Pre-installation detection and correction of potential pump system resonance (high vibration) problems

Objective:

The objective is to utilize modern Finite Element Analysis (FEA) techniques to avoid installing equipment with preventable vibration problems. The methodology is applicable for new plant construction or for plant modifications such as upgrading to more efficient motors or installing Variable Frequency Drives (VFD).

Performing a dynamics analysis – Why, how, and when

Pump and piping system dynamics analysis when properly specified and performed can greatly reduce the risk encountering life-limiting vibration problems. Conceptual levels of piping system dynamics analysis can begin as early as the 30% to 60% phase of a new plant construction project depending on factors such as plant complexity and the plant operators' aversion to risk. More typically, a dynamics analysis is specified at the time the equipment request for proposals (RFPs) are issued and completed before the equipment is fabricated and the site work is fully complete. A post-installation vibration acceptance test may also be specified.

How should one determine what is an appropriate level of analysis prior to equipment installation or modification (for example, upgrading the motor or adding a variable frequency drive)? Surely not every piece of equipment warrants the plethora of analysis options available. Experience plays a role in deciding when some level of analysis is needed. For example and as discussed in detail later, adding a VFD to an existing trouble-free pumping system without performing some level of dynamics analysis is high-risk as the VFD essentially converts the motor to a shaker which can excite previously dormant pump and piping system natural frequencies. An expensive modification can create a chronic vibration problem due to the lack of an inexpensive dynamics analysis.

In addition to experience, an example of how to scale the level of analysis based on equipment, application, and risk factors is provided in Hydraulic Institute's "Rotodynamic Pumps - Guideline for Dynamics of Pumping Machinery," Guideline 9.6.8.[1] HI 9.6.8 describes and recommends various levels of detailed evaluation and validation that are commensurate with the degree of equipment/system uncertainty and application risk. Equipment uncertainty (U) is based on the specific pump type, with weighted criteria for drive, coupling, power, etc. (Figure 1). Application risk (R) quantifies the degree to which the design has been proven in the field. When these two aspects of the project are combined, they yield a risk uncertainty number (RUN, Figure 2).

HI 9.6.8 provides various levels of analysis and suggested specification language based on the calculated RUN (Figure 3) and is especially useful for the water and wastewater industries. The

[1] Refer to Hydraulic Institutes website at www.pumps.org for more information.

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provided sample specifications can replace an engineering firm's often outdated pump vibration analysis specification templates.

Pump Type	Lateral Rotordynamic Analysis
Types OH & BB Pumps with Rigid Rotor Designs	Maximum speed > 3800 rpm, U = 2 Fly wheel driven, U = 2 Drive shaft driven, U = 2 Variable speed driven, U = 2 Power > 30 kW (40 bhp) and < 375 kW (500 bhp), U = 1 Power > 375 kW (500 bhp) and < 750 kW (1000 bhp), U = 2 Power > 750 kW (1000 bhp), U = 3 No. of vanes = 3 or fewer, U = 3
	System Configuration Total U ______ (Sum)

Figure 1. A portion of Table 9.6.8.3.1 - Uncertainty Values – from HI/ANSI 9.6.8. The excerpt shows an example of how to establish an uncertainty value for one type of pump for one of three different types of analysis.

Step 2 - Determine and enter risk value "R" from suggested values below.			Enter selected R value
RISK NUMBER, R	Unknown, new design with no field experience.	20	
	Significant modifications to standard product or similar design - no experience in field.	10	
	Minor modifications to standard product or similar design proven in field.	4	
	Identical or standard product, proven field history.	2	

Figure 2. Table 9.6.8.3 Decision Matrix from HI/ANSI 9.6.8, is used to determine a risk value (Step 2). Step 1 is reviewing Figure 9.6.8.1.1.1a in the Guideline to understand how the Guideline process works.

Products of R x U, or RUN numbers	
Step 4 - Using the calculated "RUN" value from step 3 for each analysis type (lateral, torsional, or structural), determine the suggested level of analysis for each type of analysis from the guidelines below.	
RUN value from step 3	Suggested level of analysis
≤ 15	None Required
> 15, ≤ 20	Level 1
> 20, ≤ 50	Level 2
> 50, ≤ 160	Level 3
> 160	Level 3 +Validation*

*Validation testing by the manufacturer is recommended prior to shipment.

Figure 3. The sum of risk and uncertainty is the RUN number. The RUN number establishes a recommended level of pre-construction analysis to be specified for a structural analysis of the pump and nearby piping and foundation (i.e., pump system), the pump lateral rotordynamics analysis, and the pump/driver torsional rotor-dynamics analysis (Step 4). Step 3 is understanding the pump/system attributes.

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Once specified, these analyses will then appropriately and practically evaluate pumping machinery design attributes and relevant site characteristics in order to determine the effects of dynamic performance on equipment life and reliability. For example, dynamic perturbations may result in the excitation of structural resonance. With increasing use of variable speed drives (a factor in determining “U”), avoiding these “excitation frequencies” has become increasingly more difficult, and identifying these frequencies is more important than ever to ensure that resultant problems caused by high vibration are properly addressed and mitigated during the design phase.

The results from a properly performed analysis

Often when changing from constant speed motors to motors controlled by variable frequency drives (VFD), or even by simply changing to a different motor (i.e. lighter & more efficient), latent structural natural frequencies present in the equipment and associated system that were previously unaffected by the original constant speed motor are found to be problematic. These frequencies can be anticipated and addressed prior to the new driver installation at a much lower cost when compared to the cost of fixing an avoidable field problem. Before installing new VFD controlled motors on vertical raw water pumps for the City of Cambridge, Mechanical Solutions, Inc. (MSI) was contracted to perform a structural modal analysis to identify any potential natural frequency issues associated with the motor modification.

In order to perform this analysis, MSI had to create a solid model of the pump system using FEA modeling software based off of field dimensions and drawings (Figure 4A). These models were then calibrated to match the structural natural frequencies determined by MSI using specialized field testing (Figure 4B). Once this baseline was established, the original motor used on the pumps was replaced in the FEA model by a new future motor that will be installed in the field in order to predict any potentially problematic shifts in natural frequency. The purpose of this analysis was to ensure that the new proposed motor with a different mass, center of gravity, and inertia did not cause any structural natural frequencies to interfere with the pump running speed range. Since the new pumps would no longer be constant speed, it was also important to examine if any existing system structural and pump structural or torsional rotordynamic modes (with new motor torsional characteristics) would be predicted to fall within the new running speed range.

After replacing the current constant speed 1190 RPM (19.8 Hz) motor with the future variable speed 653-1188 RPM (10.9-19.8 Hz) motor on the field-calibrated pump model, the structural analyses predicted that a combined foundation/discharge head/motor rocking mode (or above-ground structure reed frequency) parallel to the pump discharge flange would shift down to within the new pump running speed range creating a potential damaging resonance problem (Figure 5A). In an effort to resolve the potential problem before it was installed, MSI proposed a practical solution: add additional structural ribs and bolts in order to stiffen the above-ground structure (Figure 6). With these modifications, the above-ground natural frequency was predicted to shift well above the running speed range with a safe separation margin of 18.2% (Figure 5B). A separation margin of 15% is recommended based on an experienced analyst properly performing the assessment of the pump *system* (i.e., nearby foundation, pump, discharge head, motor, and piping to the nearest restraint or expansion joint). Ten percent is the recommended minimum separation margin based on experimental modal analysis (or impact) testing performed while the pump and system are operating. For completeness, MSI also looked at any other structural modes that would fall within the new variable pump running speed range and found none of concern. The conversion to new motors and VFDs was successful due to large part to identifying and correcting potential vibration issues before the modifications were made.

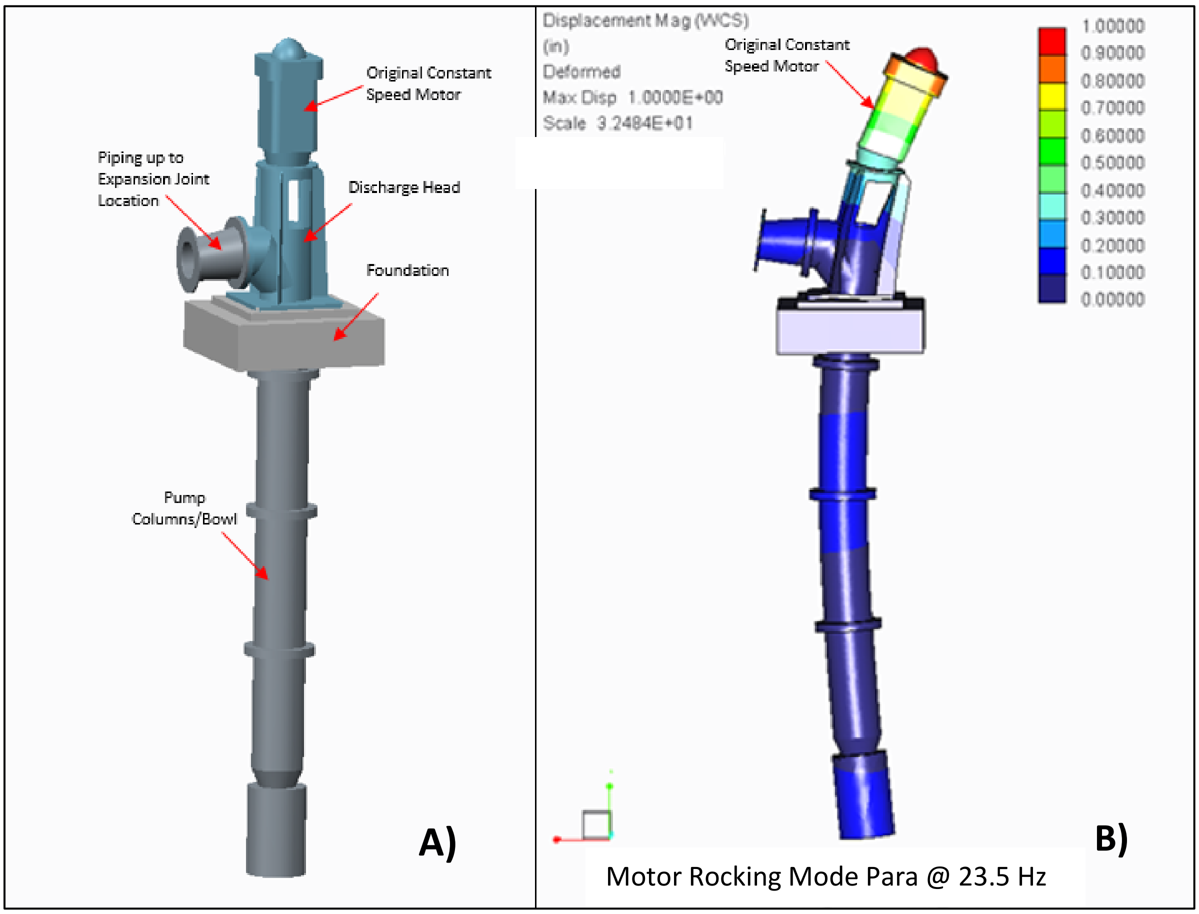

Figure 4: A) The FEA model of the existing pump system (nearby foundation, pump, discharge head, motor, and piping to the nearest restraint or expansion joint) calibrated using specialized experimental modal analysis and operating deflection shape (ODS) test results forms a baseline. **B)** Calibrated FEA results of the existing pump closely matching MSI's field-measured natural frequencies. The above-ground structural rocking mode (reed frequency) at 23.5 Hz parallel to the discharge flange and was the nearest natural frequency to the pump rotational speed. However, it had an acceptable separation margin of about 18.5 % from the original constant speed of 1190 RPM (19.8Hz) so there had not been any vibration problems caused by resonance.

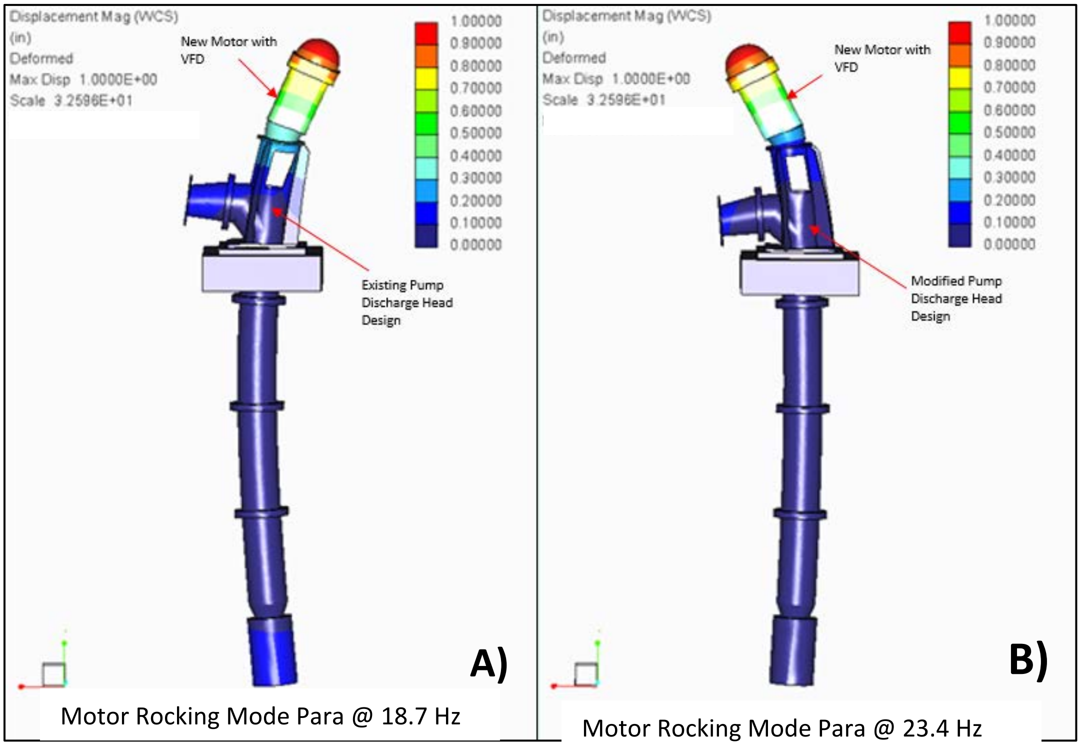

Figure 5. A) FEA analysis results of the existing pump system with the new VFD controlled motor which predicts potential natural frequency resonance within the 1x RPM range at 1,122 RPM (18.7 Hz) indicating a high potential for a resonance problem. **B)** FEA analysis results of the modified pump discharge head (details shown in Figure 6) with the new VFD controlled motor which predicts all natural frequencies to be outside of ±15% from the 1x pump RPM range, therefore avoiding resonance.

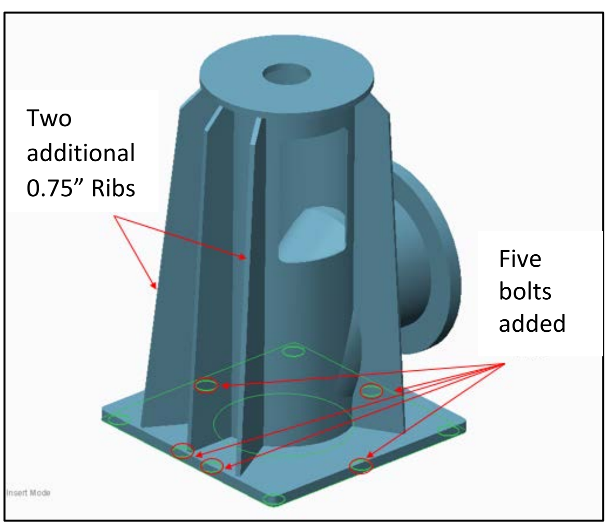

Figure 6. The FEA model of the modified discharge head showing the successful solution design before it was implemented. The additional structural ribs and bolts stiffen the above-ground structure enough to shift up the offending natural frequency away from running speed while not creating an interference problem with one of the other system natural frequencies.