Draft Tube Surging Times Two: The Twin Vortex Phenomenon

Draft tube surging has long been a problem in hydraulic reaction turbines, causing vibrations, power swings, noise, and penstock pressure surges. Although the majority of draft tube surging research has examined single vortices, some recent studies at Grand Coulee focused on a twin vortex formation. Continued research is needed to learn more about the various types of draft tube surging.

By Tony L. Wahl

Draft tube surging is one of the most fascinating–and potentially destructive–aspects of hydraulic reaction turbine operation, particularly in Francis turbines. This surging is a flow instability in the draft tube resulting from swirling flows associated with part-load or overload operation of the turbine. The breakdown of the unstable swirling flow creates a single helical vortex in the draft tube, which is a more stable flow structure analogous to the hydraulic jump in open channel flow.[1]

Surging is the source of objectionable noise, severe vibrations, and excessive shaft runout and bearing wear in a hydroelectric turbine-generator. When the surging frequency coincides with a natural system frequency, the surges can produce enormous power swings, destructive structural resonance, or uncontrollable penstock pressure surges. [An article describing draft tube surging appeared in *Hydro Review,* February 1993.—*Ed.*]

Hydropower's great flexibility normally is an advantage, but can aggravate draft tube surging problems. For example, hydropower units operating over wide ranges to meet power system and environmental needs sometimes are forced to operate in part-load draft tube surging zones. Also, remote operations can create draft tube surging problems when an operator places a unit into a strong surging region without any direct sensory feedback. (Operators stationed in a power plant feel and hear the rough operation and can immediately take steps to get out of the surging zone.) Improvements in turbine technology, such as increased use of variable pitch blades and variable speed operation, may eventually alleviate some of these problems, but it is still important for the hydro industry to learn about and to understand the draft tube surge.

Although the majority of past research has been focused on the single helical vortex, several investigators also have observed a twin vortex in swirling flows.[2,3,4] However, the phenomenon has never been studied in detail. The twin vortex is significant for hydropower designers and operators because it creates pressure fluctuations and vibration at frequencies that are not typically associated with draft tube surging. Recent research on model turbines and at the Grand Coulee Third Powerplant has better defined the behavior and occurrence of the twin vortex.

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Reviewing Past Draft Tube Surge Research

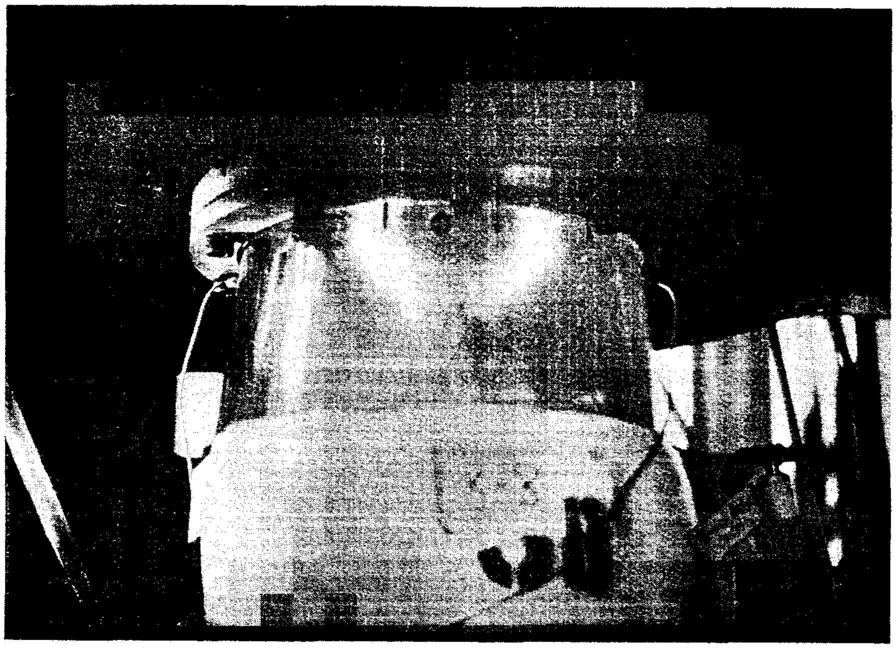
In the late 1960s and early 1970s, the Bureau of Reclamation conducted extensive applied draft tube surging research coinciding with the design and construction of the Third Powerplant at Grand Coulee Dam. The research program included basic investigations of swirling flow and the vortex breakdown phenomenon, extensive testing of various draft tube shapes, and hydraulic model testing at prototype heads using 9-inch models (1:40.33 scale) of the two turbine and draft tube designs at Grand Coulee.[5,6]

The research established dimensionless parameters for the amplitude and frequency of pressure fluctuations associated with the draft tube surge. It also related those parameters to a dimensionless swirl parameter describing the flow through the draft tube.[7] This made it possible to use small-scale model test results to predict the surging characteristics of a given turbine and draft tube combination.

In 1988, as part of my requirements for earning a master's degree from Colorado State University, I began research to better define the occurrence and behavior of a twin vortex in specific turbine and draft tube combinations. The model studies I conducted at Colorado State made use of the same model turbine used for Reclamation's draft surging research.[8,9,10] The testing also identified the conditions under which a twin vortex might occur in the prototype.

Model Testing for a Twin Vortex

The turbine model is a homologous 1:40.33 scale model of the 700-MW Allis-Chalmers Francis turbines installed at Reclamation's Grand Coulee Third Powerplant (units G-22, G-23,



The twin vortex in the model draft tube appears at the center of this photograph as two intertwined helical vortices, oriented in the form of left-handed screw threads. The vortices are visible here due to cavitation occurring in the vortex cores. The twin vortex phenomenon occurs at wicket gate openings of 30 to 40 percent, and produces a higher surging frequency than the typical single vortex surge.

and G-24). The model was originally installed in a test facility at Reclamation's Estes Powerplant and was used for draft tube surging research through the early 1980s. After the Estes facility was decommissioned, Reclamation, Colorado State, and the U.S. Department of Energy joined together to move the test facility to the Engineering Research Center at Colorado State. The model was installed on a pipeline drawing water directly from Horsetooth Reservoir west of the laboratory.

The model is geometrically similar to the Grand Coulee prototype from the penstock intake through the downstream tailrace. It operates in the prototype head range of 220 to 355 feet. In the current installation, the maximum available head is about 250 feet. A butterfly valve and a 25-foot standpipe downstream of the model can apply back pressure. Loads as high as 900 horsepower may be applied to the model turbine using a water-cooled, eddy current absorption dynamometer. Both load and speed control operation are possible at speeds of 1,000 to 3,000 revolutions per minute (rpm).

The main components of the model include a penstock, spiral case, draft tube, and tailwater tank. Twenty-four wicket gates connected to a manually operated handwheel control the water flow to the model. The runner of the model turbine is approximately 9 inches in diameter and contains 13 blades. The throat and elbow section of the model draft tube are made from clear acrylic and fiberglass. The draft tube throat is a typical divergent cone design with an included angle of 13 degrees. The steel foot of the draft tube contains two piers and the associated bulkhead gate slots. Flow discharging from the draft tube enters a tailwater tank containing a false floor to simulate the prototype tailrace geometry. Admitting compressed air into the tanks can control the water surface levels in both the headwater and tailwater tank.

A computerized system monitors the operating status of the test facility and model turbine by collecting data from pressure transducers, thermocouples, a tachometer, and the dynamometer torque load cell. A BASIC computer program controls the collection of data and performs the calculations needed to determine the operating characteristics of the turbine.

In my research, two piezoresistive transducers on the model measured pressure fluctuations caused by the draft tube surge. The transducers were on opposite sides of the draft tube throat in locations corresponding to the man-door locations on the prototype units. An oscilloscope monitored the time domain pressure fluctuations at both locations to detect changes in their phase relationship. A dynamic signal analyzer obtained frequency spectra for the pressure fluctuations at the upstream transducer (the inflow side of the powerhouse). The frequency domain plots provided the frequency and amplitude of the dominant pressure fluctuation. Dimensionless frequency and pressure parameters were calculated as:

Equation 1 (dimensionless frequency parameter):

$$\frac{fD_3^3}{Q}$$

Equation 2 (dimensionless pressure parameter):

$$\frac{D_3^4\sqrt{\overline{(p')^2}}}{\rho Q^2}$$

where:

f = frequency;
D_3 = runner exit and draft tube inlet diameter;
Q = turbine discharge;
ρ = water density; and
$\sqrt{\overline{(p')^2}}$ = rms pressure fluctuation amplitude.

The draft tube swirl parameter is defined as:

Equation 3:

$$\frac{\Omega_2 D_3}{\rho Q^2} = \frac{\Omega_1 D_3}{\rho Q^2} - \frac{PD_3}{\omega\rho Q^2}$$

where:

$\frac{\Omega_2 D_3}{\rho Q^2}$ = draft tube swirl parameter;

$\frac{\Omega_1 D_3}{\rho Q^2}$ = wicket gate momentum parameter;

P = turbine output power; and
ω = turbine shaft speed, radians/second.

In simplified terms, Equation 3 states that the draft tube swirl is the difference between the swirl introduced by the wicket gates and the swirl extracted by the runner. The geometry of the wicket gates defines the wicket gate momentum parameter. The swirl extracted by the runner can be calculated from the discharge, speed, and power output of the turbine.

Figure 1 shows the turbine efficiency hill curve, with intermittent and periodic surging zones identified. (The hill curve is similar to a topographic map of a hill,

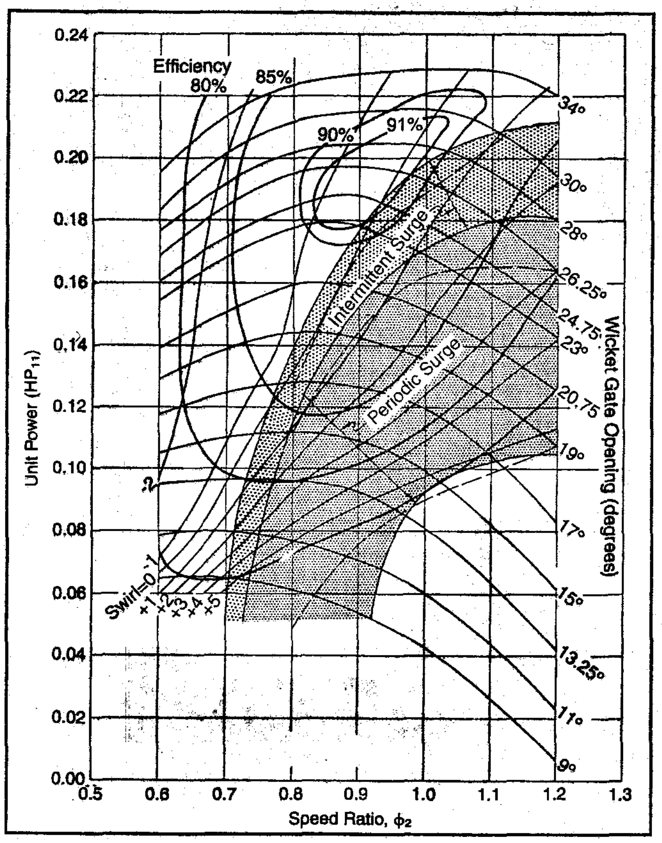


Figure 1: This figure shows the model turbine efficiency hill curve, with intermittent and periodic surging zones identified. Efficiency contours are plotted as a function of the speed ratio and unit power. Lines of constant wicket gate opening and draft tube swirl parameter are also shown on the figure.

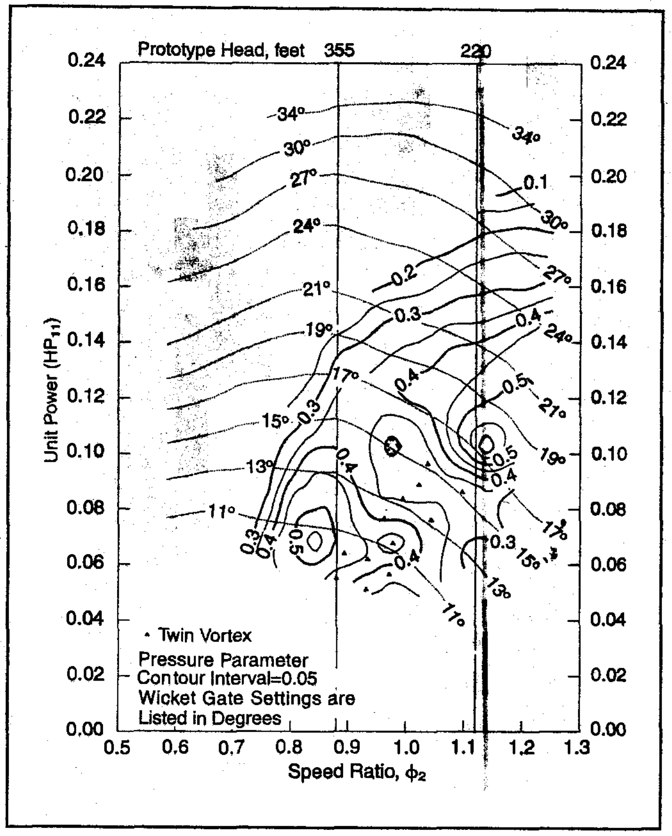


Figure 2: The pressure parameters of the draft tube surge for the 9-inch model turbine are plotted as contours. Triangles indicate points at which a sustained twin vortex surge was observed. Vertical lines indicate maximum and minimum prototype head. The twin vortex region is within the head range; thus, the twin vortex should be observed in the prototype.

with the elevation of the hill being equal to the turbine efficiency.) The hill curve shows the turbine efficiency as a function of two dimensionless parameters: the speed ratio, ϕ_2, and the unit power, HP_{11}, defined as follows:

Equation 4:

$$\phi_2 = \frac{\pi N D_2}{60\sqrt{2gH}}$$

Equation 5:

$$HP_{11} = \frac{(bhp)}{D_2^2 H^{3/2}}$$

where:

D_2 = throat diameter of the runner, feet;
bhp = brake horsepower (shaft horse power) output;
N = shaft speed, rpm; and
H = net head, feet.

Lines of constant wicket gate opening (in degrees) and draft tube swirl parameters are also shown on Figure 1.

The hill curve is a useful tool for relating model and prototype data. In the prototype, the speed of the unit is constant, so the speed ratio varies only as the head changes, with increasing head producing a lower speed ratio. In the model, we also can increase the speed to produce a higher speed ratio. In both the model and prototype, increasing the wicket gate opening produces greater power output and increases the value of HP_{11}.

During the study, the model was operated at test points throughout the part-load surging region. The tests used wicket gate openings of 9 to 34 degrees (26 to 100 percent of full gate opening) with net head maintained in the range of 110 to 130 feet for most of the tests. At a given gate setting, the runner speed was varied to allow the model to operate at the desired points on the turbine hill curve.

The clear acrylic throat section allowed me to observe the flow in the draft tube. Naturally occurring cavitation in the vortex core made the vortex visible in most cases. To minimize the effects of cavitation, pressure fluctuation data were collected with tailwater levels set as high as possible. The cavitation index, σ, was held in a narrow range, well above the critical value at which cavitation begins on the turbine runner.

Test Results

At gate openings greater than 19 degrees (56 percent of full gate opening), the part-load draft tube surge in the model was a typical single left-handed helical vortex with a precession in the same direction as the runner rotation. The precession frequency was about one-third to one-fourth of the rotational frequency of the runner. The two draft tube pressure transducers recorded strong signals at the precession frequency. These signals were 180 degrees out of phase with one another. The amplitude of pressure fluctuations and the size of the cavitated vortex core increased with increasing swirl.

At gate settings below 19 degrees, a different pattern emerged. Cavitation of the vortex core began to decrease at higher swirl values. Eventually, the single vortex was not visible at high tailwater levels, but could still be seen at low tailwater levels. Despite the loss of cavitation in the vortex core, I still detected pressure fluctuations in the draft tube at frequencies corresponding to the precession of a single helical vortex.

As the swirl increased further, the

dominant frequency of pressure fluctuations began to shift randomly between two different frequencies. The lower frequency corresponded to the precession of the single vortex. The higher frequency was generally two and one-half to three times the lower frequency. The shifts occurred at random intervals ranging from a few seconds to nearly a minute.

At gate settings of 17 to 19 degrees, the shifting between the two surge frequencies remained random, but at gate settings of 15 degrees (44 percent) and lower, the higher frequency surge became stable within a small region of the hill curve. When the tailwater was lowered, I could see two left-handed helical vortices in the draft tube. While the twin vortex was present, the pressure fluctuations at both transducer locations were in phase with one another. I observed a sustained twin vortex at 12 test points in the range of 9- to 15-degree gate openings as shown in Figure 2. Note that the twin vortex region is within the prototype operating range (from 220 to 355 feet of head). At the maximum prototype head, the twin vortex region is at about a 9-degree gate opening, while at the minimum prototype head, the twin vortex occurs at about 15-degree gate.

Figure 2 also shows the contours of the pressure parameter values, mapped onto the same axes as were used for the turbine efficiency hill curve. In general, lines of constant pressure parameter are directed diagonally across the map, from lower left to upper right. This is the same general alignment as the lines of constant swirl parameter shown in Figure 1. Thus, it appears that the pressure parameter and swirl parameters are related to one another. However, for pressure parameter values greater than 0.4, the pressure parameter lines do not maintain the diagonal alignment. Rather, there are two peaks in the pressure parameter, occurring at speed ratios of about 0.85 and 1.15. A "saddle" between the two peaks breaks up the diagonal alignment of the pressure parameter contours, disrupting the relationship between the pressure parameter and the swirl parameter. The twin vortex surging zone is located in this saddle, which falls squarely within the prototype operating range. Without the twin vortex surge, the saddle would not exist, and the two peaks would be connected to form a ridge of high pressure parameter values angling upward and to the right across the map. Overall, the effect

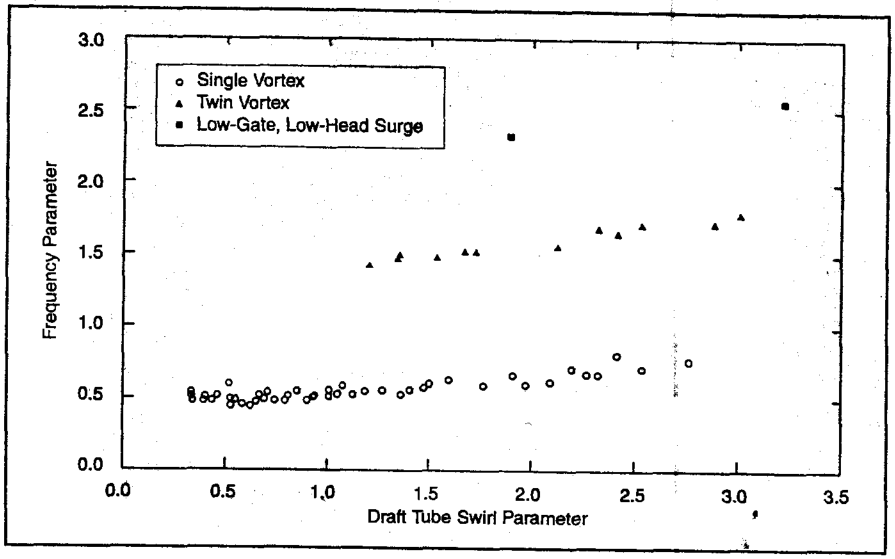


Figure 3: This graph shows the frequency parameters of the draft tube throat pressure fluctuations plotted as a function of the draft tube swirl parameter. It reveals a wide range of swirl parameters for which either the single or twin vortex surge can occur. The two additional points at the top of the graph indicate that a third type of surge also may be present. These data were collected from the 9-inch model turbine.

of the twin vortex surge is to reduce the amplitude of pressure fluctuations over a large area of the prototype operating region.

Figure 3 shows the frequency parameters plotted as a function of the draft tube swirl parameter. Over a wide range of swirl parameters, either the single or twin vortex surge can occur. Figure 2 indicates the type of surge that will occur at a given operating point on the hill curve. In the region of the 12 observed twin vortex points, a stable twin vortex will be present. Outside this region, there will be a single vortex, and on the edges there will be an unstable transition between the two modes.

Two additional points on Figure 3 indicate that a third type of surge may be present at very low gate settings and low head, outside of the prototype operating region. They occurred at a test point in the extreme lower right corner of Figure 2. Henry Falvey, president of Henry T. Falvey & Associates, Inc., has postulated that a more tightly coiled mode of the twin vortex produced these frequencies.[11] Also, they may be due to some form of triple vortex. During the twin vortex model studies, I could not confirm either theory because I could not make the vortices visible at these operating points, and analysis of pressure transducer phase relationship was inconclusive.

A review of available literature shows that other researchers have noted surge behavior similar to the twin vortex surge observed in these model tests. Model and prototype tests for the Marimbondo and Cerron Grande power plants in Brazil and additional model studies for the Grand Coulee installation all indicated unstable and higher frequency surges in operating ranges similar to those already described.[12] These plants have similar turbine/draft tube designs.

Confirming the Twin Vortex In the Prototype

In addition to my work with the model turbine, Reclamation researchers have conducted two prototype studies at Grand Coulee that revealed evidence of a twin vortex surge.[13] The first was a series of vibration signature tests conducted in December 1990 on Grand Coulee Unit G-24. The second, in December 1991, was a collection of blade strain measurements from the runner of Unit G-23.

Signature Tests, Unit G-24

The objective of the signature testing on Unit G-24 was to collect baseline data for use in making future maintenance decisions. Numerous instruments collected data including: proximity sensors at the guide and thrust bearings; accelerometers mounted near the draft tube man-door and on wicket gate stems; and pressure transducers at the draft tube and spiral case man-doors. The test procedure called for collecting data at wicket gate openings of 20 to 90 percent in 10-percent increments (30 to 790 MW). Data also were collected at speed-no-load operation and in synchro-

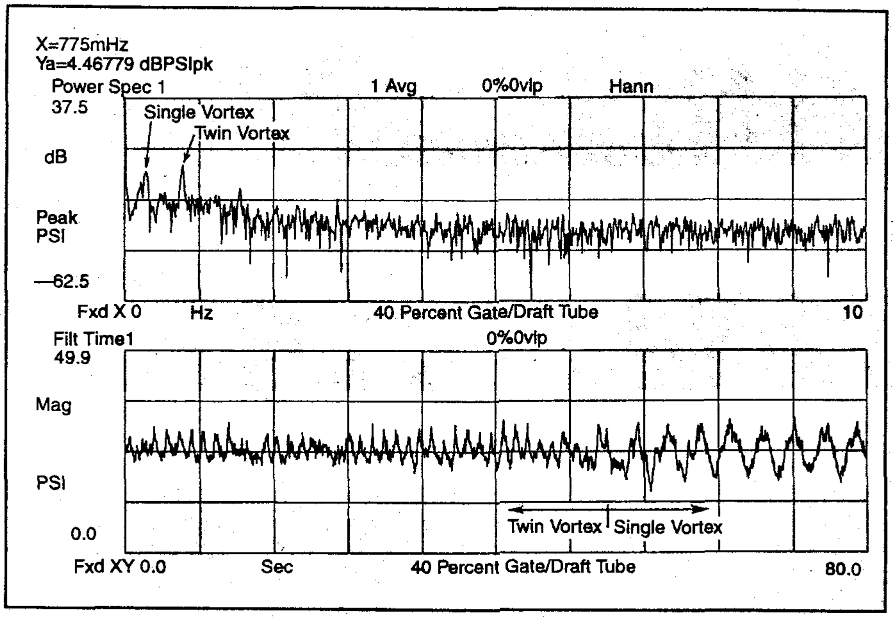


Figure 4: This graph shows the draft tube man-door pressure signal collected at 40 percent wicket gate opening during signature testing of Unit G-24 at Grand Coulee Third Powerplant. The single vortex surge has a dominant frequency of 0.29 Hz, typical of single vortex surges considered during the design of the plant. The twin vortex surge has a frequency of 0.78 Hz, about 2.7 times higher than the single vortex frequency. The figure also demonstrates the often unstable nature of the twin vortex and how quickly the surging mode can change.

nous condensing mode.

Several of the sensors recorded evidence of the twin vortex draft tube surge. At a 40-percent wicket gate opening (260 MW), the surging frequency, as seen in the pressure pulsations at the draft tube man-door, fluctuated between 0.29 Hertz (Hz), corresponding to the single vortex, and 0.78 Hz, corresponding to the twin vortex. Figure 4 shows the signal in both modes, and shows how a dramatic change in the surging behavior (switching from the twin vortex to the single vortex) can take place over a time span of a few seconds. Similar signals were recorded from the draft tube accelerometer and the proximity probes at the thrust and guide bearings. The unit's operation was not noticeably rougher or smoother with the twin vortex surge.

Blade Strain Measurements, Unit G-23

In December 1991, Reclamation researchers conducted a series of tests to collect data related to the formation of several large cracks in the runners of the 700-MW Grand Coulee turbines. These cracks were discovered during routine cavitation repair outages, and Grand Coulee maintenance personnel removed and repaired the damaged areas of several blades. We then installed 12 strain gages on the runner of Unit G-23 to measure strains and stresses in and around the welds connecting the runner blades to the runner crown.

A telemetry system transmitted data from the strain gages. Wiring from each gage ran into the hollow shaft of the unit and then through a hole drilled in the wall of the shaft at the turbine pit level. We connected each gage to a transmitter riding on the outside of the shaft. An antenna, assembled around the shaft at the transmitter location, received the data.

The unit was operated under several different conditions during a two-day period, including: speed-no-load, 120 percent overspeed, part-load surging regions, full load, and two load rejections. Ultimately, only four of the 12 gages provided useful data; only one gage survived the entire series of tests.

Because the sensor (the strain gage) traveled with the rotating impeller, the frequencies of the detected surges required adjustment using Equation 6. where:

$$f_{moving\ sensor} = n(f_s - f_p)$$

n = number of vortices in the draft tube;
f_s = shaft frequency (85.7 rpm = 1.428 Hz); and
f_p = vortex precession frequency, ($f_{stationary\ sensor}/n$).

Inserting the data from the 1990 signature tests for the values of $f_{stationary\ sensor}$ gives moving sensor frequencies of 1.14 Hz and 2.08 Hz for the single and twin vortex surges, respectively. Actual frequencies recorded by the strain gages were 2.2 Hz at 30 percent gate (twin vortex) and 1.1 Hz at 50 percent gate (single vortex). At 40 percent gate, the surge was unstable, and frequencies of 1.13 Hz and 2.27 Hz were both detected.

Although these tests showed that the twin vortex (and single vortex) draft tube surge frequencies affect the runner stresses, there was no evidence to link the observed runner cracks specifically to draft tube surging.

Summary

A twin vortex surging mode was identified in a model of the 700-MW Grand Coulee Third Powerplant Francis turbines, and subsequent prototype tests confirmed its occurrence. Effects of the twin vortex surge took many different forms in the prototype unit including: pressure fluctuations in the draft tube; vibration of the draft tube; variations in shaft runout at the guide and thrust bearings; and stress variations in the runner itself. Although there is no evidence to indicate that the twin vortex surge has been the cause of any failure or need for increased maintenance, it is an important phenomenon that should be considered in the design of new or refurbished power plants, especially if long periods may be spent in low-load operation. ■

Notes:

[1]Benjamin, T.B., "Theory of the Vortex Breakdown Phenomenon," *Journal of Fluid Mechanics,* Volume 14, 1962, pages 593-629.

[2]Sarpkaya, T., "On Stationary and Travelling Vortex Breakdowns," *Journal of Fluid Mechanics,* Volume 45, 1971, pages 545-559.

[3]Escudier, M.P., and N. Zehnder, "Vortex Flow Regimes," *Journal of Fluid Mechanics,* Volume 115, 1982, pages 105-121.

[4]Nishi, M., S. Matsunaga, T. Kubota, and Y. Senoo, "Flow Regimes in an Elbow Type Draft Tube," *Proceedings of the 11th Symposium of the IAHR/AIRH Section for Hydraulic Machinery Equipment and Cavitation*, Amsterdam, the Netherlands, 1982.

[5]Cassidy, J.J., and H.T. Falvey, "Observations of Unsteady Flow Arising After Vortex Breakdown," *Journal of Fluid Mechanics*, Volume 41, 1970, pages 727-736.

[6]Palde, U.J., *Influence of Draft Tube Shape on Surging Characteristics of Reaction Turbines*, Report No. REC-ERC-72-24, U.S. Bureau of Reclamation, July 1972.

[7]Cassidy, J.J., *Experimental Study and Analysis of Draft Tube Surging*, Report No. REC-OCE-69-5, Hyd-591, U.S. Bureau of Reclamation, October 1969.

[8]Wahl, T.L., "Draft Tube Surging Hydraulic Model Study," thesis, in partial fulfillment of the requirements for the degree of Master of Science, Colorado State University, Summer 1990.

[9]Wahl, T.L., M.M. Skinner, and H.T. Falvey, "The Twin Vortex Draft Tube Surge," *Waterpower '91, Proceedings of the International Conference on Hydropower*, Denver, Colorado, Volume III, July 1991, pages 2011-2020.

[10]Skinner, M.M., and T.L. Wahl, *Evaluation of Techniques for Detection of Cavitation on the Runner of a Model Hydraulic Turbine*, Report No. R-91-11, U.S. Bureau of Reclamation, Denver, Colorado, December 1991.

[11]Falvey, H.T., "A Primer on Draft Tube Surging," *Hydro Review*, Volume XII, No. 1, February 1993, pages. 76-86.

[12]Fisher, R.K., Jr., U.J. Palde, and P. Ulith, "Comparison of Draft Tube Surging of Homologous Scale Models and Prototype Francis Turbines," *Proceedings of the 10th Symposium IAHR/AIRH Section for Hydraulic Machinery Equipment and Cavitation*, Tokyo, Japan, 1980.

[13]Wahl, T.L., and K.W. Frizell, "Detecting the Twin Vortex Draft Tube Surge," *Hydraulic Engineering*, Proceedings of the ASCE Hydraulics Conference, Nashville, Tennessee, August 1991.

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