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INFLUENCE OF DRAFT TUBE SHAPE ON SURGING CHARACTERISTICS

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R205563 72A DRAFT TUBE SHAPE INFLUENCES SURGING CHARACTERISTICS

Draft tube surges were noted in hydroelectric plants before the surging was found to be caused by a flow phenomenon known as vortex breakdown. During 1940, Rheingans summarized experiences and presented an equation for estimating the expected frequency of surging. Investigators now accept the fact that the draft tube surge is a hydrodynamic instability occurring in the draft tube as a result of rotation remaining in the fluid as it leaves the turbine runner and enters the draft tube throat. Experimental analysis and laboratory procedures are discussed. Draft tube shapes were studied and surge data obtained for over 50 distinct draft tube shapes. Conclusions are: (1) degree of divergence of a draft tube is the most significant geometric feature affecting surging characteristics; (2) surging can be minimized by using an equivalent expansion angle of about 15 deg through the entire length of the draft tube; and (3) resonance with known natural frequencies of other features of the powerplant can be checked using results presented. Resonance can be avoided by selecting proper geometric components in draft tube design.

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IDENTIFIERS--

INFLUENCE OF DRAFT TUBE SHAPE ON SURGING CHARACTERISTICS

By Uldis J. Palde, 1/ A.M. ASCE

INTRODUCTION

Draft tube surges were noted in hydroelectric plants long before it was determined that the surging could be attributed to the flow phenomenon known as "vortex breakdown." Rheingans (12) 2/ related and summarized the experiences gained in several installations as early as 1940. He presented a plot of observed frequency versus turbine rotational speed and proposed the equation

$$f = \frac{n/60}{3.6}$$

for the expected frequency (hz) of the surge at the maximum pressure fluctuation, where n is the rotational speed in revolutions per minute. The Rheingans equation is frequently applied to obtain an estimate of expected frequency of surging.

Although it can now be shown that surging flow will occur in every reaction turbine installation over some range of partial load or overload operation, this was not necessarily assumed at one time by designers. Rather, the problem was hopefully expected not to occur in common operating ranges, and as a result, little analytical or experimental model work was reported in the literature.

In installations where the draft tube surging produced power swings or penstock vibrations due to resonance, or simply objectionable vibration and noise, remedial measures were taken in the field. These measures often included the installation of vertical vanes in the draft tube throat. The admission of air below the runner was also discovered to reduce the amplitude of the surging. Both methods (particularly the vanes) can result in reduced efficiencies.

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2/Numerals in parentheses refer to corresponding items in Appendix I. - References.

Recently the vortex breakdown phenomenon has attracted considerable attention in the published work of Benjamin (1), Chenaud (4,5), Squire (13), Harvey (10), and Gore and Rantz (9). Studies of vortex breakdown as related specifically to draft tube surges have been reported by Deriaz (6), Dziallas (7), and Hosoi (11). Investigators now generally accept that the draft tube surge is a hydrodynamic instability which occurs in the draft tube as the result of rotation remaining in the fluid as it leaves the turbine runner and enters the draft tube throat.

The experimental work presented in this paper is a continuation and expansion of the studies reported by Cassidy and Falvey (3,7). Analytical studies, experimental equipment and technique development, and application to prototype turbines were described in detail in a Bureau of Reclamation report by Cassidy (2).

ANALYSIS

Dimensionless parameters were derived by Falvey and Cassidy (7) to help generalize experimental results of surging flow in a draft tube. It was assumed that for a particular draft tube shape the frequency f and root-mean-square (RMS) amplitude $\sqrt{\overline{(p')^2}}$ of the surge are both functions of the density ρ and the viscosity ν of the fluid, the diameter D and length L of the draft tube, the discharge Q, and the flux of the moment of momentum (angular momentum) Ω. Dimensional analysis yielded the following functional relationships:

pressure parameter $$\frac{D^4\sqrt{\overline{(p')^2}}}{\rho Q^2} = \phi_1\left(\frac{\Omega D}{\rho Q^2}, \frac{L}{D}, \mathbb{R}\right)$$

and

frequency parameter $$\frac{fD^3}{Q} = \phi_2\left(\frac{\Omega D}{\rho Q^2}, \frac{L}{D}, \mathbb{R}\right)$$

where $\mathbb{R}$ is the Reynolds number $4Q/\pi D\nu$.

$\Omega D/\rho Q^2$ is referred to as the momentum parameter and is a ratio of angular momentum flux to linear momentum flux. In applying it to the experimental study, the assumption was made that regardless of the manner in which angular

momentum is introduced into the flow, the resulting surging characteristics will be the same for a particular value of $\Omega D/\rho Q^2$. The frequency parameter is a form of the Strouhal number fD/v (v is the axial velocity), written in terms of discharge.

Based on his initial experimentation with a simplified model using air as the fluid, Cassidy (2) concluded that

1. For a given draft tube shape there is a critical value of $\Omega D/\rho Q^2$ above which surging flow exists.
2. The frequency and pressure parameters can be correlated with the momentum parameter for a given draft tube shape.
3. Frequency and RMS pressure values of the surging flow are independent of viscous effects for Reynolds numbers above approximately 80,000. (Prototype Reynolds numbers greatly exceed 80,000).

The momentum parameter $\Omega D/\rho Q^2$ can be computed for a turbine if the runner diameter, wicket gate geometry, and the performance characteristics are known. If we start with the basic expression for power,

$$P = \omega T \tag{1}$$

where ω is the angular velocity and T is torque, and substitute

$$T = \Omega_1 - \Omega_2 \tag{2}$$

where $\Omega_1 - \Omega_2$ is the rate of change of moment of momentum of the flow as it passes through the runner, we obtain

$$\frac{P}{\omega} = \Omega_1 - \Omega_2 \tag{3}$$

Multiplying Equation (3) by $D/\rho Q^2$ and rearranging terms,

$$\frac{\Omega_2 D}{\rho Q^2} = \frac{\Omega_1 D}{\rho Q^2} - \frac{PD}{\rho \omega Q^2} \tag{4}$$

The left side of Equation (4) is the momentum parameter associated with the flow at the draft tube throat. The first term on the right of the same equation is the momentum parameter of the flow leaving the wicket gates and entering the turbine runner and can be computed by

$$\frac{\Omega_1 D}{\rho Q^2} = \frac{DR \sin\alpha}{BNS} \tag{5}$$

Equation (5) shows that $\Omega_1 D/\rho Q^2$ is entirely a function of wicket gate geometric variables (defined in Fig. 1), and the draft tube throat diameter.

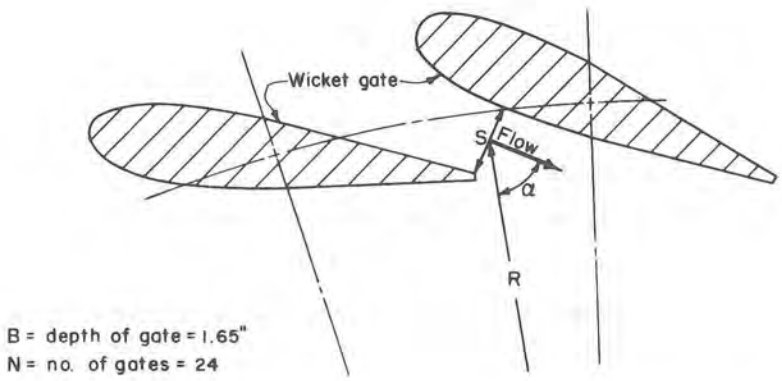


Fig. 1. - Definition sketch of flow leaving wicket gates.

The second term of Equation (4) can be computed from performance characteristics of the turbine. Combining Equations (4) and (5), we obtain

$$\frac{\Omega_2 D}{\rho Q^2} = \frac{DR \sin\alpha}{BNS} - \frac{PD}{\rho\omega Q^2} \tag{6}$$

which can be evaluated for prototype or model turbines from data normally obtained during performance tests.

LABORATORY MODEL

Laboratory experiments were conducted with air as the fluid and a model (Fig. 2) consisting of some of the components of an actual model turbine.

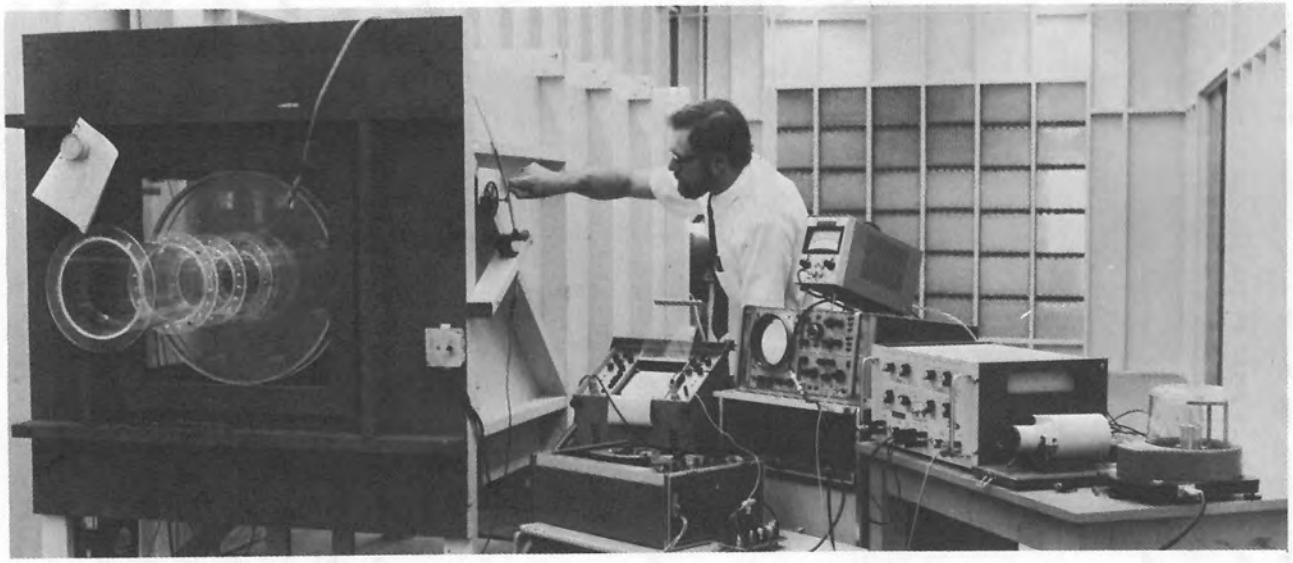


Fig. 2. - Laboratory air model and instruments

The spiral case, stay vanes, and runner were removed. The wicket gates remained and served to produce swirl in the flow as it passed from a symmetrical pressure chamber into the draft tube (Fig. 3). Radial inclination of the gates could be set at any angle between 0° (radial) and 82° (closed).

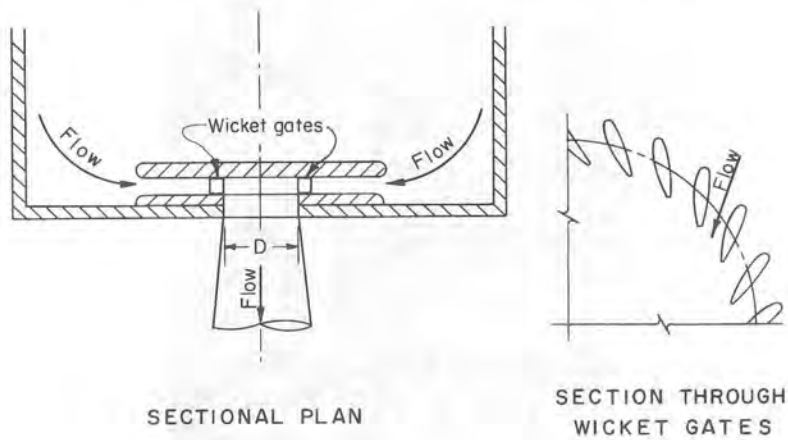


Fig. 3. - Schematic of laboratory air model.

The momentum parameter of the flow leaving the wicket gates and entering the draft tube could be computed by the same expression (Equation 5) used to compute the momentum parameter of the flow entering the runner in a complete turbine. In the simplified model the moment of momentum remains constant and therefore also the momentum parameter at the draft tube throat does not change from that existing at the wicket gate openings.

The computation of the pressure and frequency parameters required the measurement of discharge and the frequency and RMS pressure of the draft tube surges. The rate of discharge was controlled at the wicket gate openings and varied as the gate opening area varied with changes in the gate setting. The discharge was measured by a differential orifice located in the inlet pipe to the pressure box. Pressure differential across the orifice was

measured with a pressure cell and conditioned by and recorded on one channel of a dual-channel recorder-amplifier. The various plastic draft tubes had piezometer taps at several locations along the walls to which a pressure cell with a short piece of flexible tubing could be attached for dynamic pressure pickup. The signal was conditioned by the second channel of the recorder-amplifier and fed through a band-pass filter to an oscilloscope and RMS meter. Frequencies of the unsteady pressure were determined on the retentive screen of the oscilloscope. The instrumentation is shown in Fig. 2.

LABORATORY PROCEDURE

The values of R, S, and α defined in Figure 1 vary with the gate orientation. The quantities were carefully measured or graphically determined for numerous gate angle settings, and tables for use in computations were prepared from the smoothed curves of R, S, and α versus gate angle. The value of the momentum parameter for a particular gate setting could then be readily computed using Equation (5).

For a particular draft tube, the range of gate settings for which surging flow could be detected was first noted, as well as the approximate maximum and minimum frequencies. If the frequency range was not too great, the high- and low-pass circuits on the band-pass filter were set somewhat outside this range. Occasionally the frequencies varied greatly and the band-pass was set to include most of the frequencies encountered and then later adjusted as required.

For a particular gate setting, a given draft tube surges at the same frequency throughout the entire tube (with a few notable exceptions). The amplitude, however, varies at different locations along the tube wall. Data were generally taken at a location where amplitude was maximum, since the frequency was best defined at that location.

During one complete run the gate setting was repeatedly changed by small increments. Values of the discharge and RMS pressure signals were

recorded and the frequency read from the oscilloscope for each gate setting. The data, along with amplifier attenuation factors, air density, and descriptive information were recorded on data sheets suitable for ADP card keypunch use. The dimensionless parameters and other flow variables were computed by computer. Frequency and pressure parameter versus momentum parameter curves were plotted on an on-line cathode-ray tube and photographed on 35-mm microfilm for later copying and convenient storage. The graphs used in Fig. 4 through 13 are computer generated.

DRAFT TUBE SHAPES STUDIED

Surge data were obtained for over 50 distinct draft tube shapes. A few were actual models of draft tubes with minor modifications. The greater majority, however, were simple geometrical shapes or combinations thereof consisting of straight circular cylinders, truncated diverging cones, and circular cross-section elbows. These shapes are representative of the shape components found in most draft tubes. The diameter, length, and angle of divergence were varied.

A minor limitation on the draft tube shapes studied was imposed by the model itself. The downstream face of the pressure chamber had a thickness of 1.93 inches (see Fig. 3) in which a circular opening of 6.13 inches in diameter was provided for the outflow. A short, circular cylinder thus existed as a geometrical component upstream of any shapes tested (which were attached by means of a flange to the outer face of the pressure box). To eliminate the cylindrical section, a machined plastic insert of the required inside dimensions had to be positioned in the opening. In many instances, however, the 1.93-inch length of constant diameter opening was included as the upstream component of the total draft tube shape.

RESULTS

Some of the more significant results are included as plots of the dimensionless parameters in Fig. 4 through 13. In most cases the surging characteristics of several shapes are compared in the same figure. The

presence of an asterisk (*) in the legend below the graphs indicates that the described shape was downstream of a short, circular cylinder either 6.13 inches (see Fig. 4, Run 62) or 3.50 inches in diameter (see Fig. 8).

Fig. 4 shows the surging characteristics of three draft tubes. The throats of both variations of the Fontenelle draft tube were modified from the actual prototype geometry. The Grand Coulee pump-turbine draft tube is geometrically similar to the prototype. Its cross-section is circular for the entire length. For all three draft tubes the frequency and pressure parameters initially increase with an increase of the momentum parameter. This was typical of all tubes tested. For some tubes the pressure parameter continues increasing monotonously while for others one or more peaks occur. Most tubes surge over a finite range of moment parameter, as is the case with the two variations of the Fontenelle draft tube. Others, like the Grand Coulee pump-turbine draft tube, surge continuously up to the point of complete wicket gate closure, where the momentum parameter approaches infinity. A slight variation of the Fontenelle throat geometry produces significant changes in the surge parameter values, but does not change the range of surging. Removal of the piers and progressively sections of the downstream end of the draft tube has little effect on the surge parameters. A short tube including only the first 30 degrees of the elbow has only slightly different characteristics than the entire draft tube (see Fig. 5).

Simple sections of truncated 15 degree-cones surge over a smaller range of momentum parameter and display lower frequencies and amplitudes than the draft tubes (see Fig. 6). The frequencies measured from the cones were far less well defined than those from any other shape. Different inlet diameters and L/D ratios have only slight effect on the dimensionless surge parameters. Fig. 6 also verifies the validity of the dimensional analysis.

Straight cylindrical tubes display surging characteristics quite different from those of expanding cones (see Fig. 7). Short sections

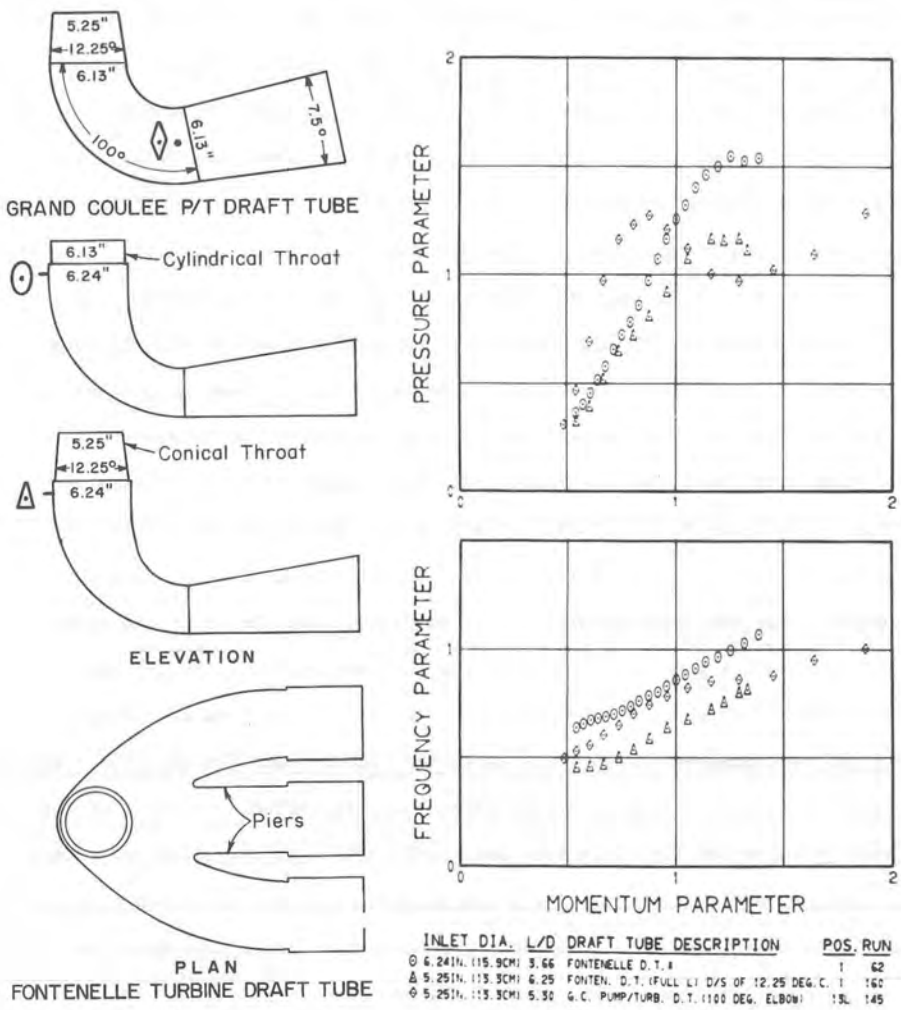


Fig. 4. - Surging characteristics of three model draft tubes.

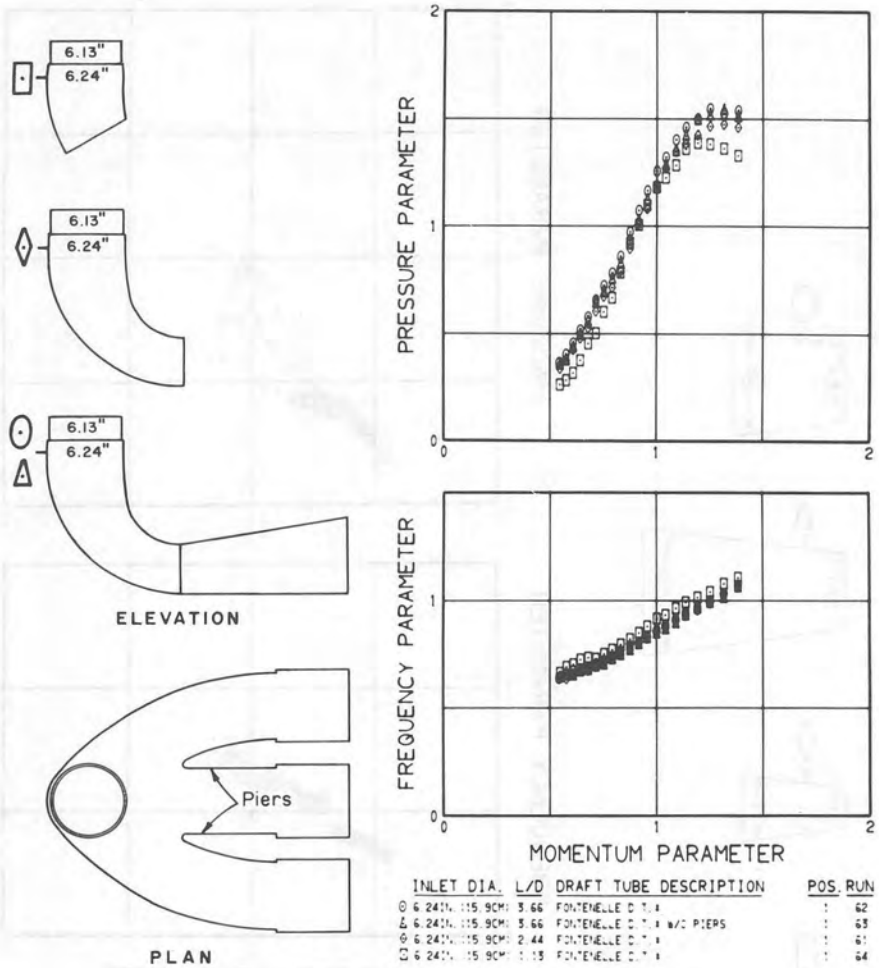


Fig. 5. - Effect of pier elimination and draft tube shortening on surging characteristics of Fontenelle draft tube.

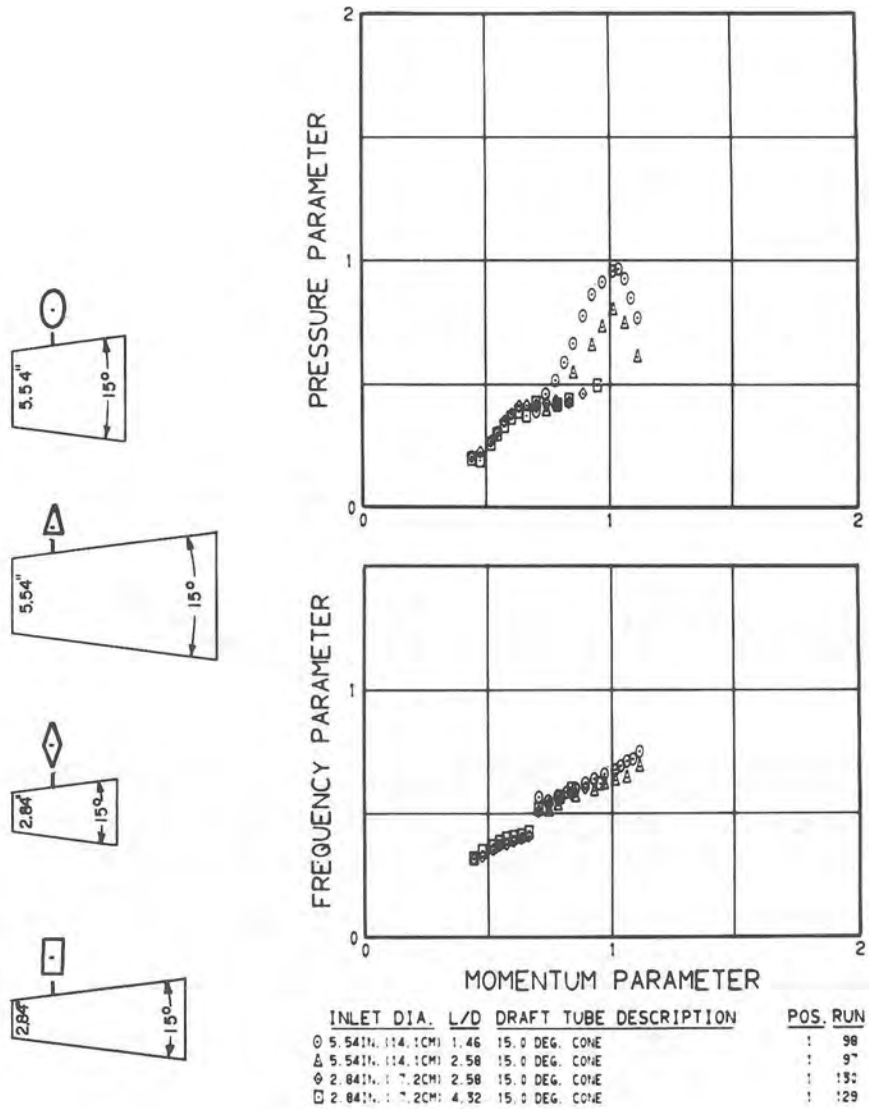


Fig. 6. - Surging characteristics of 15 degree truncated cones.

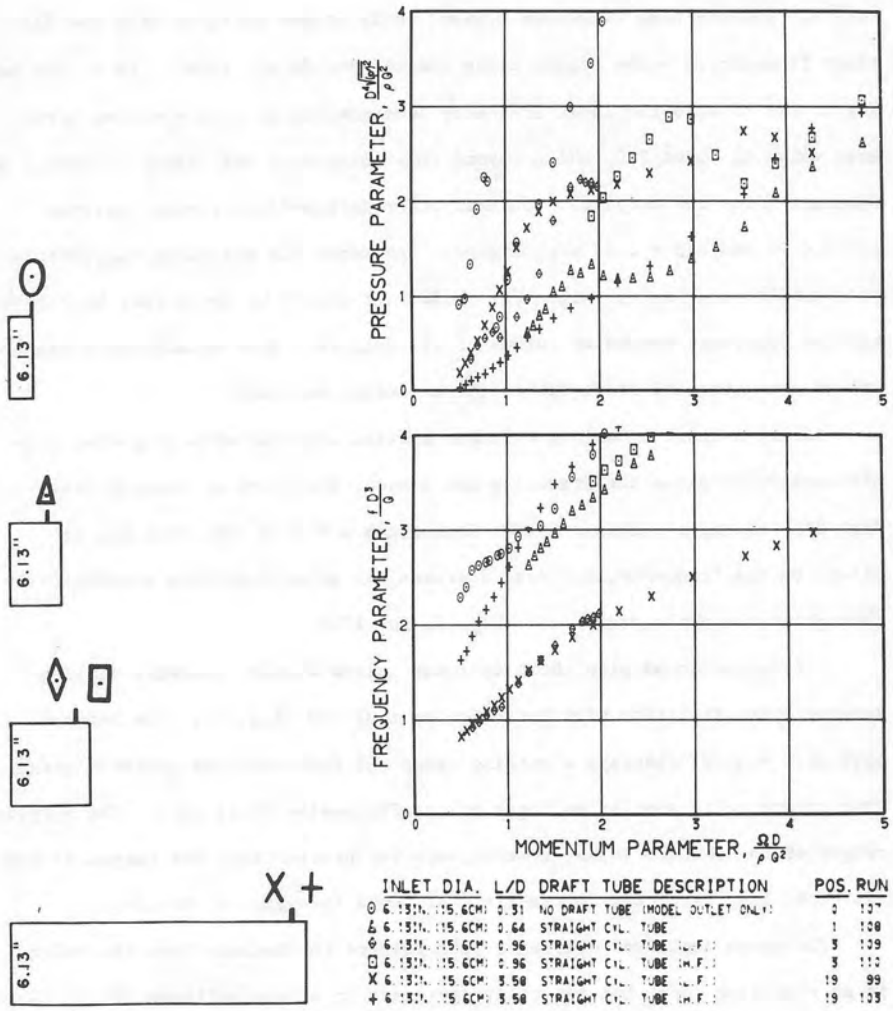


Fig. 7. - Surging characteristics of circular cylinders.

(L/D <1) produce high frequency curves, while longer sections have two distinct frequencies - the higher being exactly double the lower. In a tube having an L/D of 0.96 the lower frequency predominates up to a momentum parameter value of about 2.0, while beyond this point only the higher frequency is apparent (Runs 109 and 110). Several other intermediate lengths between L/D = 0.96 and L/D = 3.58 were tested. The tubes all had surge characteristics similar to the tube with L/D = 3.58. It should be noted that both high and low frequency parameter curves of all cylinders show considerably higher values than those of draft tubes with expanding sections.

Adding a short or a long cylinder section upstream of a long cone significantly increases the frequency and extends the range of surging (see Fig. 8). Adding a cylinder to the downstream end of a long cone has no effect on the frequency, but does decrease the surge amplitude significantly throughout the whole draft tube (Fig. 8, Run 123).

7.5-degree cones with short cylinder inlets display somewhat varying surging characteristics with variation of cone L/D (Fig. 9). The longest tube (L/D = 4.10) displays a surging range and frequency and pressure parameter curves quite similar to those of the Fontenelle draft tube. The surging ranges of the shorter tubes, however, are far greater than the ranges of the shortened lengths of the Fontenelle draft tube (see Fig. 5, Run 64).

The surge amplitude decreases with respect to distance from the inlet in an expanding cone, but generally increases in a long cylinder (Fig. 10).

A 100-degree elbow produces lower frequencies than a cylinder of the same length (Fig. 11). The range of surging is also reduced. In pipe elbows of different lengths the highest pressure fluctuations were measured near the outlet. The fluctuations were always higher at the inside of the bend than at the outside, both in pipe elbows and expanding cross-section elbows of draft tubes.

Substitution of a straight cylinder of equal length for the elbow in the Grand Coulee pump-turbine draft tube does not alter the surge

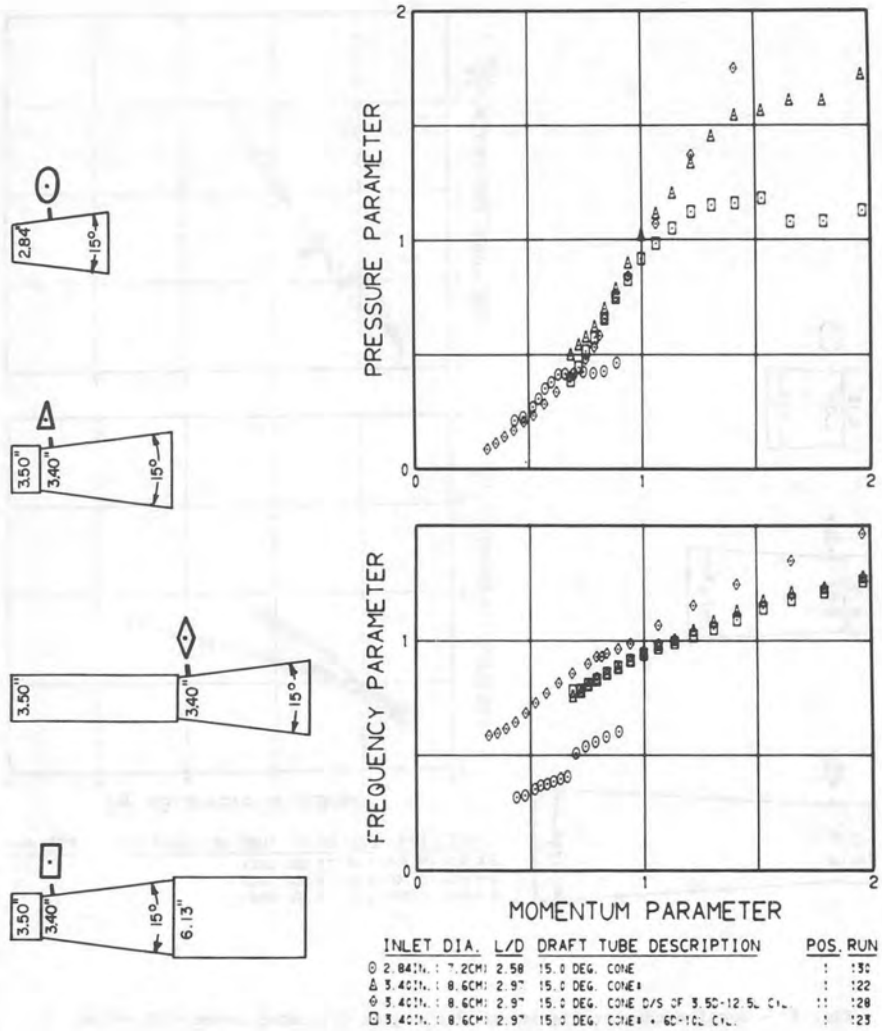


Fig. 8. - Surging characteristics of 15 degree cones in combination with circular cylinders.

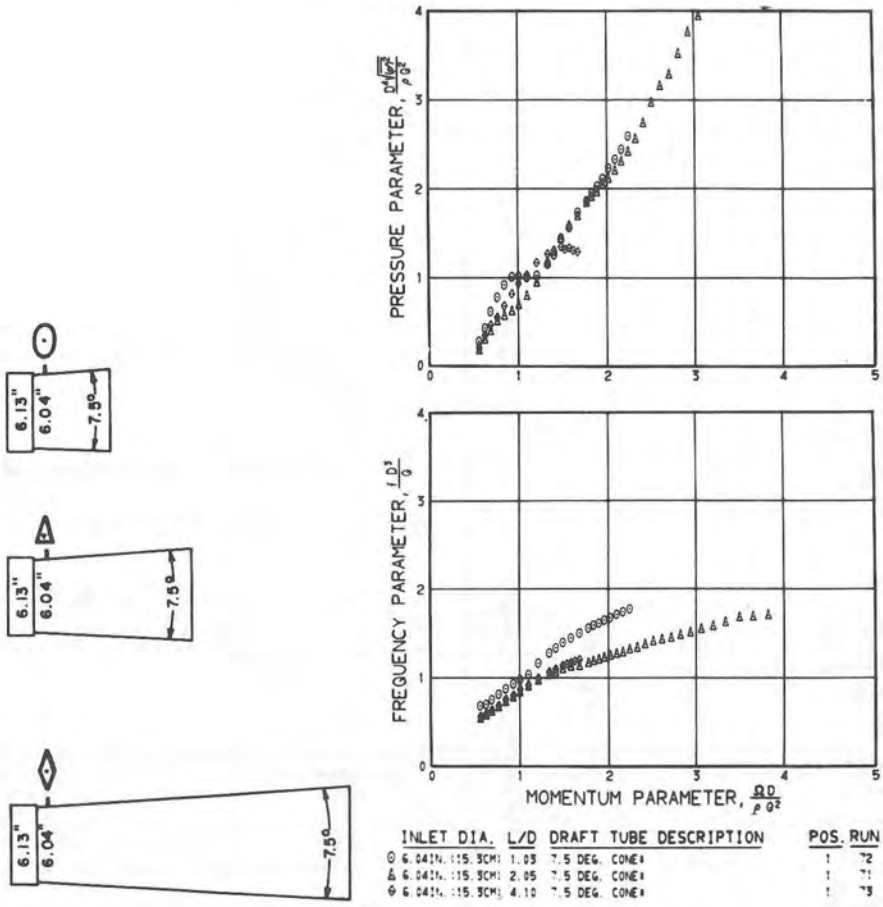


Fig. 9. - Surging characteristics of 7.5 degree truncated cones with short cylinder inlets.

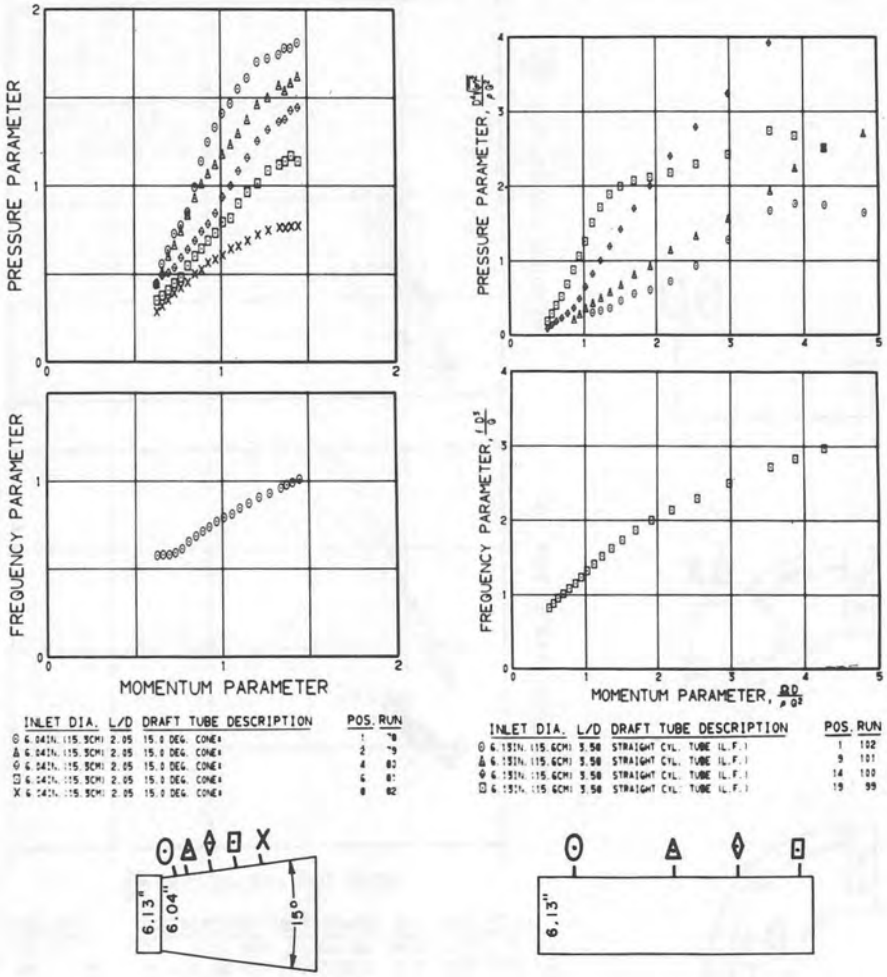
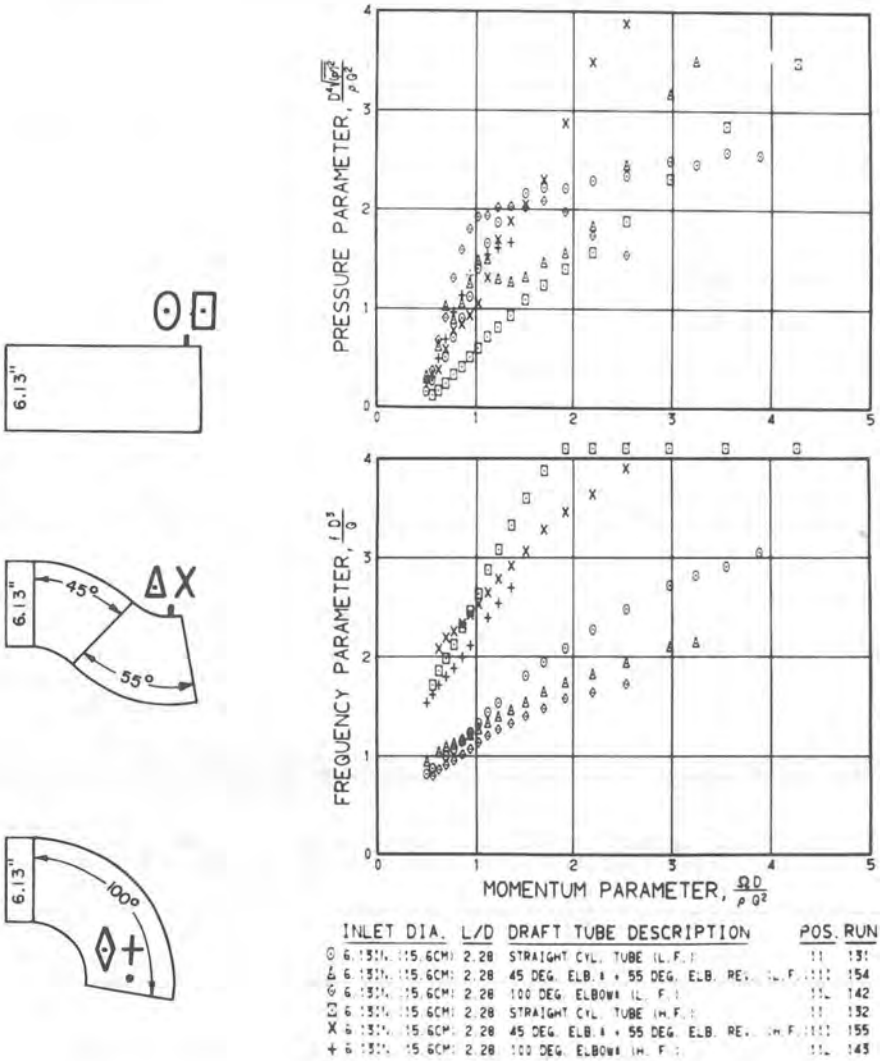


Fig. 10. - Variation of surge amplitude with respect to distance from inlet.



	INLET DIA.	L/D	DRAFT TUBE DESCRIPTION	POS.	RUN
⊙	6.13IN. (15.6CM)	2.28	STRAIGHT CYL. TUBE (L.F.)	11	131
△	6.13IN. (15.6CM)	2.28	45 DEG. ELB.& + 55 DEG. ELB. RE. (L.F.)	111	154
⊖	6.13IN. (15.6CM)	2.28	100 DEG. ELBOW& (L. F.)	11L	142
⊡	6.13IN. (15.6CM)	2.28	STRAIGHT CYL. TUBE (H.F.)	11	132
X	6.13IN. (15.6CM)	2.28	45 DEG. ELB.& + 55 DEG. ELB. RE. (H.F.)	111	155
+	6.13IN. (15.6CM)	2.28	100 DEG. ELBOW& (H. F.)	11L	143

Fig. 11. - Effect of bends on surging characteristics.

characteristics to a great extent (see Fig. 12). The maximum amplitude is typically higher in the elbow tube. An interesting phenomenon in the straight tube is the presence of a second frequency equal to about two-thirds of the predominant one. The predominant frequency parameter curve varies only slightly from the frequency parameter curve of the elbow draft tube. Parameter plots for the 12.25-degree cone, elbow, and straight cylinder have been included in Fig. 12 for comparison. The frequencies of the individual components are all higher than the two complete draft tubes. The downstream section of the 7.5-degree cone apparently helps reduce the frequency and also the amplitudes. The influence of straight cylinder sections inserted between cone sections can be seen in Fig. 13.

Two lengths of 30-degree expanding cones were also tested. No periodic pressure fluctuations could be detected with the instrument and measuring techniques used in the other tests.

COMPARISON WITH TURBINE MODEL

A 1:9.5 scale model of the Grand Coulee Pumping Plant pump-turbine units was tested by the manufacturer (NOHAB, Trollhättan, Sweden). Included in the contract were requirements for pressure pulsation measurements on the model. The manufacturer furnished the Bureau of Reclamation complete model operating data and draft tube pressure pulsation oscillograms and magnetic recording tapes. From these data it was possible to compute the dimensionless parameters for comparison with the results of the air model studies of the Grand Coulee pump-turbine draft tube. The frequency parameter comparison is quite satisfactory (see Fig. 14). Pressure parameter values were not comparable because data were not obtained at the same location, and different band-pass ranges had to be used in the two studies. The computed values were of the same order of magnitude, however.

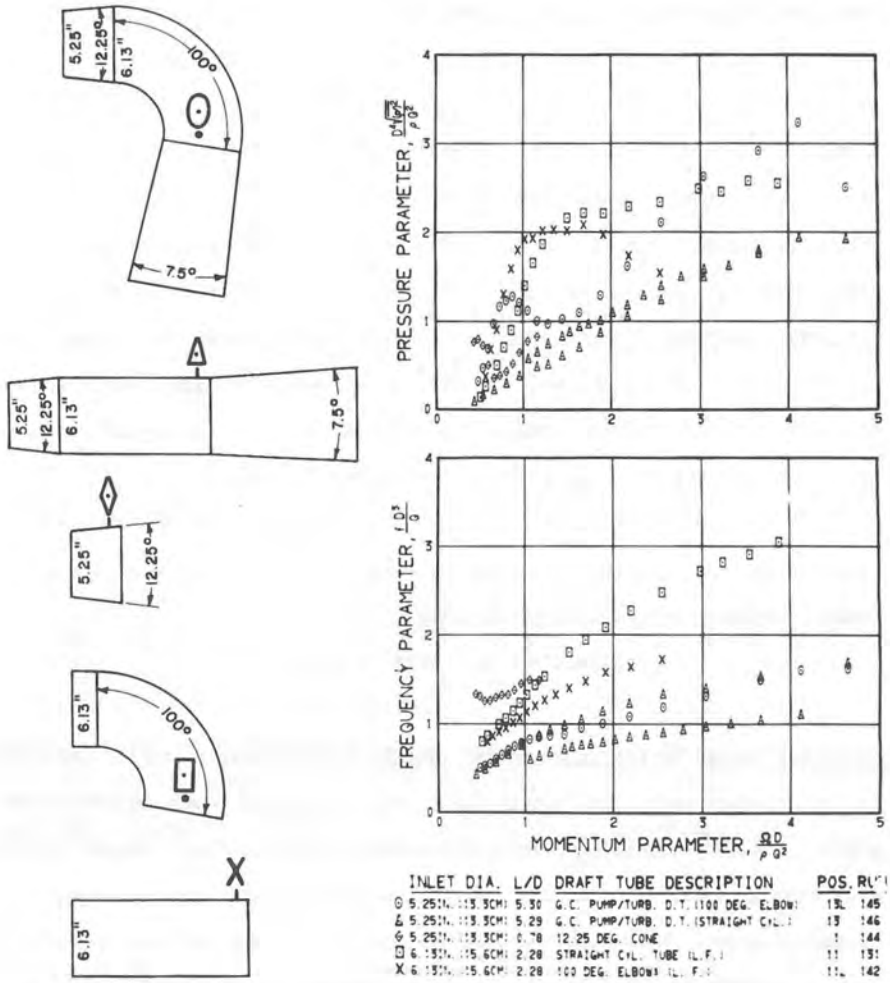
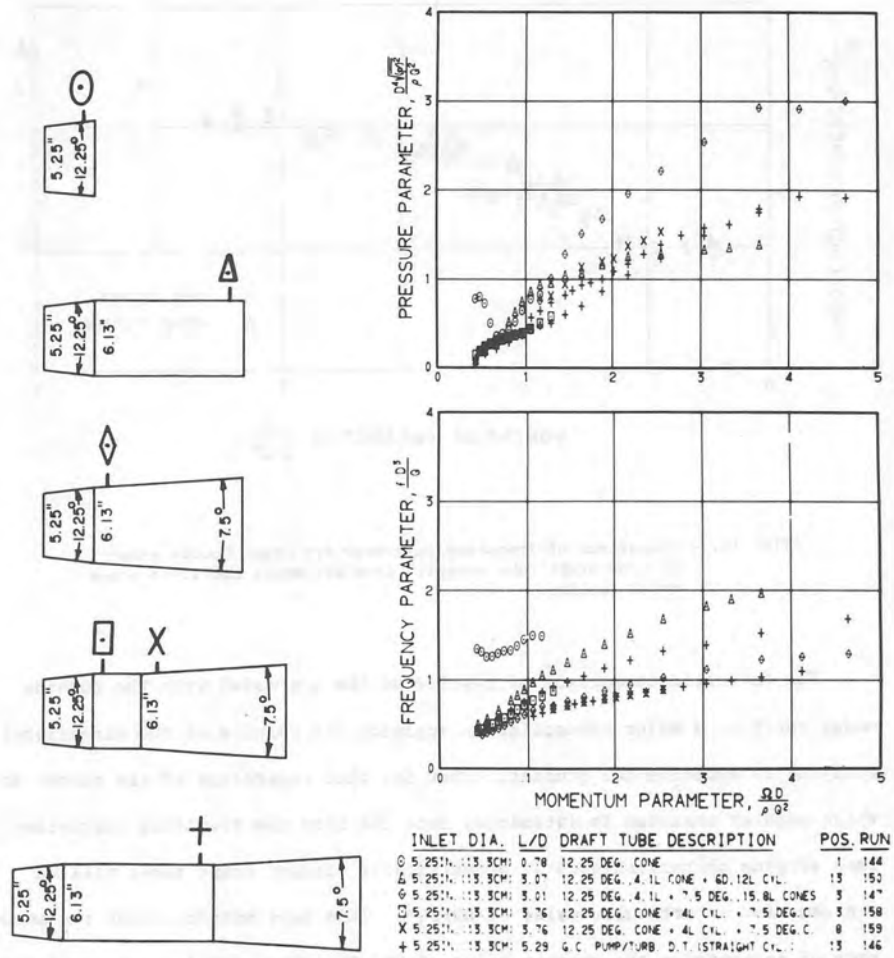


Fig. 12. - Comparison of surging characteristics of two draft tubes and their geometric components.



	INLET DIA.	L/D	DRAFT TUBE DESCRIPTION	POS.	RUN
⊙	5.25IN. (13.3CM)	0.78	12.25 DEG. CONE	1	144
△	5.25IN. (13.3CM)	3.07	12.25 DEG., 4.1L CONE + 6D, 12L CYL.	13	150
◇	5.25IN. (13.3CM)	3.01	12.25 DEG., 4.1L + 7.5 DEG., 15.8L CONES	3	147
□	5.25IN. (13.3CM)	3.76	12.25 DEG. CONE + 4L CYL. + 7.5 DEG.C.	3	158
X	5.25IN. (13.3CM)	3.76	12.25 DEG. CONE + 4L CYL. + 7.5 DEG.C.	8	159
+	5.25IN. (13.3CM)	5.29	G.C. PUMP/TURB. D.T. (STRAIGHT CYL.)	13	146

Fig. 13. - Comparison of surging characteristics of truncated cone and cylinder combinations.

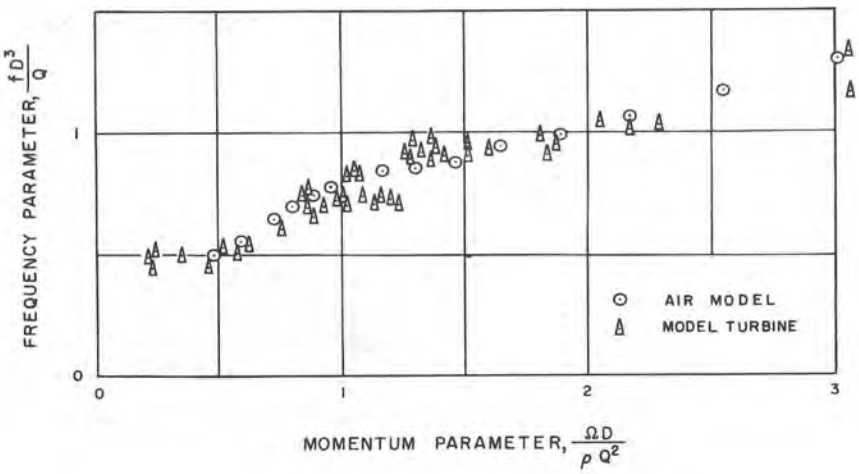


Fig. 14. - Comparison of frequency parameter for Grand Coulee pump-turbine draft tube computed from air model and 1:9.5 scale model turbine.

The favorable comparison of results of the air model with the turbine model verifies a major assumption in applying the results of the dimensional analysis to experimental studies. That is, that regardless of the manner in which angular momentum is introduced into the flow the resulting dimensionless surging characteristics in geometrically similar draft tubes will be the same for a particular value of $\Omega D/\rho Q^2$. This says nothing about the accuracy of determining the correct value of $\Omega D/\rho Q^2$. The methods used to determine the value of the moment parameter in the two studies are not as exact as could be desired, and possibly can be improved in future experiments and analyses.

CONCLUSIONS

1. A model of the type described in this paper can successfully be used to determine the surging characteristics of draft tubes. The equipment need have no more mechanical components than the minimum required to

precisely introduce, control, and measure swirling flow at the draft tube inlet.

2. The degree of divergence of a draft tube is the most significant geometric feature affecting surging characteristics. Bends and relative length have lesser influence.

3. Surging can be minimized by using an equivalent expansion angle of about 15 degrees through the whole length of the draft tube, and probably eliminated entirely with even greater (approximately 30-degree) angles.

4. The use of straight cylinder sections (any L/D) in the draft tube throat will increase the range of surging and increase the frequency and amplitude of the surge.

5. The possibility of resonance with known natural frequencies of other features of the hydroelectric plant can be checked with fair accuracy using the results presented. Resonance can be avoided by proper choice of geometric components in the draft tube design.

APPENDIX I. - REFERENCES

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APPENDIX II. - NOTATION

The following symbols are used in this paper:

B = height of wicket gates

D = diameter of draft tube throat

f = frequency (hz)

L = length of draft tube

N = number of wicket gates

n = rotational speed (rev/min)

P = power

p' = pressure surge amplitude fluctuation from mean

Q = discharge

R = radial distance to center of flow through wicket gates

S = width of opening between wicket gates

T = torque

V = axial velocity

α = radial inclination of flow through wicket gates

ϕ_1, ϕ_2 = functions

ν = kinematic viscosity

π = 3.1416

ρ = fluid density

Ω = flux of moment of momentum

ω = angular velocity (rad/sec)