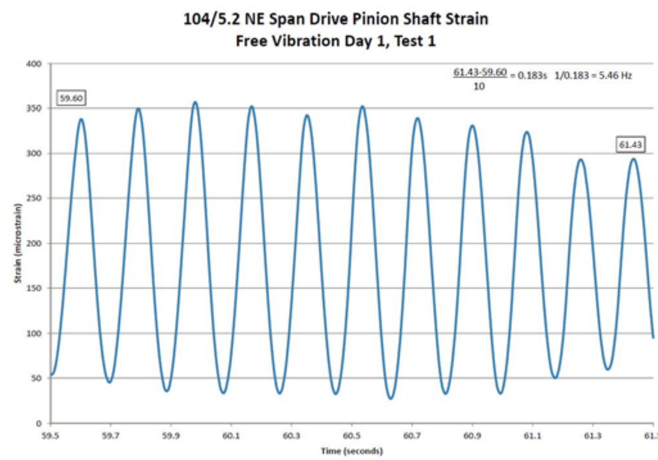

Figure 8. Chart with Close-Up of Oscillating Pinion Shaft Strain. The frequency of oscillations where determined from this and similar charts.

The design effort included additional modeling to positively identify the nature of the problem and to verify that the proposed design solution would be effective. BETA Machinery Analysis (BETA), experts in torsional vibration analysis (TVA), provided modeling based on drive parameters such as gear tooth counts, part rotational inertias, and part torsional stiffnesses. BETA also used WSDOT's strain recordings to calibrate the torque excitation for the baseline condition.

BETA's TVA included the existing machinery arrangement, the previous arrangement (before the change to the design after which the resonance issue began), and numerous other possible drive modifications targeting adjustments to the system's torsional natural frequency to move it away from bridge operating speeds. BETA's analysis included modifications such as a adding a flywheel, adjustments to the upper gear box output shaft, adjustment of the pinion shaft diameters and lengths, and grid couplings versus gear couplings at the high speed and low speed couplings.

Through their modeling, BETA confirmed that their model matched the behavior of the drive system and positively identified the idler gear mesh as the source of the undesired excitations. Based on their modeling it was determined that it was not practical to modify the torsional natural frequency of the system to a degree necessary to avoid the operating speeds of the bridge. However, based on their work it was recommended to change the upper gear box output coupling from a gear coupling to a grid coupling. This change to a "softer coupling", combined with an increase in rigidity to the lower gear frame, provided a net effect of a small increase in the torsional natural frequency of the system but did not move it outside of bridge operating speeds. The more rigid gear frame was expected to reduce the magnitude of the impacts associated with the oscillating loads, but the most significant effect impact was the change to a grid coupling which, based on information provided by the coupling manufacturer, was expected to provide a significant dampening effect to the system. See Figure 9.

Note that the recommended change from a gear coupling to a grid coupling is a return to the previous design where vibrations were not noted as a significant issue. The coupling change appears to be the one significant change from the 2009 rehabilitation that could have had a significant impact on the drive behavior.

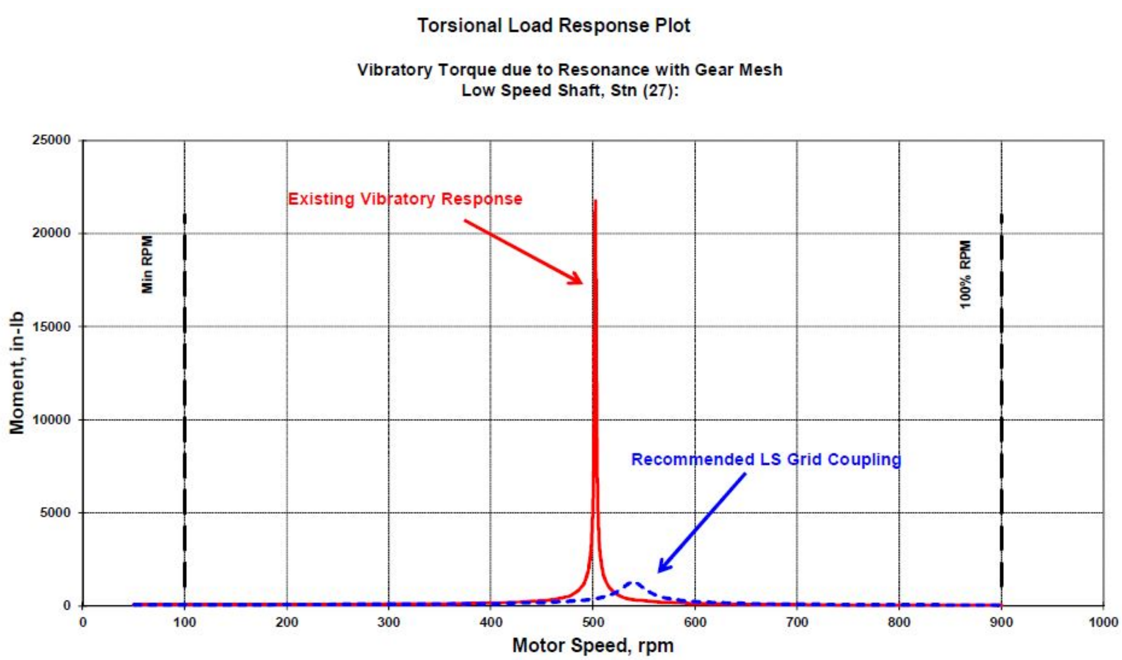

Figure 9. Torsional Load Response Plot Illustrating the Effect of the Upper Gear Box Output Coupling as a Gear Coupling (Existing Shown in Red) Compared to a Grid Coupling (Recommended Shown in Blue).

Repair Design

The replacement lower gear box assembly was designed with some similarities to the existing arrangement, maintaining gear dimensions and component spacing. The new design provides similar gear mesh adjustability to the existing design, which uses a locating pin and slotted holes for the cap screws that secure the mounting plate to the sole plate. The pin and slotted holes allow for rotation of the frame to increase or decrease engagement of the idler gear with the rack mounted to the draw span. See Figure 10.

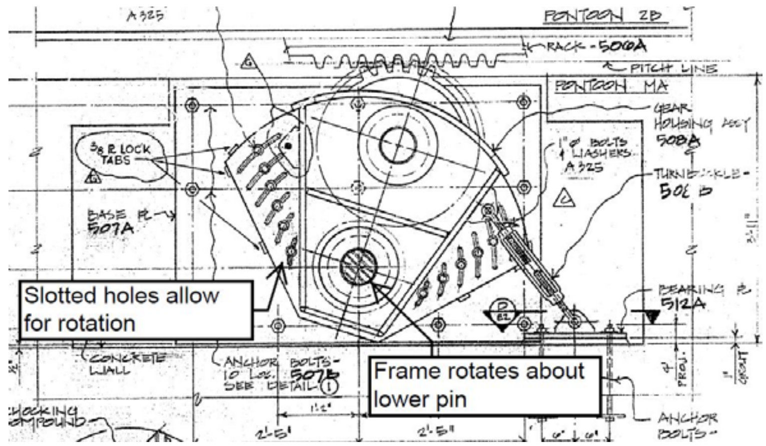

Figure 10. Plan View of Existing Lower Gear Box Assembly. The locating pivot and the slotted holes were maintained for the new design.

There were, however, a number of improvements to the system design, which are listed below. Figure 11 shows the existing assembly and Figure 12 shows the new assembly for a comparison.

Change Low Speed Coupling from Gear Coupling to Grid Coupling. Based on the modeling the most critical change was to replace the gear coupling at the output of the upper gear box assembly with a grid coupling. This change significantly dampens oscillatory behavior as the bridge speed passes through the torsional natural frequency of the system.

Improved Maintenance Procedures. With the existing design it was impossible to remove the pinion, idler, or either shaft without a complete removal of the lower gear frame from the bridge, and removing the lower gear frame from the bridge required movement of the above support for the upper gear box, motor and brake. In addition, for the existing lower gear frame, only the upper idler gear bushing could be replaced with the machinery in place. All others required complete removal.

In contrast, the new assembly, using conventional pillow block bearings, permits replacement and adjustment of the bearings, shafts and gears without having to remove the lower gear box frame from the bridge.

Inspection and Maintenance Access. The replacement frame provides enhanced access to the pinion and idler teeth for inspection and maintenance by leaving the gear frame open on one side as the needed rigidity is supplied by the base plate and brackets on the opposite side of the frame.

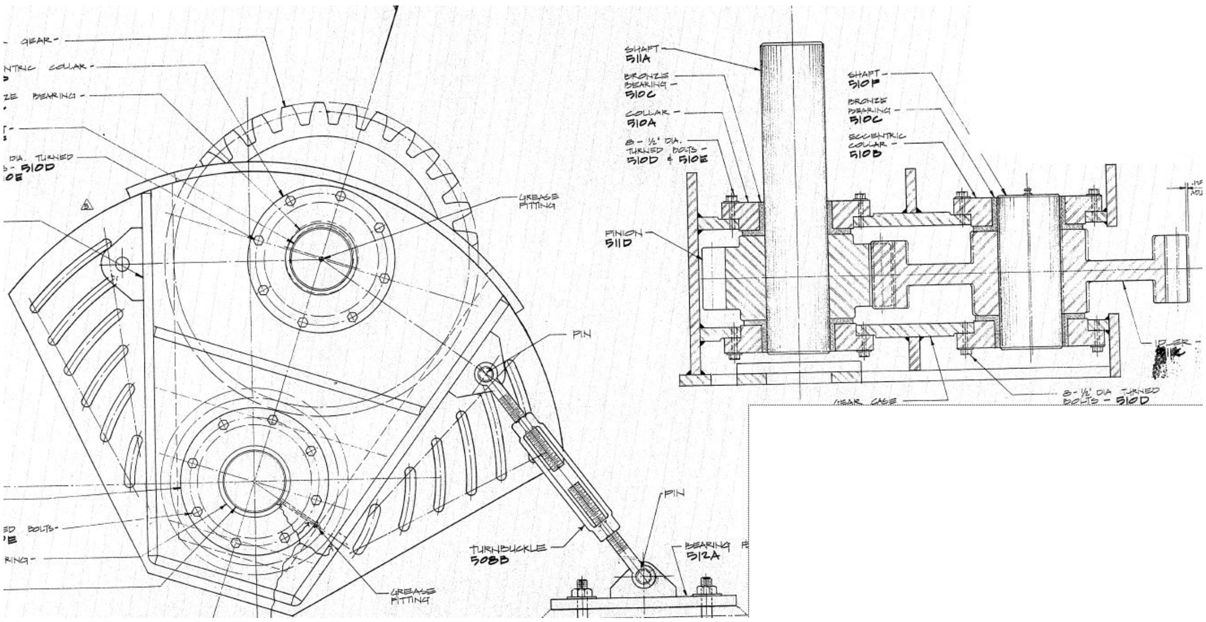

Figure 11. Plan View and Section View of Existing Lower Gearbox Assembly (Upper Gear Box Output Coupling Not Shown). The frame assembly allows for only limited access to the gears for inspection and maintenance.

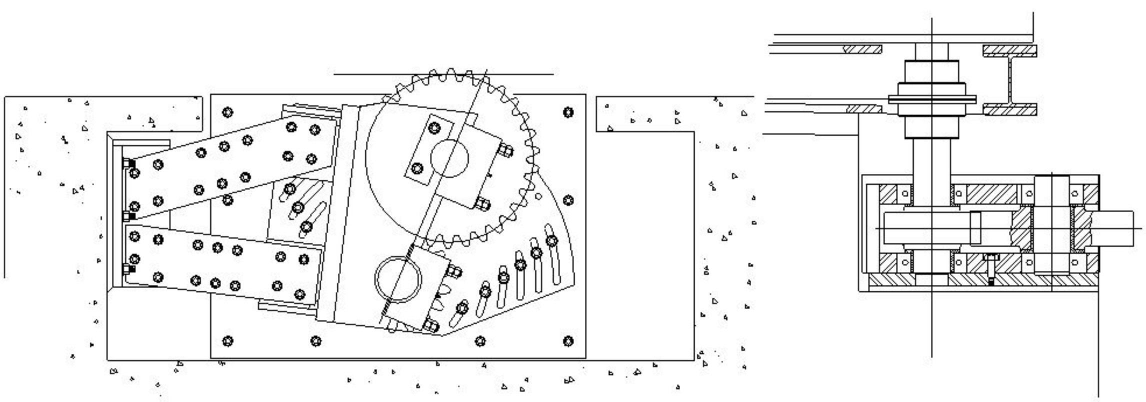

Figure 12. Plan View and Section View of the New Lower Gearbox Assembly. The assembly is open on the side opposite the brackets, allowing for access to the gears for inspection and maintenance.

Increase in Rigidity of the Lower Gear Box Assembly. The new lower gear box frame is provided with increased rigidity that will reduce operational deflections and impact loads for any future oscillating loads.

Change to Bearing Lubrication Provisions. The existing design had a single lube fitting on top of the shaft fed two bearings through a common lubrication port. With this arrangement the lower bushings were not provided with adequate grease which led to excessive wear. The replacement assembly provides the ability to directly lubricate each bearing through dedicated lubrication ports.

Improved Bearing Material. The existing bushing material was not consistent with the original design. The repair included a replacement of all bearings to meet AASHTO.

Status of Repair

The replacement of the west draw span lower gear box assemblies is currently in process. The east draw span lower gear box assemblies were replaced in the summer 2018. Drive tuning and commissioning efforts have been completed on the east half, initial results have shown this to be a successful rehabilitation with early indications that the vibration loads have been eliminated.

Conclusions

Span drive machinery vibration has been an issue at the Hood Canal Bridge draw spans since the 2009 machinery rehabilitation. Notable changes from that rehabilitation included new drives, a change in the machinery configuration, and changes to the low speed couplings.

An engineering investigation including field measurements and a torsional vibration analysis have shown that, at certain operational speeds, impacts from the idler gear mesh match the torsional natural frequency of the system and cause undesired excitations. While it was determined that it was not practical to modify the torsional natural frequency of the system to a degree necessary to avoid the operating speeds of the bridge, it was recommended to change the upper gear box output coupling from a gear coupling to a grid coupling as it would provide a significant dampening effect to the system. This is consistent with the fact that this issue was not noted prior to the 2009 rehabilitation, which included a change from a grid coupling to a gear coupling.

The design for the replacement lower gear box assemblies included the change to the upper gear box output coupling, as well as a number of other improvements to the design including increased rigidity, improved access for maintenance, inspection, and part replacement, and bearing material improvements.

The east draw span lower gear box assemblies were replaced in the summer of 2018. Drive tuning and commissioning of the east half have been completed, and initial results have shown this to be a successful rehabilitation with early indications that the vibration loads have been eliminated.