USING FIBER-OPTIC PRESSURE SENSORS TO DETECT CAVITATION AND FLOW INSTABILITIES IN CENTRIFUGAL PUMPS

by
Robert X. Perez
Senior Reliability Engineer
CITGO Corpus Christi Refinery
Corpus Christi, Texas
Chung E. Lee
Director of Engineering
Fiber Dynamics Inc.
Bryan, Texas
and
Henry F. Taylor
Professor of Electrical Engineering
Texas A&M University
College Station, Texas

Robert X. Perez is a Senior Reliability Engineer for the CITGO Corpus Christi Refinery. His primary duties include troubleshooting rotating equipment problems, leading root-cause failure analysis teams, and serving as the plant consultant in the areas of vibration analysis and rotordynamics. He has previously written and has been a coauthor on several papers in the field of machinery vibration.

Mr. Perez is a registered Professional Engineer in the State of Texas and a member of ASME, the Vibration Institute, and the Advisory Committee to the Turbomachinery Symposium. He received his B.S. degree (Mechanical Engineering) from Texas A&M University, and an M.S. degree (Mechanical Engineering) from the University of Texas.

Chung Lee has been the Director of Engineering for Fiber Dynamics Inc., in Bryan, Texas, since 1994. He was previously employed by Sam-Sung Electronics Company, where he worked on development of high power CO_2 laser systems for materials processing; conducted research on interaction of soft tissues with various laser sources at the University of Texas at Austin; joined the Institute for Solid State Electronics at Texas A&M University as a Research Associate; was appointed Assistant Research Professor of Electrical Engineering. He then joined FDI.

For the past 10 years, Dr. Lee has been engaged in research and development of novel fiber-optic devices for sensing, signal processing, and optical communication, and has authored 45 journal articles and conference presentations in this field. He holds four U.S. patents and two more patents are pending.

Dr. Lee received his B.S. degree from Hongik University in Seoul, Korea (1975), M.S. degree from the University of Texas at Austin (1983), and Ph.D. degree (Electrical Engineering, 1988) from Texas A&M University.

Henry F. Taylor is a Professor of Electrical Engineering at Texas A&M University, in College Station, Texas. Prior to joining the faculty at Texas A&M in 1985, he was employed by Texas Instruments, the Naval Ocean Systems Center, Rockwell International, and the Naval Research Laboratory. Since 1988, he has held the Irma Runyon Chair in Electrical Engineering.

Since 1970, Dr. Taylor's principal research interests have been in the fields of fiber optics, integrated optics, and diode laser applications. He has authored more than 250 journal articles and conference presentations, and holds 33 U.S. patents. He is a Fellow of the Institute of Electrical and Electronics Engineers and of the Optical Society of America. He is a Life Member of the American Society of Naval Engineers, and a member of the American Physical Society.

Dr. Taylor received B.A. (1962), M.A. (1965), and Ph.D. (1967) degrees (Physics) from Rice University.

ABSTRACT

This paper introduces the benefits of applying the fiber-optic Fabry-Perot interferometer (ffpi) pressure sensor as a means of detecting cavitation and flow instabilities in centrifugal pumps. The need for monitoring dynamic pressure pulsations in pumps as a means of preventing catastrophic failures resulting from severe hydraulic fluctuations has always existed in the pumping industry. However, the ability to continuously sense such phenomena has heretofore not been available with conventional pressure sensors. The development of the ffpi pressure sensor has made high temperature monitoring in process pumps possible. Their ability to function reliably at temperatures exceeding 700°F, and in hazardous environments, make them ideal for use in real-world process applications.

Actual pump test stand data are presented, demonstrating how harmful hydraulic instabilities, such as cavitation and low flow instabilities, can be readily detected using this new sensor. Data from field tests involving typical process pumps are also presented, showing actual cavitation and other flow maladies. For

completeness, the authors present a practical analytical method for assessing dynamic pressure data to determine its severity.

INTRODUCTION

Today, more than ever, it is vital that we design and operate our process equipment so that the catastrophic failures and product releases are extremely rare events. This means that, in addition to purchasing well designed and constructed equipment, we must monitor their condition to ensure they remain healthy during their operational lives. A vibration monitoring program is a common means of protecting mechanical equipment from catastrophic failures. For critical pumps handling highly flammable or toxic fluids, prudent operation also requires users to monitor pressure pulsations as a means of ensuring proper hydraulic operation and preventing flow related mechanical failures.

Several major fires in hydrocarbon processing plants have resulted from mechanical seal failures, shaft breakage, impeller fracturing, etc., of pumps operated at off-design flows (Nelson, 1980). In high energy process pumps, the forces generated by cavitation or internal recirculation can reduce the lives of bearings to hours or days. Large dynamic axial forces generated as a result of nonideal flow conditions have been known to cause premature thrust bearing failures, which have lead to massive product releases and fires, due, typically, to a loss in the axial position of rotating mechanical seal faces.

Centrifugal pumps are designed to produce a fairly constant differential pressure at a given flowrate. Idealized head-flow curves give users the illusion that centrifugal pumps generate only static pressure. However, in reality, this class of pump generates a dynamic pressure component along with the static pressure component. The dynamic pressure component, which rides on top of the static pressure component like an AC signal, is composed of the effects of suction and discharge recirculation, as shown in Figure 1, cavitation, vane pass pulsations, excessive wear ring leakage, etc. This dynamic pressure component is an excellent indicator of how the pump is being operated. Many have tried to use vibration information to detect flow related problems; but this evaluation method is imprecise when it comes to assessing the severity of the flow problem. Dynamic pressure, on the other hand, can be converted to force by knowing the peak-to-peak pressure magnitude and the impeller's projected area.

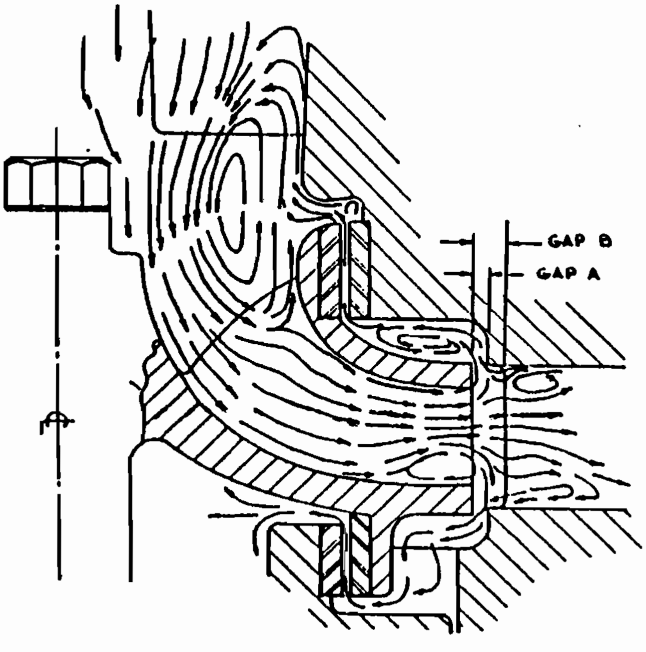

Figure 1. Eddy Current Flows Associated with Off-Design Operation.

Florjancic and Frei (1993) have defined a normalized hydraulic excitation force, K_H, as follows:

$$K_H = F_H / (\rho \; g \; H \; D_2 \; B_2) \tag{1}$$

where F_H is the dimensionless hydraulic force, ρ is the fluid density, g is the acceleration due to gravity, H is the head, and D_2 and B_2 are the impeller diameter and exit width respectively. Using this idea, the rms hydraulic excitation force, F_{rms}, can be defined as:

$$F_{rms} = D_2 \; B_2 \; P_{rms} \tag{2}$$

where P_{rms} is the root mean squared value of the dynamic pressure component at the outlet of the impeller. It can now be said that the normalized rms hydraulic force acting on an impeller is:

$$K_{rms} = F_{rms} / \rho \; g \; D_2 \; B_2 \; H = P_{rms} / \rho \; g \; H \tag{3}$$

This expression can also be written as $K_{p\text{-}p}$, which is in terms of $P_{p\text{-}p}$ instead of P_{rms}, where "p-p" refers to the peak-to-peak value of the dynamic pressure. However, K_{rms} is probably a better indicator of severity, because this value is more descriptive of the average dynamic pressure energy generated by the pump.

The expression of K_{rms} is useful and can be used intuitively. If K_{rms} is one to two percent, it can be concluded that pressure pulsations are, in general, insignificant when compared with the pump's differential pressure. However, if K_{rms} is in the 20 to 30 percent range, it can be concluded that the forces generated by pressure pulsations are becoming significant compared with the static pressure component. While there are presently no accepted guidelines for K_{rms} limits, it is hoped users and manufacturers of centrifugal pumps will work toward establishing K_{rms} or $K_{p\text{-}p}$ guidelines for prudent pump operation.

A small dynamic pressure component (< 10 percent of the static differential pressure) usually means there is plenty of net positive suction head available ($NPSH_A$) and that the pump is operating close to its best efficiency point (BEP); but a large dynamic pressure component means the pump is hydraulically unstable. Figure 2 shows the results of a test where pressure pulsations over a range of flows were measured and plotted. The onset of suction recirculation can clearly be seen at about 60 percent of BEP and discharge recirculation can clearly be seen at about 42 percent of BEP (Karassik, 1986). Prolonged operation at these undesireable flow conditions will inevitably lead to premature bearing failures and shaft deflections that usually lead to wear ring contact and seal failures. This illustrates how dynamic pressure can be a useful indicator of unsafe hydraulic operation.

Until recently, a continuous-duty dynamic pressure monitoring system was impractical, because standard pressure transducers were limited to processes operating below about 300°F. With the recent development of the fiber-optic Fabry-Perot interferometer (ffpi) pressure sensor, pumps can now be monitored in services operating at much higher temperatures. In the past year, ffpi pressure sensors have been used successfully in harsh process environments with temperatures exceeding 700°F.

PRESSURE SENSOR DESIGN

The ffpi sensing element, which is the basis for the pressure transducer, consists of two internal mirrors separated by a length, L, of single mode optical fiber, as illustrated in Figure 3. Each mirror is produced by vacuum deposition of a thin film of the dielectric material TiO_2 on the cleaved end of a fused silica (SiO_2) fiber. Electric arc fusion splicing is used to integrate the mirrors. Each has a reflectance of about five percent, into a continuous length of the fiber. For the pressure sensor, L is about 1 cm.

The next step in making a pressure sensor is to embed the ffpi along the axis of an aluminum alloy rod by a casting process. After

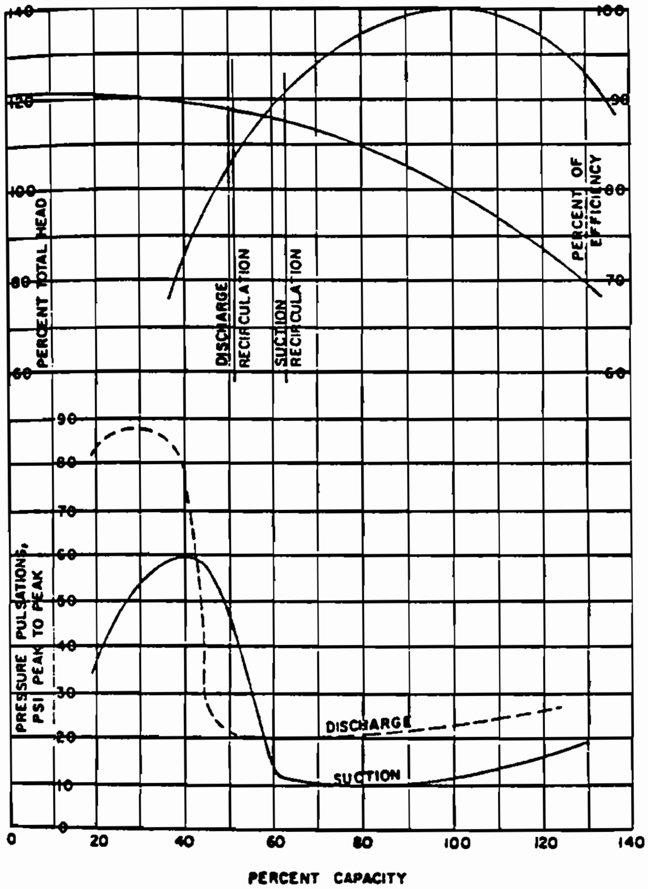

Figure 2. Pressure Pulsations Versus the Percent of BEP Flow.

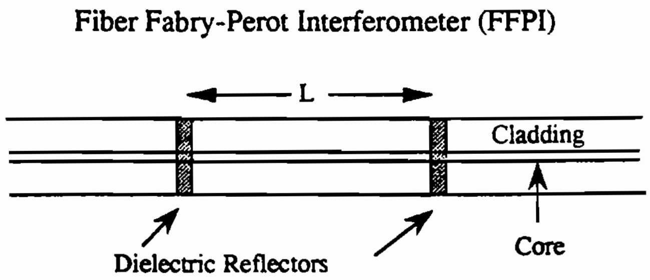

Figure 3. Schematic of Fiber Fabry-Perot Interferometer (FFPI).

machining the cast rod to the desired dimensions, it is inserted into a stainless steel housing with a thin (0.5 mm) lower wall. A nut at the top of the housing is torqued to produce a slight compression of the aluminum rod. The sensor, shown in a closeup in Figure 4, is then mounted in a threaded port in the pump inlet or outlet line. Figure 5 shows a typical sensor field installation.

To monitor the sensor, light is coupled into the fiber and a portion of the optical power reflected from the ffpi is converted to an electrical signal by a photo detector. The amplitude of the reflected power, as determined by coherent interference of light reflected from the two mirrors, is very sensitive to small changes in L. The pressure sensor is designed such that the fluid pressure produces a slight strain (of the order of 10 μstrain, or 0.1 μm change in L) in the fiber, leading to a large fractional change in the reflected optical power (Atkins, 1994, and Lee, 1991).

SYSTEM DESIGN

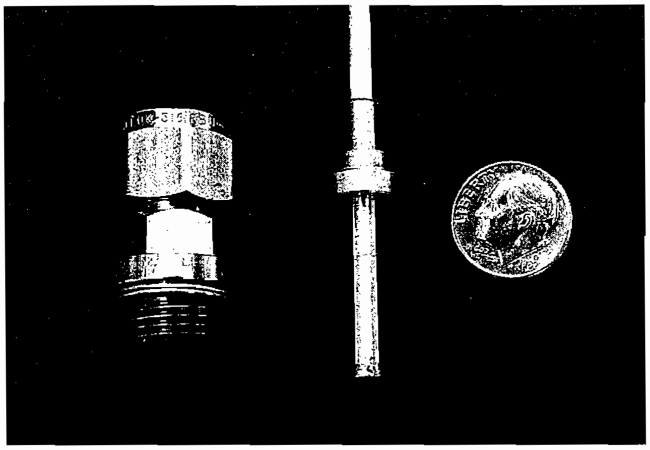

Figure 4. Photo of Fiber Fabry-Perot Interferometer (FFPI).

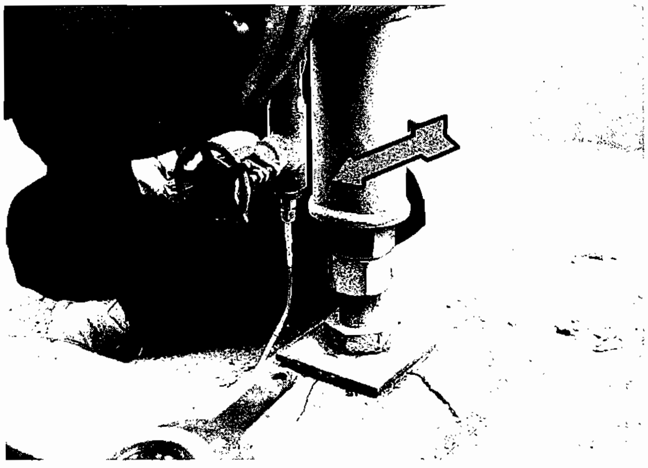

Figure 5. Photo of FFPI Sensor Installation.

A pressure measurement system, developed expressly for ffpi sensors, provides optical power for up to 24 sensors with a single laser (Figure 6). Light from a semiconductor laser diode (LD) modulated with a sawtooth waveform is coupled into a single mode fiber and through an optical isolator to prevent feedback into the laser. The laser light is split by a star coupler to provide optical power to each sensor. A portion of the reflected light from each sensor is routed through a directional coupler to a PIN photodiode, which converts the raw optical signal to an electrical signal. The two unprocessed sensor signals are digitized and a microprocessor computes the pressure. The final stage of the signal processor contains a digital-to-analog converter, providing analog pressure versus time for each sensor. Each ffpi pressure sensor is calibrated against a conventional pressure sensor using a known dynamic pressure source as a standard.

TEST SETUP AND DESCRIPTION

To test the ffpi pressure sensor, the authors' chose to monitor a hydraulic performance and net positive suction head (NPSH) test in a pump manufacturer's test facility, using ambient temperature water. In this way, they were able to investigate the effects of low flowrates and actual cavitation. As an added benefit, the owner of the pump asked for a suppression-type NPSH test, which allowed the authors to assess the effect of falling NPSH on dynamic pressure.

The pump tested was a 6 × 8 × 11 end-suction, overhung process pump rated at 125 hp and 3600 rpm, and designed to pump light hydrocarbon liquid in a refinery. The pump was instrumented with a ffpi pressure sensor on the discharge piping and one on the suction piping. At the time, it was not known if dynamic pressure

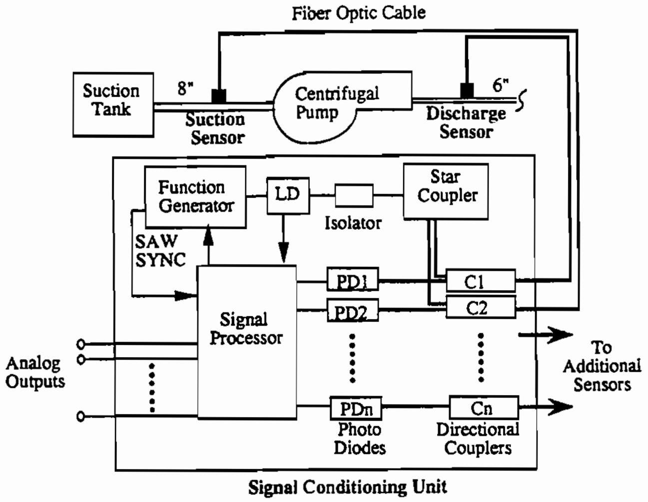

Figure 6. Schematic of Test Set-Up and Signal Conditioning Unit.

pulsations would be more pronounced on the suction or discharge of the pump. The optical fiber cables from each transducer were then connected to the ffpi signal conditioning unit through optical fiber connectors. The converted electrical signals exiting the signal conditioning unit were connected to a PC for viewing and storage in digital form.

It is important to note that the test pump had a suction specific speed (N_{ss}) of 11,800 and BEP flow of about 1688 gpm. While a N_{ss} of 11,800 is not excessively high, it is above the recognized limit of 11,000 suggested by Nelson (1980) for pumps expected to operate significantly below the design flow. For this reason, the authors expected this pump to become unstable at flows of about 60 to 70 percent (1000 to 1180 gpm) of the BEP. During the performance test, the pump was operated at flows of 300, 600, 900, 1200, 1600, 1800, and 2000 gpm, while the suction and discharge pressures were recorded. During the NPSH suppression test, the pump flows were held at 300, 1000, 1600, and 1800 gpm, while the effects of NPSH on differential pressure were recorded.

Historically, the onset of cavitation has been detected by a loss of head. The Hydraulic Institute defines NPSH to be the point where a three percent loss of pump differential pressure is observed. In this NPSH test, the flow was held constant while the NPSH was reduced by pulling a vacuum in the test stand suction tank. (Readers should note the pump manufacturer employed a vacuum and heat controlled NPSH test loop as opposed to a constant level NPSH suppression test loop. This test configuration required the $NPSH_A$ to be calculated from measured suction temperature and pressure conditions.) Once the $NPSH_A$ equaled the NPSH required ($NPSH_R$), a drop in discharge pressure was observed. During the 1000 gpm suppression test, for example, the $NPSH_A$ was varied from 32 ft down to about 8.4 ft. Since, by testing, the three percent drop in discharge pressure for this flow was found to be about 9.2 ft, it can be said that the ratio of $NPSH_A/NPSH_R$ was varied from 3.48 to .91.

TEST RESULTS AND CONCLUSIONS

Several key observations were made from the resulting dynamic pressure waveforms recorded during the pump test. There seemed to be three major categories of pressure pulsations that arose during the test. First, when there was plenty of NPSH available, i.e., $NPSH_A/NPSH_R > 2$, there were only rare signs of cavitation. Typically, components of vane pass frequencies and lower were seen. At flows of 50 percent of BEP flow and less, dynamic pressure pulsations at the pump's discharge rose to about 30 psi (peak-to-peak). These types of pulsations are expected during off-design operation due to internal recirculation and inefficient flow distribution in the impeller and cutwaters.

The second category of pressure pulsation seen at the pump's discharge was of classical cavitation. At all flows, when the $NPSH_A$ equaled the $NPSH_R$, high frequency suction (>> vane pass frequency) and discharge pressure spikes were observed. These pressure spikes were clear signs of vapor bubble implosions in the impeller suction. The magnitude and frequency of occurrence increased at lower values of $NPSH_A$ and at lower flows.

The third category of suction and discharge pressure pulsation observed was that of pressure surging. This phenomenon resulted in pulsation frequencies of about 5 Hz and was only detected at flowrates less than 60 percent of BEP and when the $NPSH_A$ equaled the $NPSH_R$ (Figure 7). At the onset of surging, dynamic discharge pressure amplitudes, at times, exceeded 40 psi (peak-to-peak). At these lower flows, as the $NPSH_A$ fell below the $NPSH_R$, dynamic discharge pressure pulsation became erratic, random, and destructively large (> 80 psi peak-to-peak), as seen in Figure 8.

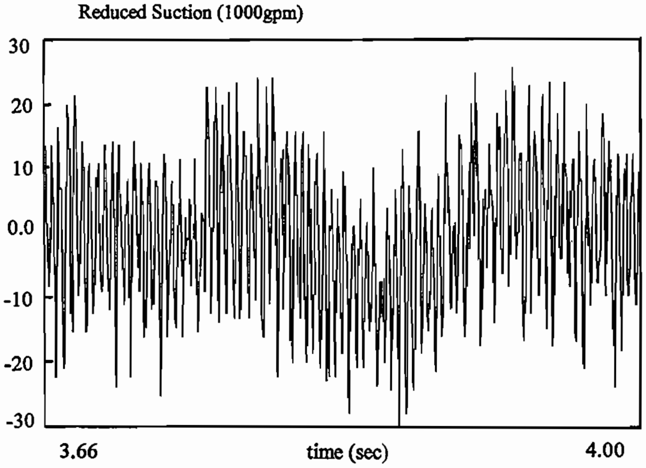

Figure 7. Discharge Pressure Waveform at 1000 GPM and with the $NPSH_A < NPSH_R$.

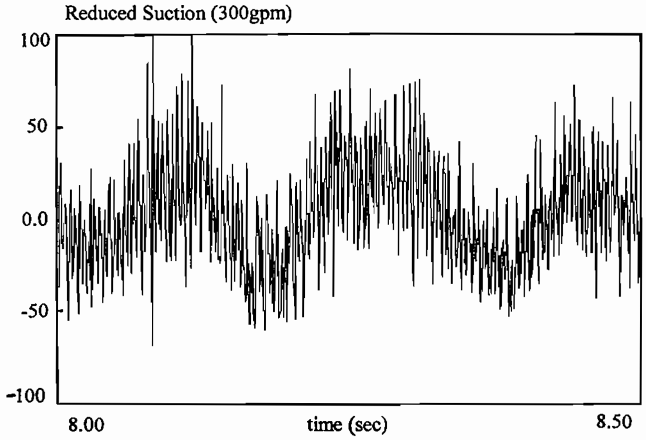

Figure 8. Discharge Pressure Waveform at 300 GPM and with the $NPSH_A < NPSH_R$.

As a result of this testing, the authors draw the following conclusions:

- Dynamic pressure pulsations increase dramatically whenever a pump is operated at flows significantly below its BEP flow.
- Dynamic pressure pulsations increase dramatically whenever the $NPSH_A$ drops to/or below the pump's $NPSH_R$.
- The combination of low flow and $NPSH_A$ can lead to excessive and potentially destructive pulsation levels. The authors hope users and manufacturers will work together in the near future to

establish guidelines for safe levels of dynamic pressure pulsations in the form of K_{rms} or K_{p-p} for high performance centrifugal pumps.

- The ffpi pressure sensor has the sensitivity and dynamic response required to sense hydraulic phenomena typically seen during events of cavitation and hydraulic instability.

CONVERTING DATA INTO INFORMATION

Waveforms from ffpi sensors are worthless unless they can be interpreted and presented in a useable form. So, unless the dynamic pressure waveform from a pump can be reduced, interpreted, and displayed in a clear and concise manner to its owner, the cost of these sensors and their installation will never be justified. Operators of mechanical equipment have no use for "bell or whistles" that are not helpful. To overcome the pitfalls of "bell and whistles," a great deal of study will be required to develop a better understanding of the hallmarks of common hydraulic maladies, such as cavitation, suction recirculation, discharge recirculation, wear ring degradation, casing wear, etc. As seen in the performance testing with ffpi sensors, clear differences between internal recirculation and cavitation were seen. Using dynamic pressure sensors at the discharge and suction nozzles, suction and discharge recirculation problems can also be readily identified. Eventually, sufficient knowledge of dynamic pressure waveforms will be acquired to instill a high level of confidence in the prediction of common hydraulic problems.

Once common hydraulic malfunctions are discernible using dynamic pressure sensors and associated software, users will be capable of troubleshooting their pumps without the need for outside experts. This diagnostic ability will allow users to better protect their equipment, better control their processes, and maximize run lengths. Here are two examples illustrating the potential of this technology:

- A dynamic pressure alarm from a hot oil, bottoms pump signals a problem. The operator wonders if the pump is cavitating or if the pump is operating below its minimum flow. The expert system senses there is a normal liquid level and that the dynamic pressure waveform is characteristic of suction recirculation. The expert system signals the minimum flow spillback line to open, resulting in a return to normal pressure pulsation levels. For this control scheme, the control valve would be stepped open incrementally, similar to a surge control system on a centrifugal compressor, until pressure pulsations were reduced to acceptable levels.

- A dynamic pressure alarm from a feedpump signals a problem. The waveform is indicative of cavitation, but both the tower level and output flow appear normal. However, there has been a rising trend of the pressure pulsation levels. This leads the expert system to conclude wear ring degradation had occurred, causing a loss of NPSH margin. The expert system could also issue a work order to initiate a repair.

It will be this marriage of ffpi sensors, expert systems, and educated operators that will allow us to better manage our pumps and processes in the future.

"SMART PUMPS"

By combining ffpi sensors with other pump-mounted sensors, such as a speed sensor, accelerometers, etc., "smart pumps" can be created that are capable of providing users with full-time pump status information. As described above, users can tie their "smart pumps" into expert systems that can interpret hydraulic and mechanical data, and convert these data into useable information. By evaluating pump vibration levels along with dynamic fluid pressure, users can better determine overall pump condition. Instead of waiting for catastrophic failures to occur, users can, in some cases, preclude failures by taking measures, automatically or manually, to improve hydraulic conditions. This holistic approach will be the key to overall pump reliability and risk management in the future.

THE FUTURE OF FFPI SENSORS

Ongoing development of fiber optic sensor technology is directed toward establishing long-term durability, improving sensor capability, and reducing system cost. Durability tests of in-cylinder pressure sensors at operating temperatures in the 200°C to 300°C range in reciprocating engines are continuing. New sensor designs that can extend operating temperatures to 500°C to 800°C range and improve the sensitivities by one to two orders of magnitude are being investigated. The replacement of laser diodes (LD) in the present signal conditioning units with less expensive light emitting diodes (LED) shows promise as a cost-saving measure.

The widespread use of fiber optic sensors in industrial monitoring and control should become a reality within the next decade. The authors can envision networks of tens to hundreds of point sensors connected to computers that process the raw optical signals, store parametric data, and implement feedback algorithms in the control of equipment and processes. Fiber optic sensor networks will eliminate electromagnetic pickup problems so common with conventional electrical sensors, and they will enhance safety by making it possible to physically isolate all electrical cables and electronic components from volatile materials. It is anticipated that technology will become affordable in the years ahead as the application of multiplexing techniques makes it possible to operate an increasing number of sensors and control loops from a single signal conditioning unit.

REFERENCES

Atkins, R. A., et al., March 1994, "Fiber-Optic Pressure Sensors for Internal Combustion Engines," *Journal of Applied Optics* Magazine.

Florjancic, S. and Frei, A., 1993, "Dynamic Loading on Pumps—Causes and Vibration," *Proceedings of the Tenth International Pump Users Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, pp. 171-184.

Karassik, I. J., et al., 1986, *Pump Handbook*, Second Edition, New York, New York: McGraw-Hill, Inc.

Lee, C. E., et al., 1991, "Metal-Embedded Fiber-Optic Fabry-Perot Sensor," Optics Letters.

Nelson, W. E., January 1980, "Pump Curves Can Be Deceptive," *NPRA Refinery and Petrochemical Plant Maintenance Conference*, San Antonio, Texas.