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# MODEL AND PROTOTYPE TURBINE DRAFT TUBE SURGE ANALYSIS BY THE SWIRL MOMENTUM METHOD

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## SYNOPSIS

Turbine draft tube surges result from excessive swirl in the flow entering the draft tube. A quantitative measure of the swirl is obtained by computing the dimensionless "momentum parameter" of the swirl, $\Omega D_3/\rho Q^2$ (where $\Omega$ is the flux of angular momentum, $D_3$ is the draft tube inlet diameter, $\rho$ is the fluid density, and $Q$ is the discharge). Turbine model study results show that surging occurs only at operating points where the momentum parameter is greater than a critical value for the particular draft tube. The method is used to identify surge-free and surging areas on model and prototype turbine performance diagrams. A prediction of the surging range and frequencies is compared to measurements subsequently obtained on the prototype.

Les ondes de surpression dans l'aspirateur de la turbine proviennent d'un tourbillonnement excessif du courant y pénétrant. Une mesure quantitative de ce tourbillon peut être obtenue en faisant intervenir le "paramêtre du moment" de ce dernier $\Omega D_3/\rho Q^2$ (où $\Omega$ est le flux du moment angulaire, $D_3$ - le diamètre à l'admission du conduit, $\rho$ - la densité du fluide, et $Q$ - la décharge). Les résultats de l'étude d'un modèle de turbine montrent que les ondes de surpression n'apparaissent qu'en certains points, là où le paramêtre du moment est plus grand qu'une certaine valeur critique pour ce genre de conduit. La méthode est utilisée pour déterminer les zônes avec et sans ondes de surpression d'après les diagrammes de fonctionnement d'un modèle et d'un prototype. L'estimation de l'importance et de la fréquence des ondes de surpression est alors comparée aux résultats obtenus ensuite sur le prototype.

## INTRODUCTION

Turbine draft tube surges arise as a result of excessive swirl remaining in the flow leaving the runner and entering the draft tube. Cassidy and Falvey [1] proposed that a dimensionless "momentum parameter,"

$$\frac{\Omega D_3}{\rho Q^2}$$

where $\Omega$ = angular momentum (moment of momentum per second)

$D_3$ = draft tube inlet diameter

$\rho$ = fluid density

$Q$ = discharge

could be used as a measure of the amount of swirl in the flow. The momentum parameter reflects the ratio of angular to linear momentum of the swirling flow. Thus, when there is no net angular momentum in the flow, the momentum parameter equals zero. Experiments indicated that for a particular draft tube shape, periodic pressure pulsations occur only above a critical $\Omega D_3/\rho Q^2$ value, and that frequencies and amplitudes, expressed in dimensionless form, were unique functions of the momentum parameter.

Cassidy and Falvey showed that the pressure pulsations are initiated simultaneously with the occurrence of the flow phenomenon known as "vortex breakdown." After vortex breakdown has taken place, the flow is characterized by a spiraling (helical) vortex and reverse flow along the axis. The spiraling vortex produces periodic, high-intensity pressure fluctuations in the tube. Evaluation of the momentum parameter for the swirl in the flow leaving a Francis turbine runner was first presented by Falvey and Cassidy [2] in 1970. The effect of the draft tube shape on surge frequencies and amplitudes was thoroughly investigated and reported by Palde [3]. All experimental work in connection with the above studies was performed at the Bureau of Reclamation laboratories on a special model where the swirl could be easily controlled and measured, using air as the fluid.

## METHOD OF ANALYSIS AND COMPUTATION

The evaluation of the momentum parameter for the flow entering a turbine draft tube consists of computing the dimensionless momentum flux introduced by the wicket gates and subtracting the amount of momentum flux converted to torque by the runner,

$$\frac{\Omega D_3}{\rho Q^2} = \left(\frac{\Omega D_3}{\rho Q^2}\right)_{W.G.} - \left(\frac{\Omega D_3}{\rho Q^2}\right)_r \qquad (1)$$

$$\text{where } \left(\frac{\Omega D_3}{\rho Q^2}\right)_{W.G.} = \frac{D_3 R \sin \alpha}{BNS} \qquad (2)$$

$$\text{and } \left(\frac{\Omega D_3}{\rho Q^2}\right)_r = \frac{P D_3}{\rho \omega Q^2} \qquad (3)$$

The symbols used in Equation (2) are defined in Figure 1.

In Equation (3),

- $P$ = turbine power output
- $\rho$ = density of water
- $\omega$ = angular velocity of the turbine
- $Q$ = discharge through the turbine

The direction of flow through the gates is defined to be perpendicular to the minimum space between the tail of a gate and the body of the adjacent downstream gate. R, $\alpha$, and S are evaluated for several gate positions using a graphical gate layout, and the results can be used to construct the curves shown in Figure 2a. The entire term $D_3 R \sin\alpha / BNS$ can be evaluated for each gate opening, resulting in a single wicket gate momentum parameter curve shown in Figure 2b. The shape of the curve is a function of the particular wicket gate shape and layout.

Inspection of Equations (1), (2), and (3) reflects the advantage of employing the momentum parameter method to define the amount of swirl in the flow. The momentum parameter can be computed if the wicket gate layout and shape are known, and the performance characteristics of the turbine are available. The procedure is much simpler than direct measurement on a model of the entire velocity vector distribution in the flow entering the draft tube. The method, however, does not always yield accurate results. Much of the inaccuracy is thought to be due to the oversimplification inherent in the graphical method of determining the angular momentum of the flow through the wicket gates. Laboratory studies of flow through the wicket gates are being planned to determine how the accuracy of the momentum parameter method could be improved.

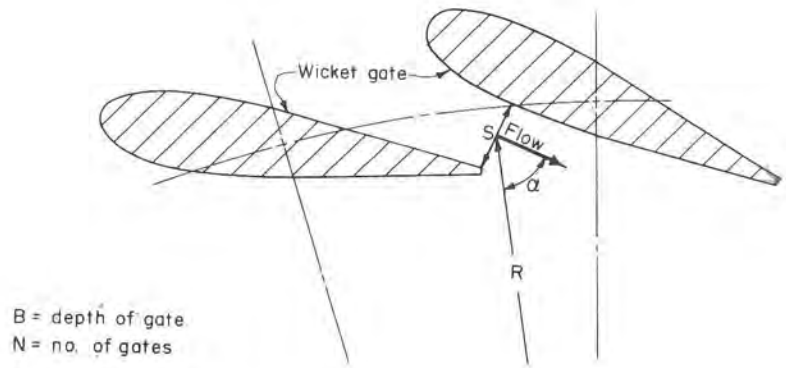
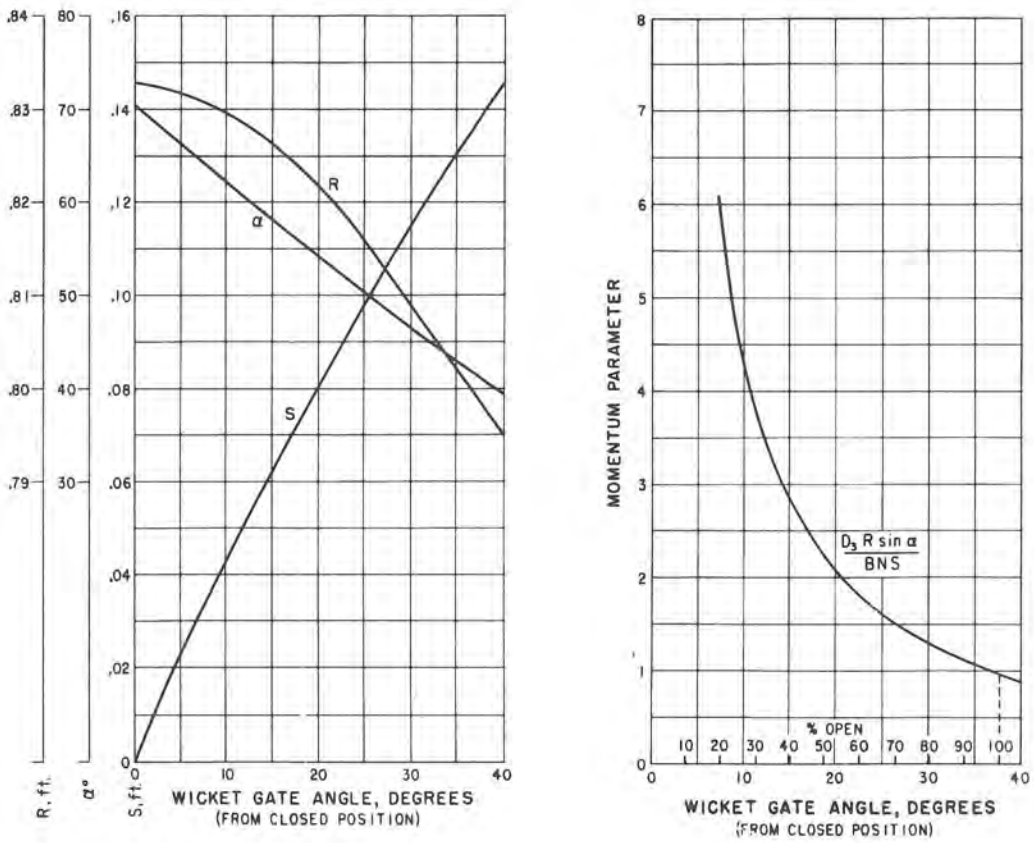



Figure 1. Definition sketch of flow leaving wicket gates and entering turbine runner.




a. Variation of R, α, and S with wicket gate angle.

b. Wicket gate momentum parameter as function of gate angle.

Figure 2. Wicket gate geometric characteristics for Grand Coulee Pumping Plant pump turbines (Units 7 and 8).

## TURBINE MODEL STUDIES

The Bureau of Reclamation recently installed a high head model turbine test stand at its Estes Powerplant in Colorado. A 40.333 scale model (9" throat diameter) of the Francis turbines for the first three 600 MW units of Grand Coulee Third Powerplant was initially installed in the stand. Dominion Engineering Works of Montreal designed the turbine and built the model. The primary emphasis during the initial tests performed during 1973 was on draft tube surge investigations.

### Model Test Data

Data were obtained to evaluate performance characteristics using an automatic data acquisition and computation system. Draft tube pressures were measured at two locations in the throat by means of piezometers and pressure transducers. The pressure output signal was recorded by an oscillograph. The signal was also monitored on a retentive-screen oscilloscope, allowing for convenient determination of surge frequencies. Amplitude of pressure fluctuations was monitored on a root-mean-square meter.

For each model turbine test point the combination of Equations (1), (2), and (3) was used to compute the momentum parameter:

$$\frac{\Omega D_3}{\rho Q^2} = \frac{D_3 R \sin\alpha}{BNS} - \frac{PD_3}{\rho\omega Q^2} \qquad (4)$$

The dimensionless frequency parameter

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

and the dimensionless pressure parameter

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

as well as the root-mean-square pressure $\sqrt{\overline{(P')^2}}$ as percent of net test head, were also computed for each run.

### Range of Surging in Model

Although the model could be tested under the prototype range of net heads of 67 meters to 108 meters, most of the tests were performed at lower than prototype heads. The speed coefficient

$$\phi_2 = \frac{\pi D_2 n}{60\sqrt{2gH}} \qquad (5)$$

where $D_2$ = runner throat diameter

$n$ = rotational speed in RPM, and

$H$ = net head across turbine

was used as the independent test point variable. From the test results it was verified that at a given opening and a particular value of $\phi_2$ the same value of $\Omega D_3/\rho Q^2$ is computed by Equation (4) for any combination of rotational speed and head yielding the given $\phi_2$ value. In other words, the momentum parameter is a function of the gate opening and $\phi_2$. The characteristic momentum parameter contours (plotted, for instance, on a specific power, $P_{11}$, vs $\phi_2$ diagram) can therefore be obtained from tests at any head. The range of surging is then defined by the $\Omega D_3/\rho Q^2$ contour above which surging occurs for the particular draft tube being used. Figure 3, plotted from the results of the Grand Coulee model draft tube surge tests, illustrates the above principle. The critical momentum parameter value in the model was observed to vary between about 0.31 and 0.34, depending on gate opening and the cavitation factor, sigma. A critical momentum parameter value of 0.33 has been used in Figure 3 to delineate the periodic surge area.

Range of Surging in Prototype

Equation (4) can be applied to the prototype in the same manner. The wicket gate momentum parameter curve derived from Equation (2) is the same for the model and the prototype, since it depends entirely on geometry. The first term on the right of Equation (4) is therefore already known for all gate openings. The second term is evaluated from prototype quantities stepped up from model data. Instead of presenting the predicted prototype draft tube surges for the Grand Coulee 600 MW turbines, a prediction (using the same method) for the Grand Coulee Pumping Plant Pump-Turbines, for which comparative data from actual prototype operation are available, is presented later in the paper.

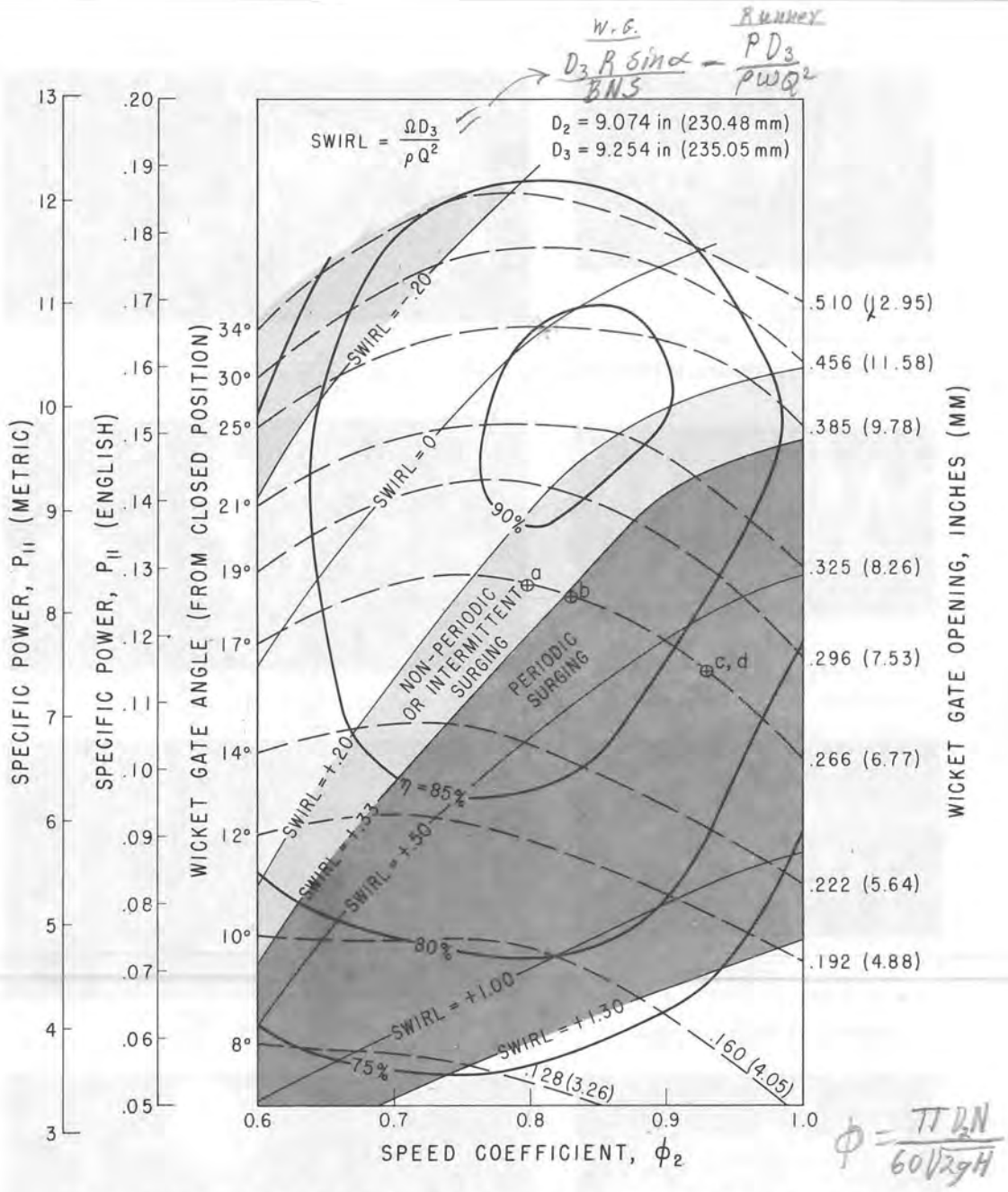
Effect of Draft Tube Vortex Core on Surging

A visible vortex core below the turbine runner at certain gate openings and operating conditions is commonly accepted as somehow related to the occurrence of draft tube surging. The association is valid only in this respect: If a hollow vortex core is present, its instability and draft tube surging are one and the same occurrence. This fact offers no information, however, about the operating points at which surging will occur.

Observations of flow in the draft tube over a wide range of test conditions disclosed that a hollow vortex core in the flow below the runner was neither necessary now sufficient for draft tube surging to occur. Rather, the model studies indicated that the intensity of swirl (as measured by the value of the momentum

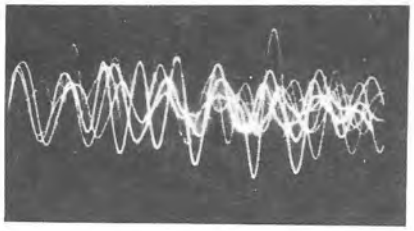


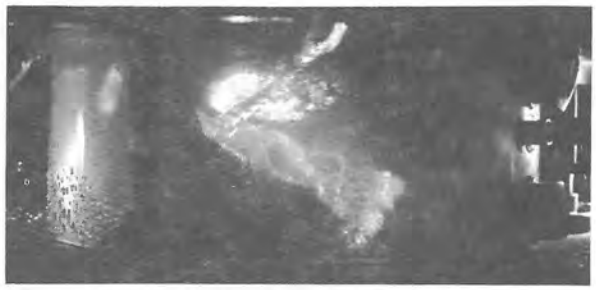
$P_{11} = \frac{BHP}{H^{3/2} D^2}$




GRAND COULEE THIRD POWER PLANT UNITS 19, 20, 21
DEW 9" MODEL TURBINE

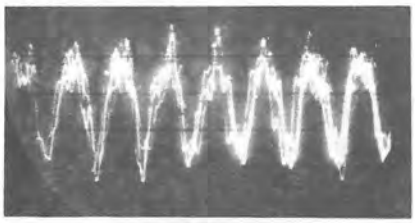
Figure 3. Range of surging as determined from model tests of the Grand Coulee Third Powerplant 600 MW turbines (model scale 1:40.333).





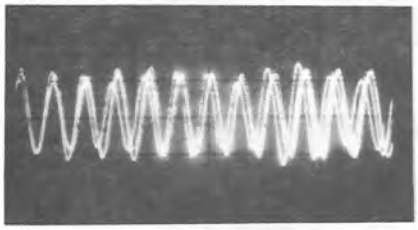
$f = ?, \sqrt{\overline{(P')^2}} = 0.8\%$ of H

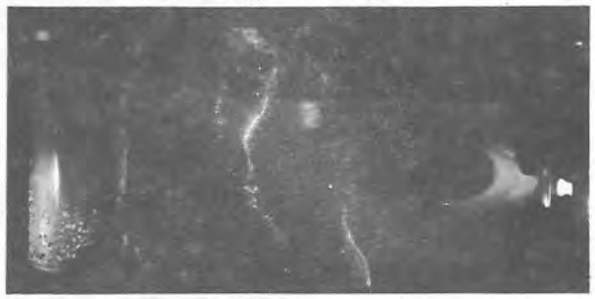
a. Irregular pressure pulsations. $\Phi_2 = .80$, $\delta = .12$, $\frac{\Omega D}{\rho Q^2} = .27$, $\frac{fD^3}{Q} = ?$



$f = 7.8$ Hz, $\sqrt{\overline{(P')^2}} = 0.7\%$ of H

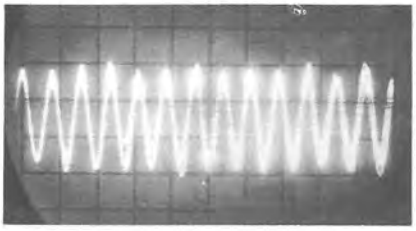
b. Surging at critical swirl. $\Phi_2 = .83$, $\delta = .12$, $\frac{\Omega D}{\rho Q^2} = .33$, $\frac{fD^3}{Q} = .34$

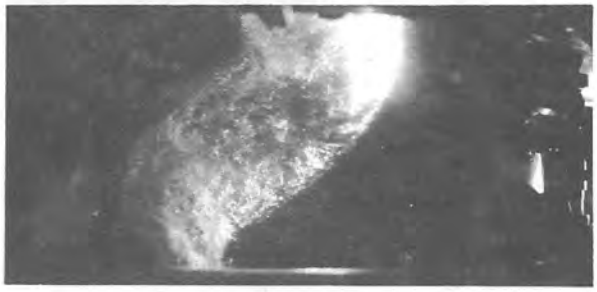




$f = 12.0$ Hz, $\sqrt{\overline{(P')^2}} = 2.1\%$ of H

c. Surging at high tailwater. $\Phi_2 = .93$, $\delta = .26$, $\frac{\Omega D}{\rho Q^2} = .58$, $\frac{fD^3}{Q} = .52$





$f = 13.0$ Hz, $\sqrt{\overline{(P')^2}} = 2.5\%$ of H

d. Surging at low tailwater. $\Phi_2 = .93$, $\delta = .10$, $\frac{\Omega D}{\rho Q^2} = .59$, $\frac{fD^3}{Q} = .54$

Figure 4. Photos of draft tube wall pressure fluctuation traces displayed on a retentive oscilloscope screen, and corresponding flow conditions. Wicket gates at 17°, or approximately 45% of rated output gate.

parameter) was clearly the governing factor for the occurrence of surging. Figure 4 illustrates some relationships between the vortex core and surging. Figure 4b. shows a hollow vortex core which appears to be vertical. However, the vortex does in fact deflect toward the wall (thus becoming a spiraling vortex) farther downstream in the draft tube, producing low amplitude pressure pulsations throughout the tube. At lower momentum parameter values (between about 0.10 and 0.20) a vertical hollow core exists at some gate openings and sufficiently low tailwater values. The overall swirl is not high enough, however, to deflect the vortex core, and thus surging does not occur. The condition shown in Figure 4c., with higher swirl, produces high amplitude surging without the presence of a hollow vortex core. Figure 4d. shows flow conditions with the same amount of swirl as in 4c., but with lower tailwater producing a highly visible, spiraling hollow vortex core. The above operating points have been marked on the model hill curves, Figure 3, with letters on the plot corresponding to letters designating the photos in Figure 4.

PROTOTYPE SURGE ANALYSIS

The swirl momentum method was used to predict the surging characteristics of the Grand Coulee Pumping Plant Pump-Turbines, Units 7 and 8. Performance and draft tube surge test data from a homologous model were available from the model test report of the manufacturer, NOHAB of Trollhättan, Sweden. Additional surging characteristic data for the particular draft tube shape were obtained with the Bureau of Reclamation simplified air model. The relationships between the

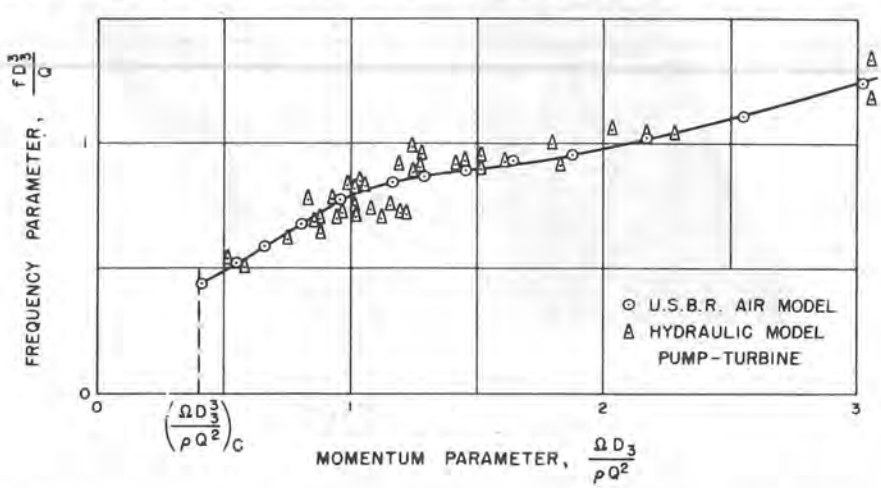



Figure 5. Frequency parameter curve for the Grand Coulee Pump-Turbine draft tube computed from two independent model tests.

mementum and frequency parameters determined from the two tests are shown in Figure 5. The critical momentum parameter value was found to be between about 0.4 and 0.5, but a value of 0.40 has been used in this application.

Method of Computation from Model Data

The value of the momentum parameter for each point of computation was determined from Figure 2b. In the second term P and Q were obtained from expected prototype quantities given in the NOHAB model test report. The computed value of the momentum parameter for each point was entered in Figure 5 to obtain the value of the frequency parameter, $fD_3^3/Q$, from which the frequency was determined. Figure 6 shows the results of the surging prediction. Surging is expected to occur over the dark shaded areas, where the value of the momentum parameter is greater than 0.40 (absolute value). Intermittent periodic and/or irregular high amplitude pressure pulsations can be expected to occur between contours of about 0.25 and 0.40 (absolute value), the light shaded areas in the figure.

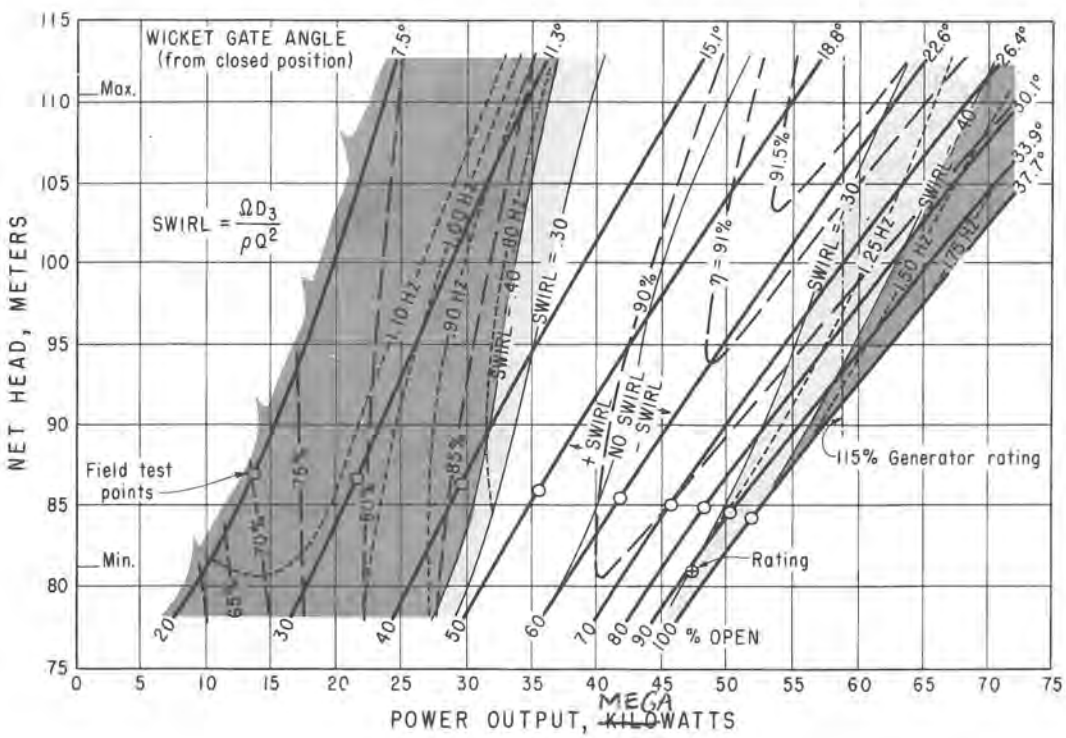



Figure 6. Expected turbine performance and predicted draft tube surge range and frequencies for the Grand Coulee Pump-Turbines.

Prototype Field Tests

Draft tube surge test data were obtained at several gate settings over the entire operating range, at a gross head of about 87 meters (286 feet). The test points are shown as circles on the plot of Figure 6. The predictions and results of the field tests are compared in the table below.

| RUN NO | GATES % | GATES DEGREES | PREDICTED SURGE | PREDICTED FREQ. (Hz) | MEASURED SURGE | MEASURED FREQ. (Hz) |
|---|---|---|---|---|---|---|
| 1 | 14 | 5.2 | YES | ? | NO | — |
| 2 | 20 | 7.4 | YES | 1.10 | YES | .70 |
| 3 | 30 | 11.3 | YES | 1.07 | YES | 1.30 |
| 4 | 40 | 15.1 | YES | .85 | YES | 1.47 |
| 5 | 50 | 18.8 | NO | — | YES | 1.14 |
| 6 | 60 | 22.6 | NO | — | NO | — |
| 7 | 70 | 26.4 | NO | — | NO | — |
| 8 | 80 | 30.1 | NO | — | NO | — |
| 9 | 90 | 33.9 | INTERM. | 1.25 | NO | — |
| 10 | 100 | 37.7 | INTERM. | 1.50 | NO | — |

The measured range of surging at about 87 meters net head extends to slightly higher gate openings than the predicted range. Measured frequencies are higher than those predicted (by as much as 75 percent at 40 percent gate) over most of the surging range. It should be noted that for this turbine (n = 200 rpm) the well-known Rheingans [4] formula, $f = n/(60 \times 3.6)$, predicts a surge frequency of 0.93 Hz. The above comparison may therefore be considered good in relation to the available knowledge of surge frequency prediction.

IMPROVEMENTS NEEDED IN THE METHOD

The above example is the first known instance where predicted surge computations using the swirl momentum method were checked in the field. The comparison indicates that the method needs improvement. This has been confirmed by recent computations for model turbines also, where the surging range predicted by application of Equation (4) did not agree with observations in the model.

The most likely cause for the disagreement can be attributed to the evaluation of Equation (2), i.e., the curve in Figure 2b. On examining the definition sketch in Figure 1 it is evident that the effective values of R and $\alpha$ (and possibly S) could be considerably different than those obtained from the simplified graphical analysis, which does not take into account the influence of upstream conditions.

Stay vanes could certainly influence the flow direction. Circulation arising from flow through the spiral case could also influence the angular momentum of the flow.

A correct evaluation of the wicket gate momentum parameter curve is absolutely necessary for usefulness of the momentum parameter method. Experimental or improved analytical methods could be employed to achieve the desired accuracy. A study to better define the flow through the wicket gates is presently in progress at the Bureau of Reclamation.

The effect of an improved momentum parameter curve can be applied qualitatively to the surge prediction for the case of the Grand Coulee Pump-Turbines. A momentum parameter curve (Figure 2b) giving values only about 0.25 to 0.30 higher in the vicinity of 50-percent gate would have produced a prediction agreeing much more closely with the field measurements. The range of surging would cover the field test point at 50-percent gate, as it should. The predicted frequencies would be about 20 percent higher. Also, the computed zero swirl line shown in Figure 6 would fall to the right of the efficiency contour peaks, as it probably should.

## FUTURE APPLICATIONS

The swirl momentum method can be improved to produce better predictions of prototype surging. Even with present limitations, the method can be used to evaluate proposed changes in turbine design directed toward increasing the surge-free operating range of Francis turbines. Equation (4) relates turbine dimensions or quantities affecting the value of the momentum parameter, i.e., the amount of swirl. Continued investigations may disclose how flow passages may be shaped to reduce the swirl in common turbine operating areas, thus increasing the surge-free operating range.

## CONCLUSION

The swirl momentum method is a useful tool for the analysis and prediction of surging characteristics of prototype Francis turbines. The accuracy of the method must be improved, however, before it can be applied with full confidence for prototype predictions.

ACKNOWLEDGMENT

Appreciation is expressed to Fred Ruud, Bureau of Reclamation, for his special effort in obtaining the field data needed for the comparison of the Grand Coulee Pump-Turbine surging characteristics. The data were obtained on Unit 7 during acceptance tests in November 1973.

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