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CAVITATION DETECTION IN HYDRAULIC TURBINES

by

K. Warren Frizell

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K. Warren Frizell[1]

Introduction

All types of hydraulic turbines, from a low-specific-speed Francis to a high-specific-speed Kaplan, have been found to be susceptible to cavitation. While cavitation may be enhanced by a poor design, it can occur in even the best designed equipment if operated under unfavorable conditions. In hydraulic turbines, as cavitation develops there is a decrease in both power output and efficiency. However, while decreased performance is a definite result of cavitation, perhaps the most widely recognized effect of cavitation is damage. Often, the terms "cavitation" and "cavitation damage" are used synonymously. Typically, cavitation damages solid flow boundaries by removing material from the surface. In hydraulic turbines, the most common damage occurs on the runner. The repair of cavitation damage can be a major maintenance concern, requiring weld repair or in especially severe cases, runner replacement.

Cavitation is the process which occurs when a liquid changes state and vapor or gas- and vapor-filled bubbles or cavities are formed. When this is a result of a temperature rise, it is known as *boiling*. If the bubble growth is due to a static pressure reduction, this is known as *degassing* or *gaseous cavitation*; if it a result of a dynamic pressure reduction, it is known as *vaporous cavitation*. Vaporous cavitation, is generally the type we are interested in when dealing with hydraulic machinery.

One of the most common identifiers of cavitation, is the noise which is created throughout the process. In most powerhouses, where the ambient noise levels are already high, the increased noise due to a cavitating turbine runner may not be noticeable to the human ear. Still it is possible by using microphones or hydrophones to monitor increased noise levels due to cavitation. In addition to increased noise, the general vibration level can also rise. Since cavitation is an unsteady process, it can involve large fluctuating forces. In a turbine, specific parts (i.e., runner blades, wicket gates, etc.) could be excited into vibration through these fluctuating forces. There is also the possibility that, where attached cavities are formed due to a separation, those cavities have a characteristic frequency which can excite a component of the machine to vibrate.

The process of cavitation damage is similar to fatigue wear, as surface and subsurface cracks are formed due to repeated attack by high pressures caused by bubble and cavity implosions. In addition to causing oscillations in the fluid over a wide range of frequencies, high frequency vibrations known as acoustic emissions (A-E), result from microscopic failures in the material bonds which typically occur during the plastic deformation of metals. Due to their high

[1]Research Hydraulic Engineer, Water Resources Research Lab (D-8560), Technical Service Center, Denver CO, 303/236-2000 ext. 456, wfrizell@ibr8gw80.usbr.gov.

frequencies, A-E attenuate rapidly with each material interface, especially through fluids. The use of A-E sensors has been widely applied to detecting cavitation in a variety of applications by sensing various types of vibration. You need to have a direct acoustic path for an A-E sensor to be effective; however, many times cavitation results in sufficient transfer of acoustic energy to excite other parts of the machine to vibrate.

Cavitation has been a major area of study over the past century and while we have advanced in our knowledge on the subject, we still don't have all the answers. In the area of hydraulic turbines, the major question remaining, Can we differentiate between cavitation which is occurring in the flow and that which is causing physical damage to the machine?

Detecting Cavitation in Hydraulic Turbines

Many techniques and processes for detecting cavitation in hydraulic turbines have been around for many years. As mentioned previously, the detection of cavitation is relatively easy, especially by acoustic methods. The question which still remains, Is cavitation imploding on a solid boundary and causing damage? This problem becomes increasingly complex when you are dealing with rotating machinery. There have been extensive studies on sound and vibration monitoring of cavitation in pumps, marine propellers, and water turbines [Wolde 1974, Beyer and Smith 1982, and Lindgren and Bjarne 1974].

The Tennessee Valley Authority (TVA) is carrying out a large research program where cavitation and machine efficiency are monitored simultaneously. They use A-E sensors to monitor the presence of cavitation [March and Jones 1991]. Their results show that real-time monitoring is possible with an A-E based system as long as there is a direct acoustic path between the eroding metal and the A-E transducer. Several other researchers have been experimenting with new techniques in data analysis methods using traditional accelerometer and A-E sensor outputs [Abbot and Greeley 1984, Bourdon, et al. 1993]. Many of the methods have shown promise but there is still room for further development of a system which can identify damaging cavitation, real-time, at a reasonable cost, without site-specific (i.e., geometry) effects.

Reclamation's Research Program

The Water Resources Research Laboratory (WRRL, formerly the Hydraulics Lab) has had a long history in Reclamation dealing with cavitation and the problems which can result. While the highest profile cavitation problems have largely dealt with hydraulic structures, i.e., Glen Canyon and Hoover Dam spillways, we continue to have problems involving various types of hydraulic equipment and machinery. While they may not involve catastrophic failures, many of the cavitation problems with hydraulic turbines are of the continuous, nagging sort, which require time and effort to control.

In the past, our major interest in cavitation damage to hydraulic turbines has been largely related to maintenance activities required to repair damage. These repairs can be very expensive, not only in materials and labor to perform the repair, but also in revenue loss due to downtime, the cost of replacement power and reductions in equipment service life [Knapp et al.,1970, Arndt et al. 1986, March et al. 1988]. In addition, if a damaged unit continues to operate, decreased efficiencies result in more losses. For this reason, it makes sense to begin to focus on ways to avoid damage and hence repairs. One approach is to provide a system which will alert the operator when actual damage is occurring to a unit. While this is not a method which guarantees that damage will not occur, it can give the power managers and operators additional information which they can use in scheduling and operation.

Over the past 3 years, a portion of our research program on the Operation and Maintenance of Hydraulic Machinery has been dedicated to cavitation detection, and in particular to the detection of "damaging" cavitation in hydraulic turbines. The research has consisted of a thorough literature review, evaluation of sensors and sensor development, and model and prototype measurements. We are currently evaluating the model and prototype measurements in a effort to come up with a generic cavitation detection instrumentation package which could be used in Reclamation facilities.

Cavitation Detection Instrumentation

The general results of the literature review have shown that a combined instrumentation/data analysis technique referred to as "full wave rectified spectral analysis" has shown much promise in the evaluation of cavitation noise in hydraulic turbines. In general, this technique uses an accelerometer mounted on one of the wicket gate stems or links; and then, through a filtering and detection phase, provides information on the presence of cavitation by evaluating the power at the blade passing frequency of the particular unit. While not entirely understood, researchers have shown results of this method to correlate fairly well with historic records of cavitation damage.

The basic instrumentation package consists of a sensor (high-frequency accelerometer or A-E sensor configured as an accelerometer), amplifier, filters, full- or half-wave rectifier (true RMS detector) and a spectrum analyzer, see figure 1 for a schematic. A large part of this application relies on the data analysis procedure and interpretation of the frequency spectra. Various parts of this procedure can be accomplished either by hardware or software.

The premise of this method postulates that high-frequency vibrations due to the presence of cavitation are modulated at lower frequencies which are characteristic of the major rotational frequencies of the turbine, i.e., the blade passage frequency (unit r/min X number of buckets on the runner). If there is a peak in the spectrum at the blade passing frequency, then many researchers believe that it indicates there is cavitation present on all the runner buckets. In addition, harmonics of the blade passage frequency can exist, as well as the fundamental rotational frequency and many of its harmonics. The significance of these other frequencies is not well understood, and the theoretical explanations are largely unproven.

There has been work to look at the equivalence of measurements taken from fixed locations and rotating locations on hydraulic turbines [Bourdon et al. 1993] The general conclusion is that there is equivalence; however, for a fixed sensor the cavitation noise is modulated at the blade passing frequency and for a rotating sensor the cavitation noise is modulated at the wicket gate passing frequency. In this same work, experiments were carried out on a hydrofoil in a water tunnel where actual cavitation damage was correlated with this modulated frequency peak. The one thing that still remains is the general application of this technique, i.e., comparison of actual amplitudes measured on one unit compared to another. This technique can be easily applied to a variety of hydraulic turbines and pumps; however, there is no defined amplitude of the modulated spectral line which definitely corresponds to the occurrence of cavitation damage. There appears to be considerable acoustic effects caused by actual geometry, especially in the varying lengths of acoustic paths just due to different sized units.

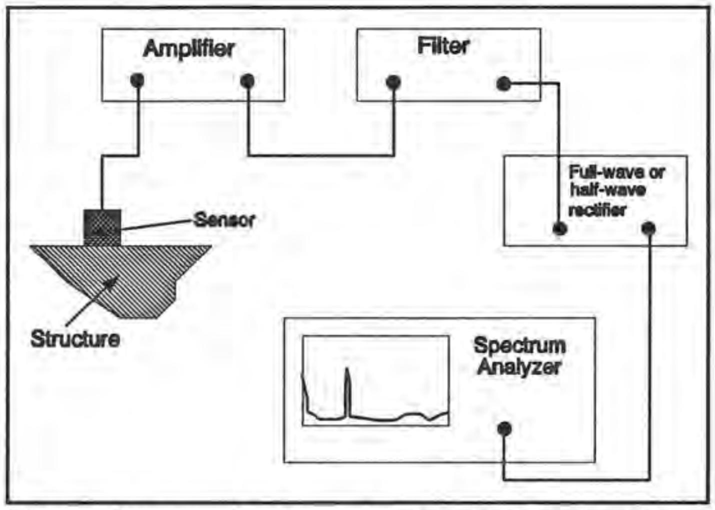

Figure 1: Schematic of cavitation detection instrumentation.

Reclamation Experiments

During the past several months, we have carried out a number of experiments, both in the lab and in the field. We have used the demodulating instrumentation to observe leading edge cavitation on a wicket gate model, and to verify cavitation on the wicket gates at Flatirons Powerplant. In addition, we also took machine signatures at J.F. Carr Powerhouse Unit 1 and Shasta Powerplant Unit 2.

Wicket gate cavitation

The cavitation detection instrumentation package was first tried on a model wicket gate location in the WRRL. The main purpose of the test stand is in the evaluation of environmentally-safe wicket gate lubricants; however, we are able to create leading edge cavitation on the scaled wicket gate. The instrumentation package showed a typical random noise spectrum; however, when a closed vapor cavity was formed separating off the leading edge of the gate, an audible tone was noticed and observed on the spectrum, figure 2. The raw signal from the A-E sensor, when fed directly into the spectrum analyzer, showed a peak at 444 Hz, or the frequency that the cavity was singing at. When the signal was run through a high-pass filter set at 20 kHz and then through the full-wave rectifier, we were able to see a peak near 500 Hz. The presence of this peak means that the high-frequency vibration picked up on the wicket gate stem was being modulated at a frequency characteristic of the cavity size. As the cavity was vented, causing extremely loud and vigorous crackling (also characteristic of cavitation), this frequency peak disappeared.

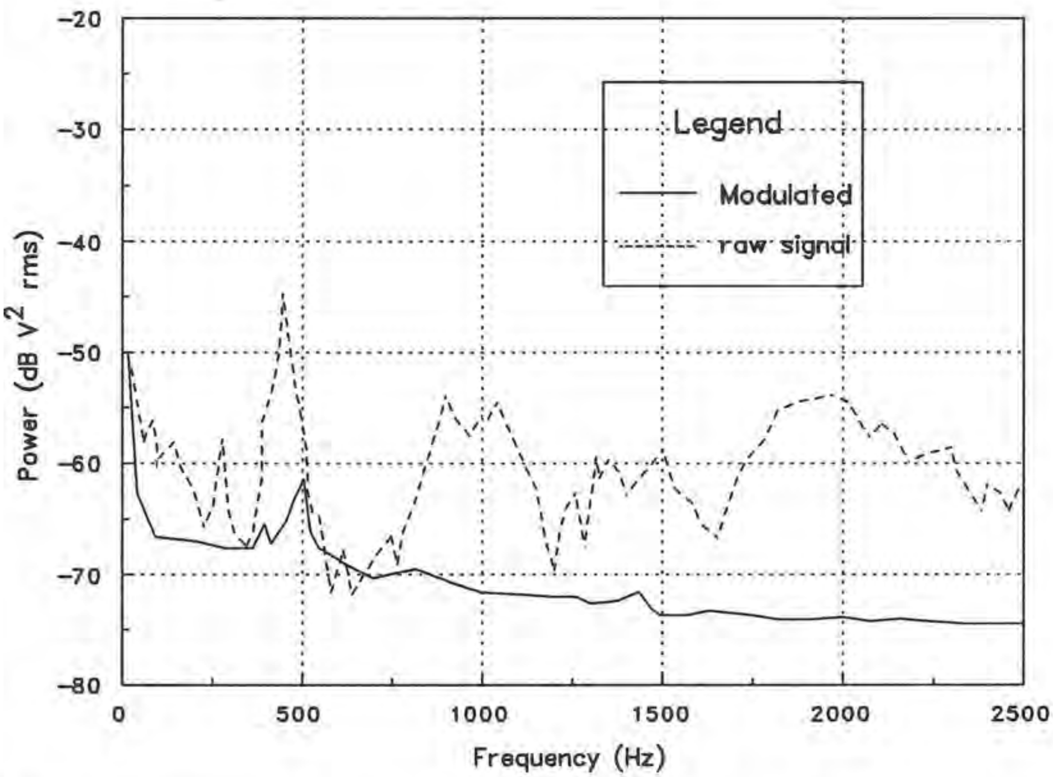

Figure 2: Wicket gate model with attached vapor cavity.

We attempted to show similar results at Flatirons Powerplant in Loveland, Colorado, since they have known cavitation damage on their wicket gates. We set up our instrumentation package, mounting the A-E sensor on the bottom of the wicket gate stem. Flatiron has two Francis units operating under heads of about 1,000 ft. Operation of the units was quite noisy at this location with lots of turbulent flow noise. Leading edge cavitation was undiscernible from the other noise sources. We were never able to pick up a similar type of singing caused by an attached cavity; however, using the A-E sensor and another sensor commercially available from SENACO, we were able to identify cavitation on the wicket gates.

J.F. Carr Powerhouse

Cavitation detection was attempted at J.F. Carr Powerhouse using the described instrumentation package with the sensor mounted on a wicket gate stem. Unit 1 was instrumented. This is a Francis turbine, rotating at 225 r/min with 17 buckets and 20 wicket gates. Heads vary from the summer to the winter. We tested the unit while at the low tailwater condition. These units have experienced recurring cavitation damage which must be weld-repaired every 2-3 years.

We took readings as the unit was loaded, up to a full load of 86 MW (92 percent wicket gate). Figure 3 shows the full-wave rectified spectrum at a 77 percent wicket gate opening. This appears to be the largest component of the blade passing frequency and its magnitude was about 25 dB above the background spectral levels. In addition there were other frequencies which showed peaks, including 2 X rotation and the wicket gate passing frequency (75 Hz).

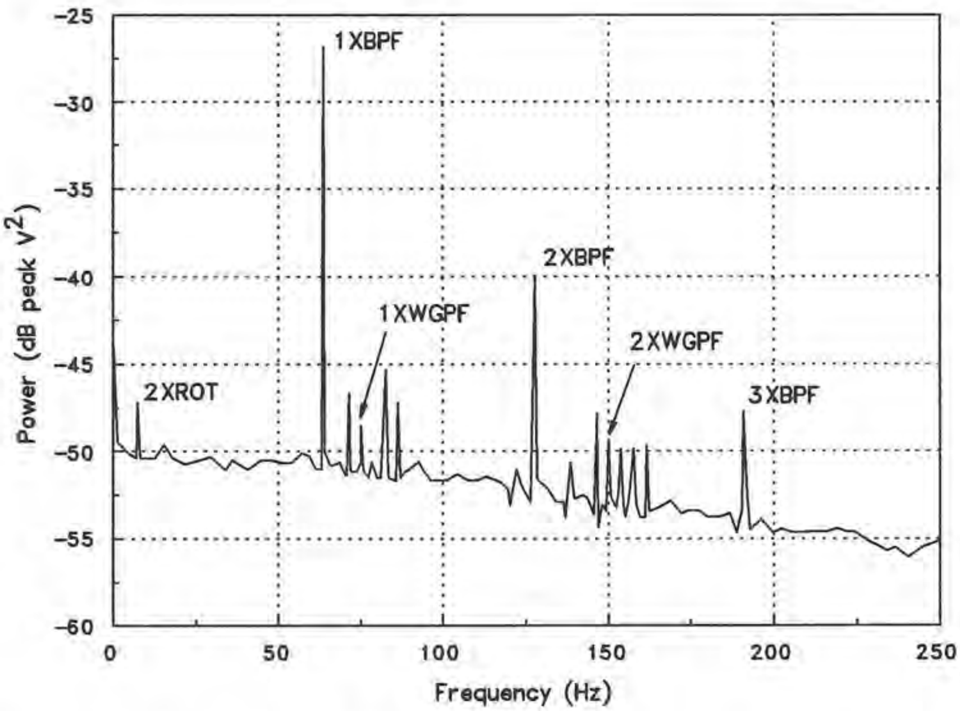

Figure 3: Full-wave rectified spectra from J.F. Carr Unit 1.

Shasta Powerplant

We also instrumented Unit 2 at Shasta Powerplant. This unit has been recently uprated. The unit is a Francis type and rotates at 138.5 r/min with 24 wicket gates and 15 bucket on the runner. Maximum head is 475 ft with a design head of 380 ft. The A-E sensor was again mounted on the end of a wicket gate stem. We recorded data from speed-no-load up to a full load of 122 MW at an 80 percent wicket gate opening. Figure 4 shows the magnitude of the blade passing frequency above the surrounding background levels throughout the operation. These data indicate that the two worst conditions for cavitation are probably speed-no-load and a wicket gate setting of 70 percent. Historical damage on these units has been minimal prior to the uprate. At the original rating, maximum load occurred around a 60 percent wicket gate opening.

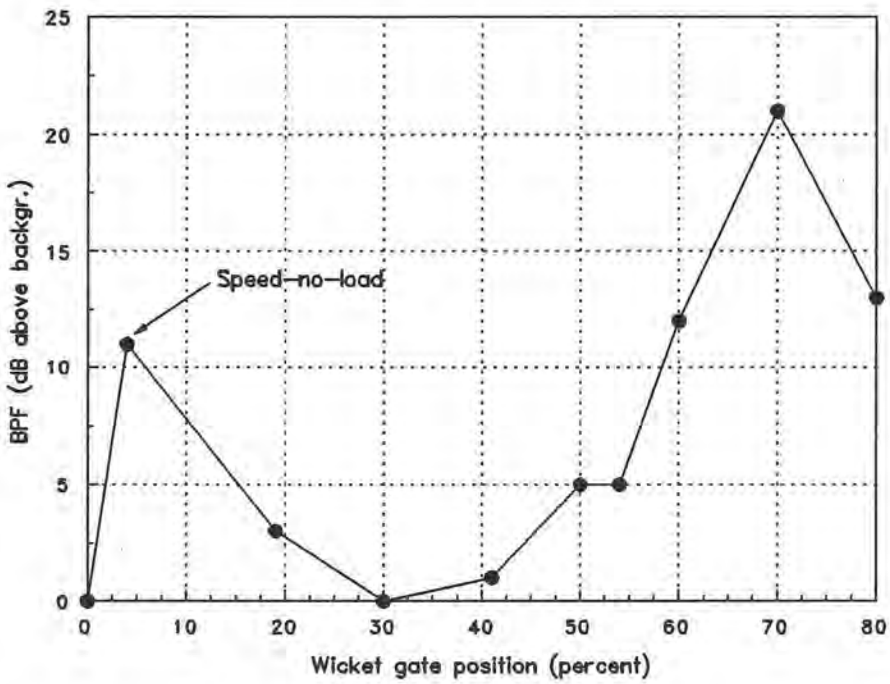

Figure 4:Blade passing frequency magnitude above background, Shasta #2.

Conclusions

The detection of cavitation on turbine runners is a difficult task. While detecting that cavitation is present is not difficult, to determine when there is damage occurring is much harder. Acoustic emissions seem to lend itself to detecting damage; however, to successfully do this, you must mount the sensor on the piece of equipment which is being damaged. In the case of a turbine runner, it means the sensor would be rotating and some type of telemetry system would have to be used to look at the data. The problem with this scenario is that the high frequencies which A-E sensors operate at would require a highly specialized telemetry link. Many researchers have found that when cavitation is present on the runner, enough energy is transmitted to adjacent structures that detection can take place from a fixed location. Problems begin to arise here because of geometric effects, most importantly the acoustic path from the noise source to the sensor. It has also been shown that the presence of bubbles or cavities in the flow highly attenuates the signal making it even more difficult to characterize.

We have shown that there is definitely some promise in the technique of full-wave rectification spectral analysis for detecting cavitation in hydraulic turbines. Additional data need to be taken so that comparisons from unit to unit can be made. In addition, lab experiments under more controlled conditions would be helpful in trying to sort out what the harmonics and subharmonics of the rotational and blade passing frequencies truly indicate.

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