

VIBRATION MONITORING OF VERTICALLY MOUNTED PUMPS— TOOLS FOR MANUFACTURERS AND USERS

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ABSTRACT

Recent efforts to develop and implement techniques to monitor and diagnose problems in submerged vertical shaft pumps are summarized. Projects based on iterative analytical and experimental efforts were implemented on several different types of vertical pumps typically found in power plants.

Although modelling aspects are briefly described, the major focus is on the results of the experimental aspects, including the "lessons learned" in instrumenting and monitoring six vertically mounted pumps in operational power plants.

INTRODUCTION

For many years, utilities and other industries have monitored vibration to detect failures and to plan maintenance for horizontal machinery. In many instances, however, this technique has not been successfully applied to vertical pumps for several reasons, including lack of experience in measuring vibration of submerged portions of the pumps and lack of understanding of how such factors as unbalance and shaft alignment affect machinery health. In addition, mathematically modelling vertical pumps often involves assumptions that differ from those involved in modelling horizontal pumps, thus making it difficult to predict wear or damage from typical vibration measurements. As a result, failures often occur without warning.

Attempts to more thoroughly measure vibration on the submerged portion of vertical pumps have often resulted in data that cannot be readily interpreted.

When compared to horizontally mounted pumps, vertical pumps can exhibit high vibration levels and yet continue to operate satisfactorily. The pumps often operate with signs of unstable operation, large misalignments, and other characteristics that would dictate immediate shutdown in most machinery. Many of these phenomena go undetected at traditional vibration sensor locations (e.g., on drive motor housings). Experiments have also shown that significant changes to the mechanical properties of the pump (e.g., large changes in (unbalance) do not always result in expected changes in vibration level. Experimental data have also shown that some changes in the vibration level may be associated with the pump hydraulic load [1].

To address these problems, projects have been undertaken to develop analytical techniques to interpret vibration measurements, verify these techniques by in-plant tests, and develop recommendations for application of submergible vibration sensors.

The projects combined both analytical and experimental efforts. Following an initial survey of available literature and inquiries with pump manufacturers and users regarding modelling and vibration analysis of vertical pumps, three types of vertical pumps were selected for study at a gas-fired power plant on the Pacific Coast in northern California. Subsequently, additional circulating pumps have been studied at an oil-fired plant on the Hudson River near Poughkeepsie, New York.

DISCUSSION

Project Methodology

Each of the selected pumps was studied under analytical and experimental efforts through iterative and interactive processes. In general, an initial mathematical model of the pump was made, and a computer program was used to

predict natural frequencies and mode shapes. This information was used to select the types and locations of sensors. Each pump was then opened and inspected, and precise measurements of fits and clearances were made and used to update the model. Following reinstallation, vibration and performance parameters from the instrumented pump were continuously monitored. Resulting information was used to tune the model to reflect actual operation. The model was then used to predict the effect of a given change in the pump.

All pumps were to be removed from service, inspected, and modified (i.e., changes made in unbalance, misalignment, hydraulic loading). The pumps were then to be reinstalled and run for several additional months and the resulting test data used to tune and simplify the model. Test data were used to refine the sensor types and locations needed to adequately monitor pump vibration.

The initial intent was to implement on subsequent pump types those modelling and sensor techniques that were successful on the first pump. Availability of these pump units for study was limited, however, because all pumps are in operational power plants. Consequently, some adjustments in the planned schedule were necessary, namely the need to instrument and monitor several pumps, simultaneously, rather than sequentially. Plant power requirements and overhaul schedules also limited the number of pump removals accomplished.

Analytical Efforts

A basic objective was to evaluate the ability of rotordynamic analysis to predict the vibration performance of vertically mounted submerged shaft pumps. However, the overall goal was not to produce a complex model that duplicates the actual performance of the pump being analyzed, but rather to develop a modelling technique that includes only those elements pertinent to predicting the general vibration performance. Although the techniques may not be sufficient to accurately simulate precise operation of the units, a primary objective was to develop guidelines, so an interested vertical pump manufacturer or user will be able to adequately model a vertically mounted pump to reliably predict its operational vibration characteristics.

Experimental Efforts

The analytical model initially provided important direction for determining optimum sensor locations on the pump. However, experimentally acquired data were required to both verify and, when necessary, tune the model. The tuned model, in turn, provided further direction to modify the experimental setup.

An important objective was to develop recommendations for proper application of submergible vibration sensors. The work was not intended to develop new types of sensors but to evaluate the ability of existing sensor types to measure vibration reliably while they were submerged.

The experimental efforts were directed toward establishing guidelines for the selection and use of sensors to monitor vertical pump vibration. Sensor survivability, practicality, and ease of use were parameters considered for instrumentation selection.

Pumps Studied

The following pumps were studied:

- *Heater Drip Pump* (7 stages, 13-ft long shaft, 40 hp, 3600 cpm, 210 gpm, 500-ft total head). This pump normally runs continuously with load varying as a function of plant load.

- *Condensate Pumps* (2) (5 stages, 15-ft long shaft, 150 hp, 1770 cpm, 760 gpm, 520-ft total head). These pumps normally cycle on a weekly basis with load varying as a function of plant load. The pumps are identical except one contains an inner shaft "spider" bearing near midspan of the pump shaft; the second pump has no such bearing.

- *Main Circulator Pumps* (2) (1 stage, 19-ft long shaft, 125 hp, 880 cpm, 12,900 gpm, 30-ft total head). These units pump sea water and normally operate continuously at fairly constant load. Tidal action is nominally ± 5 ft.

- *Raw Water Pump* (1 stage, 41-ft long shaft, 2250 hp, 240 cpm, 160,000 gpm, 50-ft total head). This unit pumps tidal-influenced fresh water and nominally operates continuously at uniform load. Tidal action is nominally ± 3 ft.

These pumps are all located at operational power plants. This aspect was important, because many of the problems usually associated with laboratory tests and the difficulty in applying such results to actual in-plant pumps were avoided through onsite testing.

Results of Research Efforts

Recent work [2] has resulted in a number of "lessons learned" that may be applicable in future efforts to monitor and diagnose problems in submerged vertical pumps. The following is a summary of some of the findings on the pumps studied.

Modelling

Computer simulation of a pump's rotordynamic characteristics has provided valuable insight into understanding the vibration performance of vertically mounted pumps. Modelling is especially useful in:

- Determining initial sensor types and locations.
- Identifying the source of unknown frequencies in the pump's vibration signature.
- Assessing "what if" scenarios to help determine "sensitive" modes and in correcting pump vibration problems.

Modelling guidelines [2] have been developed to assist the interested user, manufacturer, or diagnostician assess vertically mounted pumps. Together with an existing computer program,* these guidelines** have been effective in predicting the behavior of the pumps studied. The models do not have to be overly complex to achieve results with sufficient accuracy to determine natural frequencies, mode shapes, and approximate damped response of the pump. The work accomplished has demonstrated that only a reasonable amount of care is needed to develop a pump model that realistically simulates the vibration modes that are of primary interest to users and manufacturers of a variety of submerged shaft vertical pumps.

* The Finite Element Analysis Tool for Utility Rotordynamic Evaluation (FEATURE) computer program [3] performs linear critical speed, damped response, and stability calculations for a wide range of rotor geometries, including multiple, concentric, counter rotating spools and large, multispans, rigidly coupled rotors. A finite-element formulation gives the program numerical stability. A companion program [4] provides fluid film bearing properties. Zorzi, et al., [5] further describe the FEATURE program.

** These guidelines incorporate applicable concepts from seal and fluid film bearing theory as part of the techniques for modelling submerged shaft vertical pumps [6, 7, 8, 9].

It is important to note that pumps with shafts exceeding 40 feet and those with many intermediate bearings have not

been studied at this time. Therefore, the capability of the computer program and the modelling guidelines to accurately simulate response of this type of pump has not been assessed.

Monitoring without Modelling

Even though computer modelling can provide valuable assistance in determining the probable source of many types of vibration in vertical pumps, it is not an essential ingredient of a monitoring project. Although one's prognostic ability may be limited, many vertical pumps can be effectively monitored for trends and changes in vibration without the assistance of a computer model. The remainder of the discussion will focus on recent experience in instrumenting and monitoring several types of vertically mounted pumps. All of the pumps studied were modelled as part of the overall effort. Some of the findings are based on the modelling accomplished; others are independent of that work.

Impact Tests

Impacting structures and measuring their response constitutes a good method of identifying the sources of some of the frequencies that may be observed in the vibration spectrum of the operating pump. The opportunity to acquire such data on intermediate tubes, bearing support structures, assembled pump casings, etc., should not be missed. However, "hang and bang" responses of a pump's rotating elements should not be expected to coincide with those observed in the running pump. The frequencies measured on the rotating elements of a multistage pump during impact tests and during operation are shown in Figure 1. The differences are mainly due to the stiffening effect of the bearings and wear rings (water lubricated) in the pump.

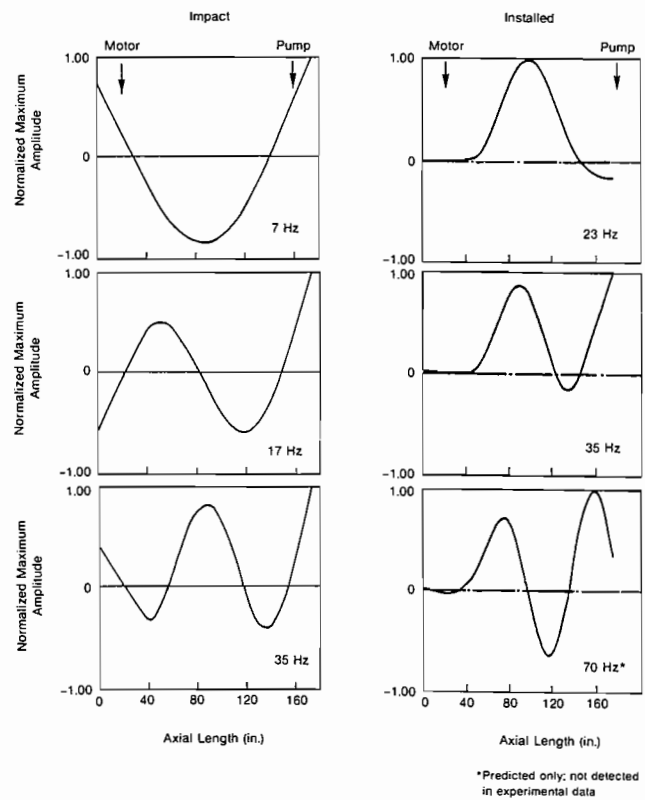


Figure 1. Comparison of Natural Frequencies and Mode Shapes for Impact and Installed Configuration of a Vertical Pump.

The response of components to impact tests can, in conjunction with a computer model, provide a high degree of confidence that the model is an accurate representation of the unit under test. A comparison between the impact and model data (at near-zero values of support stiffness) was made for the pump depicted in Figure 1. The resulting close agreement was later confirmed by comparing actual mode shapes and frequencies with those predicted when the model included normal stiffness values.

Sensor Selection and Placement

To detect early onset of problems, all of the studied pumps required sensors at normally inaccessible locations. For example, a number of predicted modes for the heater drip pump (3600 rpm) are shown in Figure 2. Of particular concern was the 23-Hz mode, which could be excited by bearing whirl. The shape of the mode indicates that typical

sensor locations (i.e., on the motor and/or coupling) would not detect this frequency.

Equally important, the pumps monitored often had modes which, although they could be measured at exposed locations, were typically not of major concern since the shaft and surrounding intermediate tube moved together. For example, mode 2 of Figure 2 represents a resonance found in many vertical pumps. It is often combatted with sand bags on top of the motor and support struts to adjacent structures. However, the rotating and adjacent nonrotating components move in phase with little relative motion between them. Because they affect the overall support stiffness of the system, such "corrective" actions to eliminate this type of pump response can actually cause problems by shifting other modes into undesirable frequency ranges.

As shown in Figure 2, modelling can provide important guidance in selecting the type and location of sensors. However, inaccurate modelling can put shaft motion sensors at risk by placing them at locations where actual shaft motion exceeds the sensor's tip clearance. For example, placement of sensors on the first pump instrumented at Roseton was largely based on a model that, because of a lack of manufacturer information, included assumptions of motor geometry and weight. Shaft motion sensors were placed in regions that during initial startup may have encountered motion that exceeded the sensor tip clearance. Since the pump has not yet been removed for overhaul, the cause of the sensor failures has not yet been confirmed. However, the immediate failure of several sensors is an indication they were damaged on startup. Updates of the model to include the recently acquired manufacturer data show the possibility of large displacements at several sensor locations.

Without the guidance of a computer model, the most conservative approach is to place shaft motion sensors near bearings, where the amount of motion is limited by the bearing clearance. A potential penalty in this approach, however, is the increased probability of not detecting vibration modes, as bearings are often nodal points for such modes.

Since bearing areas are often the most difficult regions to back fit sensors, pump manufacturers should design pumps that at least include provisions to allow the user to easily install sensors.

As a general rule, shaft motion sensors should be included in or near the lowest bearing of a single-stage pump. For multistage pumps, a similar sensor should be first installed at the bearing or wear ring near the final stage. Any inner shaft spider bearing should also contain provisions for measuring shaft motion.

In general, a single sensor should be sufficient to determine overall pump health. However, an X-Y pair of submerged sensors may be worthwhile, principally for the following reasons:

- **Redundancy**—Although sensors form a significant portion of the cost of a monitoring system, they are usually an insignificant part of the total expense associated with removing and reinstalling a pump. A backup sensor can be inexpensive insurance.
- **Orbit Analysis**—A pair of sensors in the same plane can provide important diagnostic information, including determination of the running position of the shaft within a bearing.

Acceleration measurements also provide valuable information concerning the high-frequency vibration of vertical pumps. Although no such problems have been detected in the pumps studied to date, accelerometers located on bear-

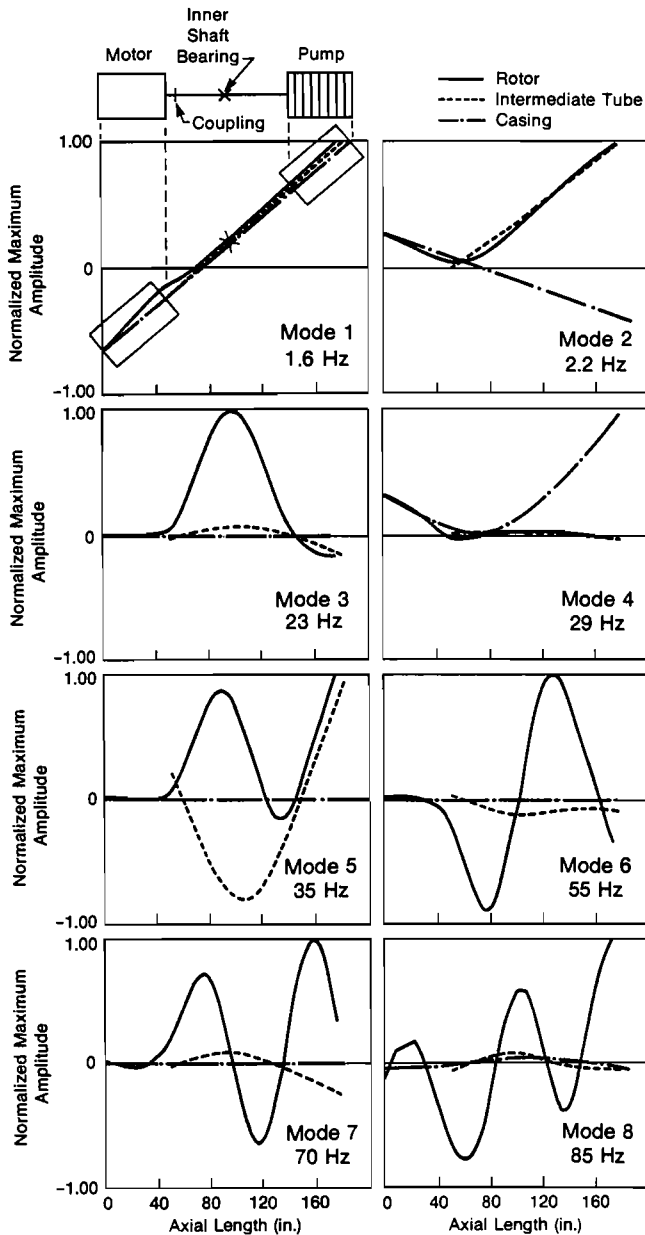


Figure 2. Analytical Natural Frequencies of a Three-Level Pump Model.

ing housings and near shaft motion sensors can detect cavitation and rubs and indicate the amount of base vibration the shaft motion sensor is experiencing. Redundancy factors should also be considered.

Sensors to determine motor condition can also be included. Since these sensors are on exposed portions of the unit, their installation is generally more routine. It is interesting to note, however, that none of the pumps studied have exhibited any problem that was first detected by sensors mounted on the motor or shaft coupling area. On the other hand, sensor survivability problems (see the following discussion) have resulted in having instrumented pumps with few operational submerged sensors. The conservative approach is, therefore, to include one or two sensors for the motor portion of the unit.

Sensors placement for typical single-stage and multistage vertical pumps is depicted in Figure 3. Also shown is a general priority for each location, based on experience gained from modelling and monitoring the pumps studied. The unique needs of a particular pump, along with available space, installation/overhaul schedule, type of monitoring, and other constraints should be considered when determining the amount of instrumentation to be installed on a particular unit.

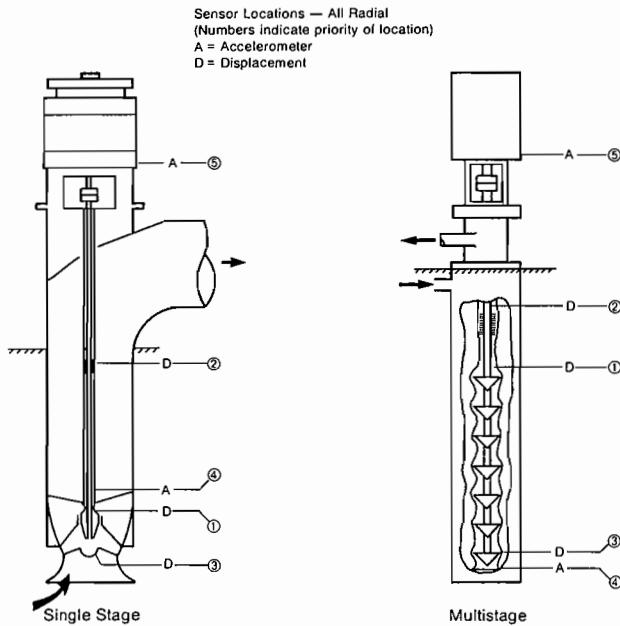


Figure 3. Typical Sensor Locations for Submerged Shaft Vertical Pumps.

Sensor Installation and Survivability

One of the major “surprises” in efforts to monitor the pumps studied has been the high failure rate of submerged vibration sensors. A survey of sensor manufacturers disclosed one type of displacement sensor and several types of accelerometers that were either readily adaptable for underwater use or already designed for such an application.

Although not a problem initially, sensor survivability became a significant factor in the ability to monitor and diagnose the pumps over long periods of time. In most submerged shaft vertical pumps, adequate monitoring requires sensing vibration in submerged portions of the pump. Since these sensors are inaccessible after installation and since the typical pump is to run for several years before removal, the sensors used must be reliable.

The initial plan was to install selected sensors on the first pump and assess their performance and reliability before selecting instrumentation for the next pump. However, actual operational schedules at the participating plants precluded this plan. These schedules necessitated instrumenting several pumps without fully assessing the status of the first set of sensors. As a result, sensors may have failed for similar reasons on more than one pump. To date, 51 sensors (31 eddy current displacement sensors and 20 piezoelectric accelerometers with onboard preamplifiers) have been exposed to longterm submerged operation. Of the 27 that have failed, (Figure 4) only ten (five displacement and five accelerometers), have been removed for inspection. Water leakage, mostly at accelerometer cable connections and tips of displacement probes, has caused all of the failures. Of the failures that have not yet been inspected, it is suspected that most were caused by similar reasons, although four displacement sensors that failed during startup of one pump were probably touched by the spinning shaft.

All sensors for the first pumps to be instrumented were installed as received from the manufacturers. Signal cables were routed through low flow areas and were banded to intermediate casings to minimize chafing and wear. Transition from the submerged and/or pressurized region was via individual grommet-type sealing bulkhead penetrations.

Following some initial sensor failures, one subsequent installation included leads that were encased in flexible conduit to further minimize chances of wear. No significant increase in sensor life has been observed.

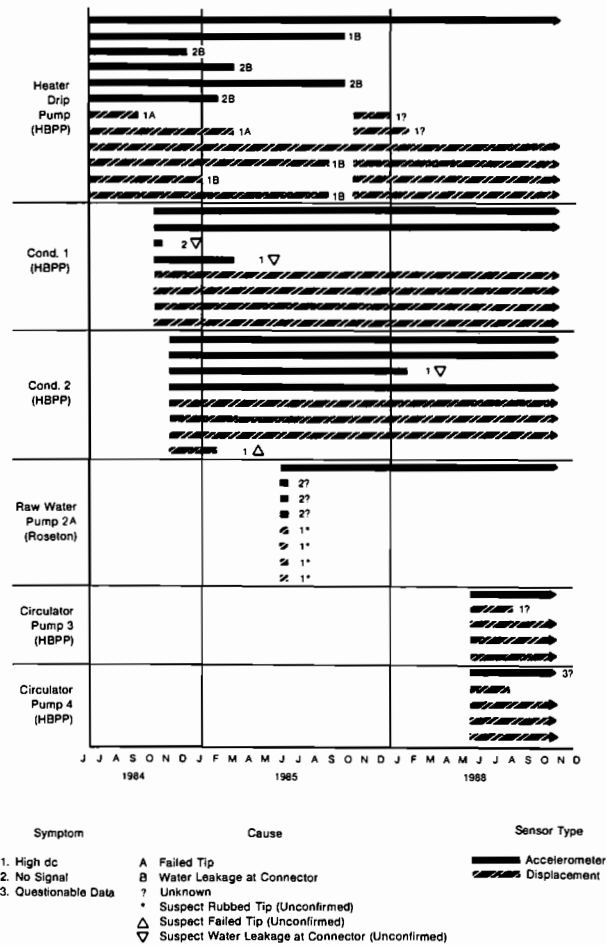


Figure 4. Submerged Sensor Life.

Long-term survivability of the submerged sensors may be enhanced by enclosing the sensors and all leads in air-pressurized rigid conduits to keep water away from cable connections. Such an installation is planned on the next pump to be instrumented. In many smaller pumps, however, space constraints prohibit such measures. An additional limitation involves the extra time these preparations add to the final stages of a pump outage, when it is often difficult to resist the usual pressure to complete the installation.

Local junction boxes are waterproof enclosures which are mounted near each pump. They are used to house signal conditioning electronics and terminations for all sensor leads. This approach is a convenient way to interface the sensor system to the monitoring system. In several instances, however, the boxes were partially flooded when water was pumped up through a sheath on the leads of the displacement sensor. This resulted in shorting out additional electronics in the box. Standard practice now includes slitting the outer tubing before the cable enters the box and drilling drain holes in the bottom of the box.

To eliminate water leakage problems, the displacement sensor manufacturer changed the sensor tip material and the way it is attached to the probe. Eight sensors with this modification were installed in June 1986. By November, two of these sensors had again failed. The accelerometer manufacturers have recommended alternative ways of sealing connections. No additional accelerometers with these revisions have yet been installed.

Although often exposed to normal weather conditions, sensors mounted on nonsubmerged portions of the pumps have been much more reliable. Of 26 sensors (12 displacement sensors and 14 accelerometers), only one of each type has failed to date.

Monitoring Performance Parameters

Recording and trending a pump's performance parameters along with its vibration have been of real value. Pumps in a utility plant's condensate/feedwater loop have exhibited major changes in vibration as a result of changes in plant load, which alters the temperature and flow of water through the pumps. For example, changes occurred in the vibration spectra of a condensate pump as plant load changed (Figure 5). As load increased, the amplitude and frequency of the subsynchronous vibrations also changed. These frequencies were predicted by FEATURE rotordynamic analyses. The increase in frequency of the subsynchronous vibration with load is attributed to shaft stiffening caused by increased hydraulic load pulling down on the shaft.

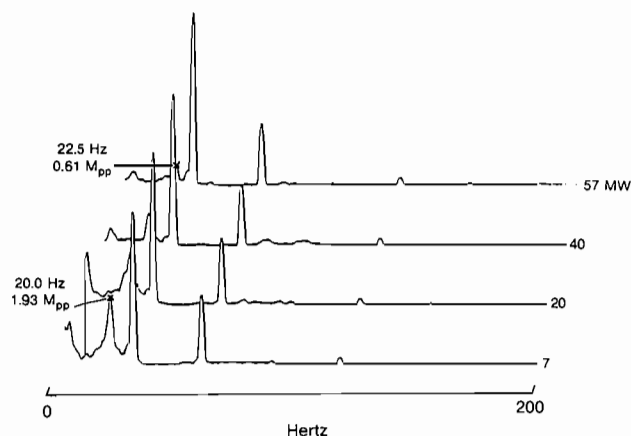


Figure 5. Condensate Pump: Midshaft Displacement.

Monitoring Pump Startup

This is an important time to monitor a vertical pump since significant changes can take place during the initial few minutes of operation. For example, the Heater Drip pump studied has a very long (13 ft), narrow (1-3/8 in diameter) shaft that runs through all seven centrifugal-type pump stages. A nut at the bottom end of the shaft holds all impellers and spacers together. Two feet above the final pump stage is a water lubricated, fluid film, inner shaft "spider" bearing. When combined with the relatively high speed (3600 cpm) of the pump, these features result in a very flexible rotating system.

Shaft displacement data recorded during the initial 90 min of operation are shown in Figure 6. The presence, sudden decrease, and subsequent return of subsynchronous vibration in the submerged portion of the pump was associated with changes in shaft straightness and was not totally unexpected since this type of phenomenon has been observed on other vertical pumps [10, 11].

In the subsynchronous region of Figure 6, two additional elements are of interest:

- The close correlation of the observed frequencies with those predicted by the analytical model (Figure 2).
- The low amplitude of these frequencies at the normally accessible measurement locations (i.e., motor and coupling), also as predicted by Figure 2.

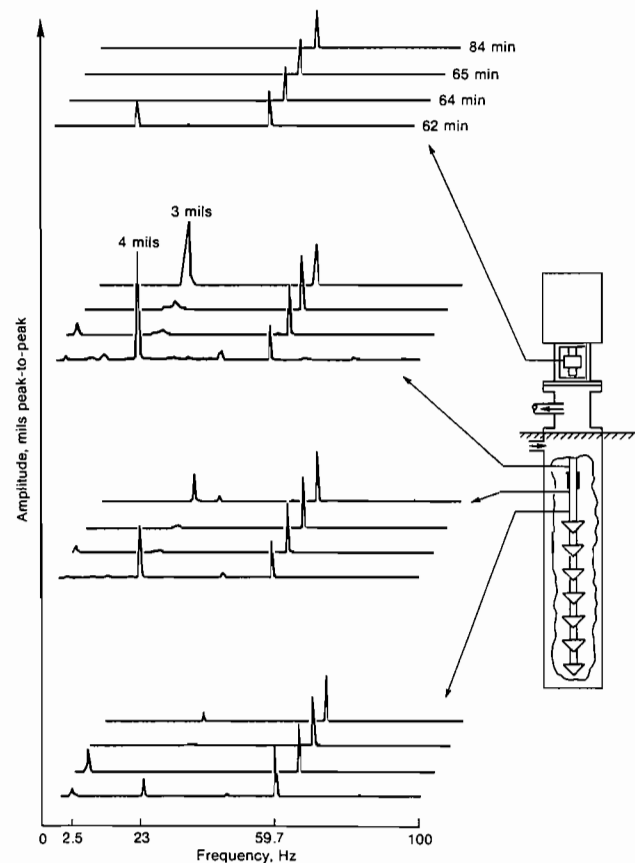


Figure 6. Initial Startup of a Heater Drip Pump.

Long-Term Monitoring

Following initial startup, all pumps studied have been monitored and trended online by an unattended vibration monitoring system. This remote system [12, 13], based on an IBM-PC XT, is used to collect, analyze, and trend changes in

vibration and process parameters. Via a modem and standard telephone lines, the system transfers spectral information and reports changes and trends in specific frequencies from the plant to offsite personnel.

Continuous vibration monitoring can result in mountains of data. An important feature of a monitoring system should be its ability to screen incoming data and store only meaningful changes in the spectra. The remote monitoring system used to monitor the vertical pumps studied to date multiplexes to each selected sensor and, as appropriate, sets the antialiasing filter and sampling rate to the proper frequencies, samples the data a user-specified number of times, and calculates an FFT. This sampling/FFT calculation is repeated a prespecified number of times. The FFTs are then averaged and stored. The averaged levels are then compared, bin by bin, to previous levels. Those frequencies which have varied more than a prespecified amount are saved in trend and report files. The system then automatically multiplexes to the next sensor.

The latest spectra and all trend and report files are available locally and/or remotely (via the modem) to the user. The system modem connects the local system with a host computer (typically, an IBM PC-XT). Via the host computer, the user can telephone and assume control of the remote system. Spectra, trend, and report information can be transmitted. The host computer can then plot spectra and generate reports and trend information. Special purpose hardware tests and error checks can also be made for troubleshooting and debugging purposes.

Continuous monitoring has enabled detection and trending of several phenomena, including the interrelationship between vibration and various process parameters. None of the monitored pumps has had in service failures, and inspection of the heater drip pump after 16 months of operation confirmed the monitoring system's indication of deterioration in pump bearings and wear rings. These indications consisted of gradual increases in the 23 Hz subsynchronous frequency, changes in the dc value of shaft motion sensors positioned near the bearings, and a gradual widening between the maximum and minimum amplitude at running speeds (associated with high and low plant loads).

Pump Modifications

To assess what effects mechanical alterations may have on pump vibration, tests on the heater drip pump were undertaken in October-November 1985. Alterations included:

- Introducing parallel and angular misalignment between pump and motor.
- Adjusting seal packing tightness.
- Altering the final stage impeller to change hydraulic load.
- Modifying the spider bearing to reduce subsynchronous instability.

The computer model was reviewed to assess what effect these alterations should have on pump operation. The predictions were as follows:

- *Modified Spider Bearing.* With any type of support (e.g., a bearing) present at the midshaft location, the pump is marginally stable. As the bearing's qualities are improved either by introducing an axial pressure gradient across the bearing or increasing the eccentricity ratio the system becomes more stable. As a bearing wears, however, clearances increase and the system again becomes less stable.
- *Modified Hydraulic Load.* The hydraulic load on the pump tends to pull down and straighten the shaft. Analytically, the effect of changing this load slightly is similar to altering shaft

stiffness. This can have some effect on the shaft's natural frequencies and change the shaft's sensitivity to bending mode-type response (modes 3, 6, and 7 in Figure 2).

- *Packing Adjustments.* For brief intervals, tighter packing can reduce vibration levels and, by adding more support stiffness, slightly raise shaft-related natural frequencies.

- *Alignment Changes.* Although no specific model adjustments were made for this mechanical alteration, most vibration diagnosticians agree that coupling misalignment often is detected by increases at running speed and multiples, especially in the axial direction. Subsequent revisions of FEATURE now permit simulation of misalignments.

Alignment and packing adjustments were accomplished without removing the pump. Safety and physical constraints limited the amount of adjustment that could be made. Small amounts of offset and angular misalignment were introduced separately. The test results showed small changes (0 percent to 15 percent) in radial vibration at the pump's running frequency and harmonics. Axial accelerometers also showed only a slight increase (less than five percent) at these frequencies. Tighter packings tended to lower vibration amplitude by small amounts. No effect on natural frequencies was observed.

To gage what changes in vibration were attributed solely to pump disassembly, an additional step was taken prior to introducing subsequent alterations. The pump was removed, disassembled, inspected for wear, reassembled, and reinstalled without any known changes being made to the unit. To aid in assessing the planned alterations, it was hoped that this step would not result in significant changes in pump vibration.

Changes did occur, however. Most of the displacement sensors saw significant increases (two to five times) in shaft motion at running frequency and a strong subsynchronous motion at 2.5 Hz. The largest increases in both frequencies were detected at the lowermost shaft sensors.

A comparison of vibration spectra is presented in Figure 7. A typical comparison between pre- and post-disassembly displacements is shown in Figures 7a and 7b. These levels changed somewhat with running time, generally following the inverse relationship between load and vibration amplitude routinely detected on this pump. Adjacent accelerometers showed only minor variation in the two tests.

Following this disassembly/reassembly test, the pump was again removed and disassembled, and a modified final stage was installed. The modified impeller was the same as the standard seventh stage, except the impeller vanes were shortened to reduce the pumping capacity of this stage. Running the reassembled unit disclosed an amplitude decrease at the 2.5 Hz and running frequencies to levels that were more similar to those observed before the pump was first disassembled (Figure 7c). Changes at those frequencies were probably associated with the set taken by the long, thin shaft as it lay in the repair shop and with the manner in which the assembler torqued the nut at the lower end of the tie-bolt type design. These uncontrolled factors can vary considerably with each rebuild and will change the amount of mass unbalance present in the assembled unit. This hypothesis is supported by the observation that the largest changes in amplitude were noted at the lowest shaft sensors, which are closest to the pump stages. All rebuilds following the initial disassembly/reassembly check included strict control of assembly techniques, including alignment, match marks, and bolt torques.

An equally important observation in the shaft motion data of Figure 7 is an increase in amplitude at the 23 Hz, first bending mode of the shaft (mode 3 in Figure 2). This

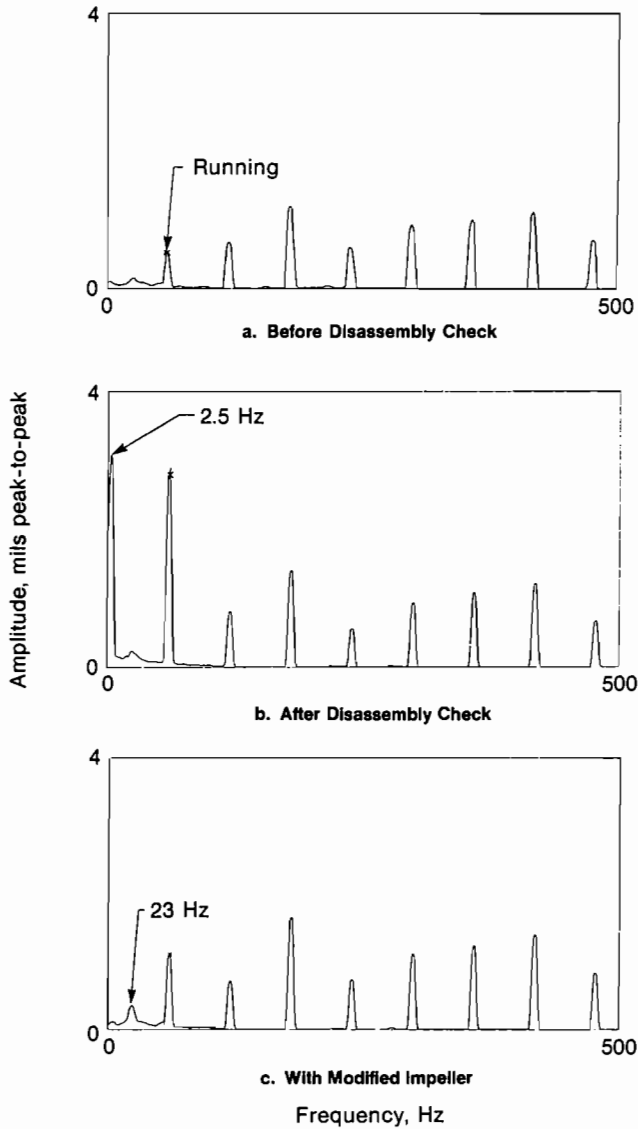


Figure 7. Comparison of Vibration Spectra above Final Pump Stage.

frequency was most evident at the submerged shaft sensors but was not observed at the coupling or motor. It is probable that the eight percent decrease in discharge pressure (and corresponding reduction in hydraulically induced axial load on the shaft) was sufficient to permit increased response to excitation at this frequency.

This modification was left in place, and the remote monitoring system trended pump performance over several weeks of normal plant operation. This monitoring showed that changes in the pump's vibration continue to follow the established pattern, with the increased 23 Hz and running frequencies still present.

The final alteration of this pump, installing a modified inner shaft bearing, was accomplished by again removing and disassembling the pump and replacing the existing sleeve bearing with a new bearing that had a 0.003-in radial offset between the inner and outer diameters. The purpose of this test was to confirm the analytical investigations that predicted an increase in pump stability (i.e., a decrease in the magnitude of the 23-Hz bearing whirl frequency). During reassembly, a standard final impeller stage was reinstalled in the pump.

The remote monitoring system has monitored the pump since its final reinstallation in November 1985. No 23 Hz vibration has been detected since the offset bearing was installed, indicating that the bearing has been effective in controlling this subsynchronous excitation. This is an important confirmation of the analytical predictions. Through October 1986, the shaft motion sensors located near this bearing show approximately 0.01 in change in shaft running position, most of which has occurred since the power plant began partial load operation in the late summer. Although the vibration levels have not yet increased a significant amount, it is expected that the 23-Hz subsynchronous vibration will return as the bearing continues to wear.

CONCLUSIONS

The work accomplished has demonstrated that existing computer programs can be applied to obtain realistic approximations of actual pump vibration performance. The FEATURE computer code is available to make these calculations, and general guidelines for applying this code to vertically mounted pumps have been prepared. The guidelines are intended for use by manufacturers or users of vertically mounted pumps; one need not be an expert analyst to obtain useful information.

Computer predictions can be used to:

- Determine "important" frequencies. Modes with little relative motion between mating components may be of less concern than those that indicate large or out-of-phase motion.
- Determine sensor locations. For the pumps studied, many frequencies of concern cannot be detected at normally accessible locations, especially in the early stage of failure. Conversely, some of the frequencies normally detected on exposed portions of the unit are not indicative of changing pump health.
- Predict the effect of prospective changes. planned changes to a pump's mechanical configuration, bearing modifications, backfits, and field changes can be assessed to determine their probable impact on the pump's vibration performance.

Although analytical models offer distinct advantages, vertical pumps can be successfully instrumented and monitored without the use of this tool. Drawbacks to this approach include a lack of knowledge concerning whether the sensors are located at or near a node or antinode. The health of a given machine, will, therefore, have to be judged by comparing vibration levels to the original level of the pump under steady-state conditions. Although this approach does not help in determining the initial health of a machine, it does provide some quantitative information from the submerged portion of the pump. Instrumenting and monitoring a submerged shaft vertical pump need not be a complex undertaking, but several elements should not be oversimplified:

- Sensor survivability is not a trivial matter. This is especially important in inaccessible regions of the pump. Care must be taken to seal all connections and protect the leads from chafing. Although space limitations are often a problem, sealed and air-pressurized cable conduits should provide additional protection. To prevent leaking fluid from causing additional "upstream" damage, any protective sheathing around the sensor cable should be terminated before the cable penetrates junction/signal conditioning boxes. Manufacturers literature concerning submerged life should be viewed with caution. Redundant sensors (i.e., an X-Y pair) are a fallback strategy.

Care should be taken to avoid locating sensors where they may be damaged by the unit itself. For example, noncontact displacement sensors positioned near midspan of a rotating shaft may be the best location to detect shaft bending, but they may be destroyed by large shaft motions during startup, shutdown, or unplanned operating modes.

- Pump performance parameters should be monitored. On many pumps, running speed, fluid temperature, flow, and pressure often affect the unit's vibration signature. A system that monitors these parameters and permits correlation with vibration can assist in determining trends that indicate deteriorating health of the machine.

- Monitoring may be done online or periodically. As a minimum, online methods should be used for initial monitoring and when studying "problem" units. A monitoring system that prescreens incoming data and retains only information that is significant will simplify data analysis tasks.

- Disassembly and reassembly of long coupled vertical pumps should be a precise operation. This is especially important for pumps being rebuilt with existing parts that may be worn and have loose fits with mating components. Experience has shown that vertical pumps require more attention to consistent assembly practices than comparable horizontal machinery. A lack of attention to detail during reassembly can cause changes in response that exceed those associated with degrading pump health:

- Maintaining concentricity, angular orientation, and stackup sequence of multistage components minimizes unplanned changes in vibration performance.

- Consistent torque-up procedures on tie bolts help reduce the variability in preload and effective stiffness in stacked components.

Work accomplished has demonstrated that vertically mounted pumps have specific requirements that must be addressed in any effort to monitor their operational health. The effectiveness of monitoring can be enhanced through straightforward applications of existing computer codes to help understand a pump's vibration modes. Because of the wide variety in the design and application of vertical pumps, additional case histories are needed to further define and verify diagnostic and monitoring techniques for vertical pumps.

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