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Review Paper (Invited)

An Outlook on the Draft-Tube-Surge Study

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Abstract

If large pressure fluctuation is observed in the draft tube of a Francis turbine at part-load operation, we have generally called it draft-tube-surge. As occurrence of this phenomenon seriously affects the limit of turbine operating range, extensive studies on the surge have been made since proposal of surge-frequency criterion given by Rheingans. According to the literature survey of related topics in recent IAHR symposiums on hydraulic machinery and systems, in which state-of-the-art contributions were mainly presented, a certain review of them may be desirable for an outlook on the future studies in this research field. Thus, in this review paper, the authors' previous attempts for the last three decades to challenge the following topics: a rational method for component test of a draft tube, nature of spiral vortex rope and its behavior in a draft tube and cavitation characteristics of pressure fluctuations, are introduced together with other related contributions, expecting that more useful and significant studies will be accomplished in the future.

Keywords: draft tube, pressure surge, swirl flow, vortex rope, cavitation, review paper

1. Introduction

The hydroelectric power system is quite usable in the electrical energy supply net-work, as it can quickly respond the demand and contribute to secure the stable net-work with high quality electricity. If the hydroelectric system based on a hydraulic turbine can be used in the wider operating range, robustness and flexibility of the system are greatly improved. However, we have still met such cases that the turbine operation is restricted due to the occurrence of severe noise and vibration of the system. In the cases of reaction turbines, those undesirable phenomena are often caused by violent pressure fluctuations in the draft tube, which is assembled downstream of a turbine runner. As those fluctuations might be amplified near the half load at a certain cavitation condition [1], their mysterious characters have attracted lots of fluid engineers and researchers. Falvey [2] summarized and surveyed the related works up to around 1970, including the well-known relationship demonstrated by Rheingans [3] who found out the dominant frequency being close to 1/3.6 times the runner rotational speed n (min^{-1}) at the greatest pressure fluctuations, which should be called the draft tube surge. If the flow field downstream of a turbine runner is examined at partial load operating condition, swirl flow is measured. For instance, radial distributions of velocity components at the draft tube inlet of model Francis turbine [4] are shown with solid lines in Fig. 1, where V_z is the axial component of velocity and V_θ is the circumferential component. We can see such features that V_z distribution has wake-like velocity defect at the center region and V_θ has the Rankine vortex pattern. And swirl (or circumferential velocity) and the central low velocity region tend to increase with the decrease of discharge [4]. As the swirl flow could be called the vortex flow, an idea of vortex breakdown was applied to understand the helical structure of cavitated vortex core observed in a draft tube. To promote our understanding on the instabilities generated by swirl flow, U.S.B.R. group conducted systematic studies using the swirling airflow which was generated by a stationary circular cascade [5 - 8]. Extensive studies have been done in various institutions since then, and the trend continues even at present. We could see great many contributions treating the draft tube issue in recent proceedings of IAHR symposium on hydraulic machinery and systems. It may be due to the fact that we are always longing to have more gentle and elegant hydraulic turbines [9].

Around the late nineteen-seventies, when one of authors was engaged in this issue, the following were not very clear:

(1) Is a component test for draft tube surge possible? If so, how to express the surge frequency?
(2) What is the vortex rope?
(3) What are the causes of pressure fluctuations?
(4) Which technique is suitable to alleviate draft tube surges?

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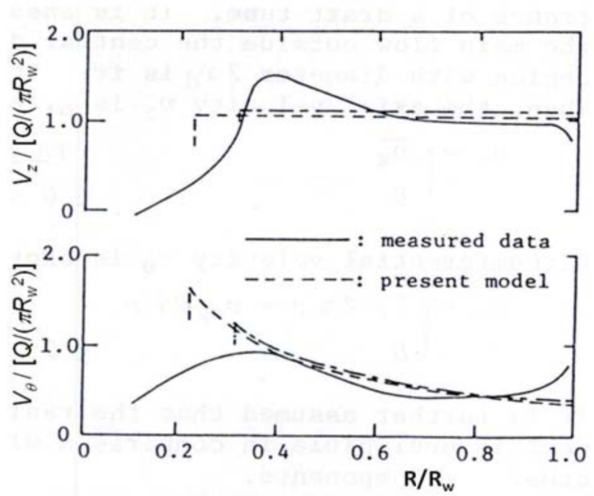


Fig. 1 Velocity distribution at the draft tube inlet of a model Francis turbine [4]

Thus, in this review paper, the authors' previous attempts for the last three decades to challenge the above topics are introduced together with other related contributions, though they were summarized once [10], expecting that more useful and significant studies will be accomplished by many researchers and engineers in the future.

It should be noted that draft-tube-surge (or pressure surge) focused in this paper expresses large pressure fluctuations in the draft tube of a Francis turbine being operated at partial load. In case of overload surge being concerned, it is noted that there are useful contributions [11 - 14].

2. Component Test for Draft Tube Surge

2.1 Parameters

At model acceptance tests [15], which are conducted to examine the hydraulic performance of a reaction turbine, the pressure fluctuations are usually measured to check the frequency and the magnitude whether it is within the admissible level. By using the model turbine, the additional test to clarify the causes of pressure fluctuations must be the convenient approach [16 - 20]. Thus, most of research works have been carried out based on this way, though the results may be regarded as special and may only be applicable to the similar turbine. If pressure fluctuations in a certain draft tube are represented by non-dimensional amplitude $\Delta H/H$ and frequency $f/(n/60)$, they are expressed by the following formula, which is obtained from previous studies together with the dimensional consideration:

$$\left[\frac{\Delta H}{H}, \frac{f}{n/60}\right] = func.\left(\frac{Q}{Q_0}, n_S, \frac{(NPSH)_i}{H}, \mathrm{Re}, Fr, We\right) \tag{1}$$

The effect of Reynolds number *Re* is generally disregarded, as the flow in a conventional reaction turbine is turbulent. If a model turbine having the small scale ratio of model to prototype is used in the cavitation test, the cavity volume fraction cannot be regarded as identical with that in the prototype at same cavitation number ($NPSH_i/H$) due to the effect of the Froude number *Fr*. As a kind of its compensation, modified cavitation number has been introduced by changing the suction head [21]. Namely, the head is the elevation from the tail-water surface to the reference plane, location of which is nearly the mid height of draft tube. Regarding the Weber number *We*, its effect is assumed to be minor, though surface tension at the interface between cavitated core and the surrounding water may have a certain influence on the behavior of the core.

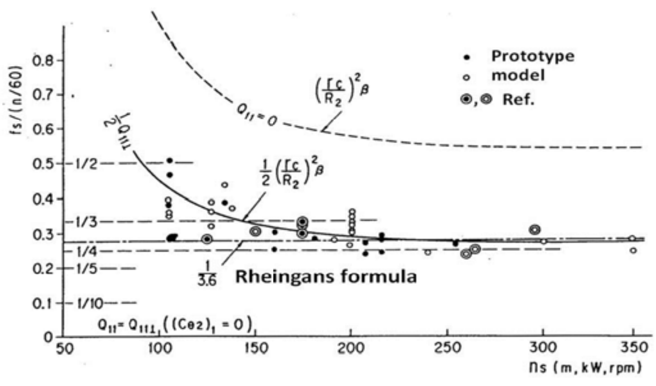
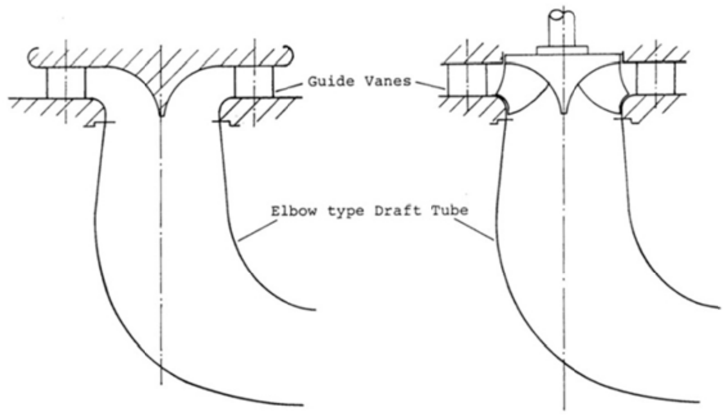


Fig. 2 Correlation between surge frequency and turbine specific speed [22]

Consequently, eq. (1) is simplified as follows:

$$\left[\frac{\Delta H}{H}, \frac{f}{n/60}\right] = func.\left(\frac{Q}{Q_0}, n_S, \frac{NPSH}{H}\right) \tag{2}$$

It is noted that the effect of specific speed n_s on the surge frequency was studied by Hosoi [22]. As reproduced in Fig. 2, the frequency increases with decrease of specific speed.



(a) Component test [24] (b) model turbine test

Fig. 3 Test method

If we consider that discharge ratio Q/Q_0 and specific speed n_s in eq. (2) are related to the swirl flow at the draft tube inlet and such flow pattern shown in Fig. 1 might be macroscopically reproduced by stationary swirl generators [5, 23], we will be able to study pressure fluctuations from a component test of draft tube if we use water as working fluid. That is, we can use a water test apparatus without a runner but with stationary guide vanes to generate swirl flow, as illustrated in Fig. 3(a) [24]. Making use of the previous results on axisymmetric swirling flow in a conical diffuser [23], swirl rate (or swirl number) m and the dimensionless radius of dead water region in swirl flow r_d defined at the draft tube inlet are introduced in place of Q/Q_0 and n_s respectively. Those parameters are expressed as

$$m = \frac{\dot{\Omega}}{R_w \dot{M}} = \int_0^{R_w} V_\theta V_z R^2 \cdot dR \,/\, (R_w \cdot \int_0^{R_w} V_z{}^2 R \cdot dR) \tag{3}$$

$$r_d = R_d / R_w \tag{4}$$

If the simplest velocity distributions of swirling main-flow consisting of uniform axial velocity and free vortex type circumferential velocity outside the dead water region are assumed at the entrance of a draft tube neglecting radial velocity, they are given as follows [25]:

$$V_z = 0 \quad (0 \le R < R_d) \qquad V_z = Q/[\pi R_w{}^2(1-r_d{}^2)] = \overline{V}_z \quad (R_d \le R \le R_w) \tag{5}$$

$$V_\theta = 0 \quad (0 \le R < R_d) \qquad V_\theta = V_{\theta w} R_w / R \quad (R_d \le R \le R_w) \tag{6}$$

In this swirl flow model, eq. (3) becomes

$$m = V_{\theta w} / \overline{V}_z = \tan\beta_w \tag{7}$$

where $V_{\theta w}$ denotes the nominal circumferential velocity at the wall, which is calculated from circulation Γ of swirling main-flow, i.e, $V_{\theta w} = \Gamma / (2\pi R_w)$. β_w is the flow angle from the circumferential direction. Thus, the swirl rate, which represents the strength of swirl, is understandable as the parameter related to the flow angle adjacent to the draft tube wall.

For our reference, the above velocity model is compared to the measurement data given in Fig. 1. The dash-dot lines show the velocity distributions obtained from experimental m and r_d with Q and R_w as the input data. And the dash lines are obtained from experimental m with Q and R_w by using the following empirical relationship between m and r_d [25].

$$m = r_d + 3 \cdot r_d{}^3 \tag{8}$$

It is seen in Fig. 1 that those two lines are close together and the measured data are almost reasonably represented by them. Therefore, the single parameter method based on the swirl rate is acceptable as the first-order approximation to represent the swirl flow in a draft tube of Francis-turbine at partial load operation.

To characterize the cavitation condition in a draft tube, the following cavitation parameter is used.

$$K = 2g \cdot NPSH / [Q / (\pi R_w^2)]^2 \tag{9}$$

In place of $\Delta H/H$ and $f/(n/60)$, the following dimensionless pressure amplitude and frequency might be adequate for the component test of draft tube.

$$\Delta\psi = 2g \cdot \Delta H / [Q / (\pi R_w^2)]^2 = 2 \cdot \Delta p / \rho / [Q / (\pi R_w^2)]^2 \tag{10}$$

$$St = f \cdot 2R_w / [Q / (\pi R_w^2)] \tag{11}$$

Consequently, the following relationship is derived in place of eq. (2).

$$[\,\Delta\psi, St\,] = func.(\,m, r_d\,, K\,) \tag{12}$$

For those turbulent swirl flows to which eq. (8) is applicable, eq. (12) is simplified as

$$[\,\Delta\psi, St\,] = func.(\,m\,,\,K\,) \tag{13}$$

If we prepare such a water test apparatus that the dimensionless parameters m and K can be adjustable, we will be able to investigate the general nature and characteristics of pressure fluctuations associated with draft tube geometries.

The following are additional notes, when we apply eq. (13) to processing test data of a Francis turbine operated at partial load:

1. The swirl rate m increases if we reduce the discharge ratio Q/Q_0.
2. The cavitation parameter K increases if we reduce the discharge ratio Q/Q_0 under the constant cavitation number ($NPSH/H$).

2.2 Validation

Validity of the preceding dimensionless consideration was confirmed from the experiment, where a test draft tube was a 1/3 scale model of the elbow draft tube of model Francis turbine [4]. A typical example is reproduced in Fig. 4 [24], where cavitation characteristics of pressure fluctuation measured at the wall of inlet conical diffuser (or inlet cone) of the model draft tube are compared with those of model turbine at m = 1.1. As for amplitude parameter $\Delta\psi$ (peak-to-peak value) in Fig. 4(a), similar cavitation characteristics are observed between them, though there is a certain difference in the critical cavitation parameter, at which the maximum pressure surge occurs. In the case of frequency parameter St, as shown in Fig. 4(b) good agreement is observed between them.

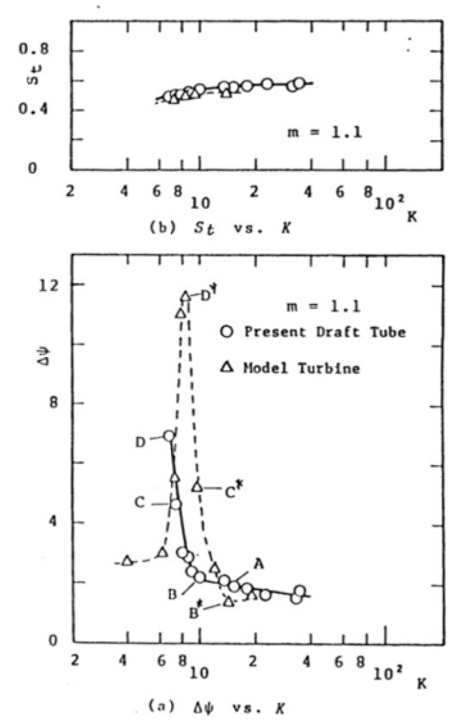


Fig. 4 Comparison of cavitation characteristics between component test and model turbine test [24]

Since it is recognized that draft tube surge of a model turbine is reasonably reproduced from the component test of a model draft tube without a runner, we may understand that the effect of inertia in the runner passage on draft tube surge is negligible and the surge is primarily related to the condition of swirl flow at the draft tube inlet. Further, the Rheingans frequency may be interpreted as follows: As the draft tube surge is normally observed where the discharge ratio at the operating condition of a Francis turbine is around 0.5~0.6, the velocity triangle at the runner exit may be regarded as identical. Therefore, there is a certain relationship between angular velocity of the runner and the swirl rate of the flow entering the draft tube. And both parameters are usable to correlate the surge frequency.

It is noted that the test apparatus shown in Fig. 3(a) cannot be applied to the over-load test of a Francis turbine, since the swirling flow pattern is quite different. That is, the axial velocity at the center region is faster than that at the outside zone in the over-load case [26], because the flow in the runner tends to deflect toward the crown side due to heavy blade load near the band side.

Another note is that a sophisticated swirl apparatus consisting of guide vanes and a free runner was designed in recent years so as to improve the similarity of swirl flow at the draft tube inlet of a Francis turbine at partial load operation [27].

3. Vortex Rope and its Behavior

3.1 Spiral Vortex Rope

Figure 5 shows a picture of vortex rope (or vortex core) in the model draft tube taken during the experiment described above. Note that it rotates around the center axis of draft tube together with swirling main-flow. If the nature of swirl flow in the inlet cone is considered, it might be summarized as follows:

1. Increasing the swirl, water in the center region loses the energy to move downstream against the pressure gradient and it tends to reach the stagnant condition at some point along the axis, and the stalled region (i.e., reverse flow region or dead water) is formed downstream.
2. If the swirl is sufficiently strong, the stagnation point along the center axis may almost always exist near the inlet.
3. At this condition, vortex sheet may appear between the central stalled region and the main flow with swirl surrounding it. And the sheet consisting of vortex filaments may be easily rolled up into a single vortex due to the disturbance [24]. This description is illustrated in Fig. 6 [25].
4. If the pressure in the vortex is low enough to cause cavitation, the vortex is visible like a spiral rope, as shown in Fig. 5.
5. Stronger the swirl is, larger the pitch of a spiral vortex rope is, because the rope might appear almost perpendicular to the velocity vector of swirling main-flow. And if the swirling main-flow rotates in the clockwise direction, the spiral rope trails in the counter-clockwise direction [28].

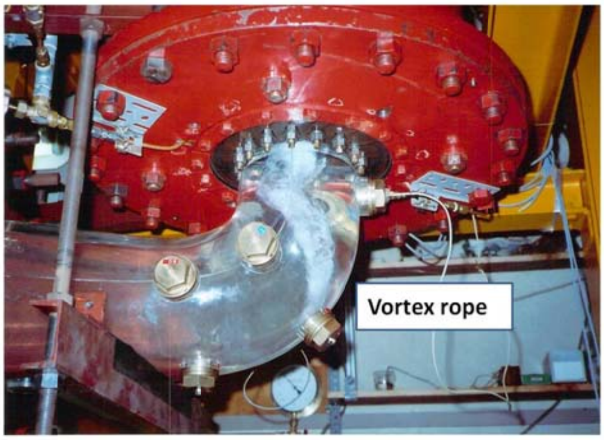


Fig. 5 A vortex rope observed in the draft tube

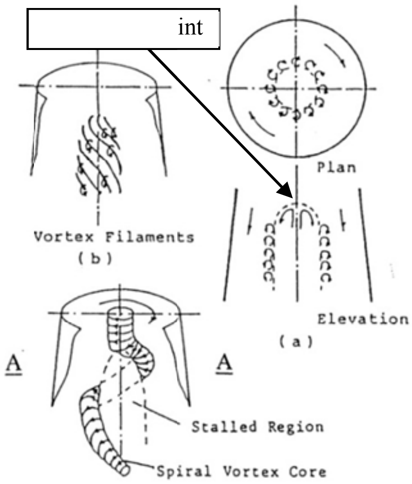
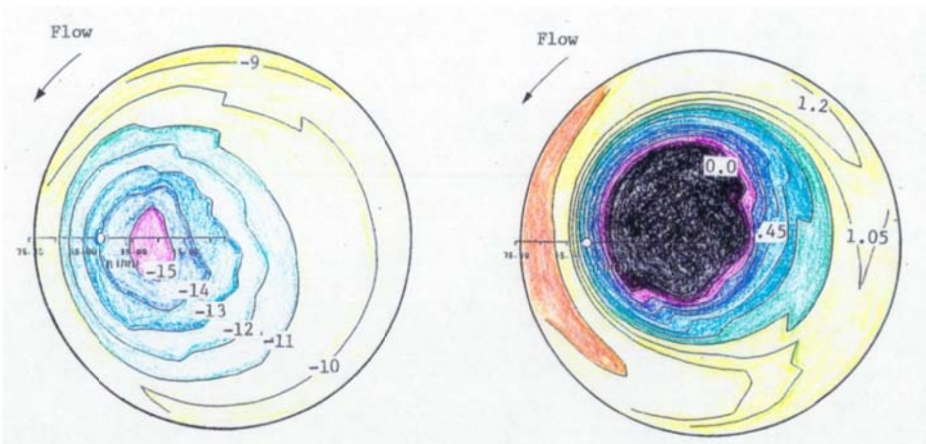


Fig. 6 Origination of vortex rope [25]



(a) Pressure distribution (b) Axial velocity distribution

Fig. 7 Ensemble--averaged flow behavior in the swirling flow with a vortex rope

3.2 Distorted Flow Field

Figure 7 shows phase-locked ensemble-averaged distributions of axial velocity and static pressure in the cross-section of inlet conical diffuser measured with a five-hole Pitot probe system [29]. From contour plot of axial velocity where the vortex rope is located at the shear layer between central stalled region and swirling main-flow, we will be able to accept that the illustration in Fig. 6 is sound. It is noted that recent PIV measurements made by Ciocan-Iliescu [30] and Kirschner-Ruprecht [31] demonstrate the corresponding feature more precisely.

From the distorted pressure pattern shown in Fig. 7(a), we will come to understand that the wall pressure varies periodically due to the rotation of this pattern together with a vortex rope in the draft tube. Besides, an interesting finding might be the location of vortex rope (shown with a small circle), which is not at the center of low pressure zone at a non-cavitating condition.

3.3 Rotating Frequency of Vortex Rope

The frequency of draft tube surge might be predictable, if we will be able to correlate the rotating (or precessing) frequency of vortex rope with the swirl rate. An earlier attempt was made by Wang, et al. [32], assuming that two-dimensional treatment was applicable to the precessional motion of vortex rope. Based on a partially rolled-up vortex model, where the vortex filaments around the central stalled region are partially rolled up to form the vortex rope and the rest diffuses in the whole flow field, they obtained the following relationship for the rotating frequency:

$$St_{ro} = \frac{\Gamma R_w}{2\pi r_a^2 Q}\left[\frac{r_a^2}{1-r_a^2}\frac{\Gamma_a}{\Gamma} + 0.632\left(1-\frac{\Gamma_a}{\Gamma}\right)\right] \tag{14}$$

where r_a is the dimensionless radial distance from the center axis to the position of vortex rope. Γ and Γ_a denote the circulation of swirling main-flow and that of the vortex rope respectively. All these variables in the right hand side of eq. (14) are determined, if the wall radius and the swirl rate are prescribed. Their result in Fig. 8 [32] shows that fair agreement between the solid line of eq. (14) and experimental data.

A further refinement of the model (called as Q3D model) was made, considering the spiral shape of vortex rope [33]. An additional note is that Kuibin, et al. [34] demonstrated their mathematical models, including various contributions on this topic for the last few decades.

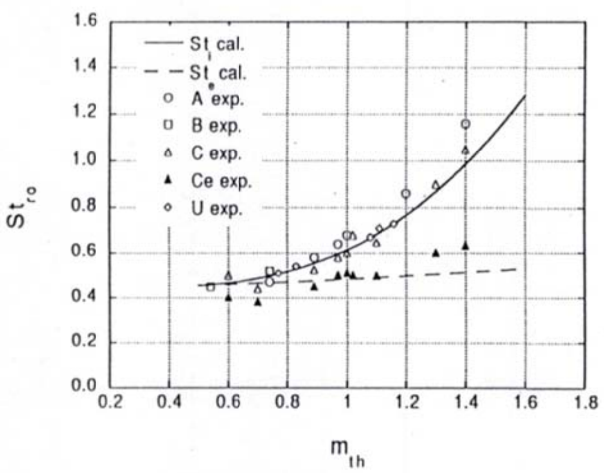


Fig. 8 Comparison of predicted rotating frequency of vortex rope with measured data [32]

3.4 Flow Regime

The swirl flow in an elbow draft tube is generally divided into following four flow regimes by using the swirl rate at the draft tube inlet. For our reference, a typical flow regime chart for a model draft tube is shown in Fig. 9 [25], where each vortex rope is illustrated from its observation. As described in section 3.1, the shape of vortex rope and its behavior depend on the stagnation point which has a trend to move upstream along the center axis in the inlet conical diffuser, if strength of swirl in the flow at the draft tube inlet increases.

(1) Regime I: A nearly straight vortex rope is observed.
There is no stalled region in the inlet conical diffuser so that swirl flow smoothly proceeds into the elbow due to weak swirl.

(2) Regime II: Various shapes of vortex rope appear irregularly.
The swirl flow has transitory nature in this range of swirl rate.
Axial location of stagnation point in the inlet conical diffuser varies irregularly.

(3) Regime III: A single vortex rope is observed stably.
The swirl is strong enough so that the stagnation point locates near the inlet.
Thus, the vortex rope and its behavior discussed in section 3.1-3.3 correspond to this flow regime.

(4) Regime IV: Double (or twin) vortex ropes [35] are observed.
The swirl is so strong that the large stalled region extends to the center cone upstream of the draft tube.

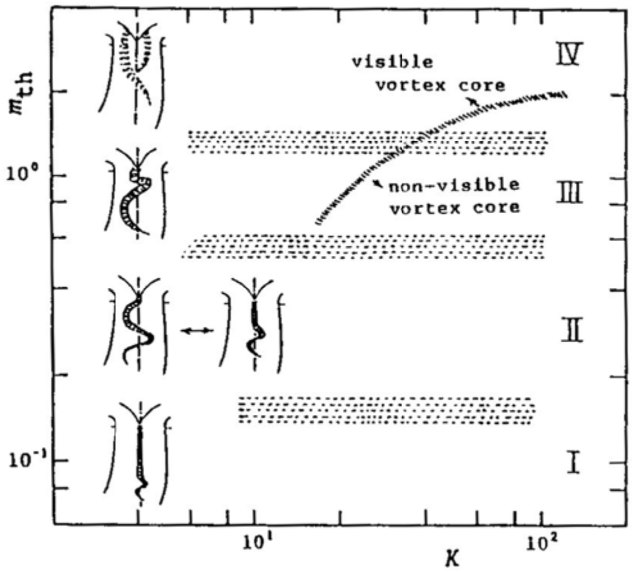
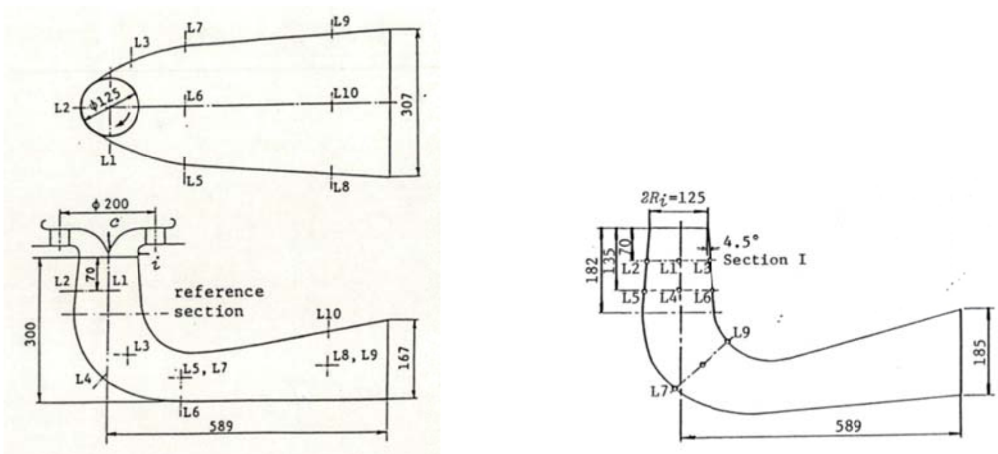


Fig. 9 Flow regime chart (mod A: inlet cone angle of 9 deg.) [25]

One note is that the boundaries of flow regimes are influenced by draft tube geometry [36] to some extent since the flow regimes are primarily characterized by size and location of the stalled region in the draft tube. The other is that the draft-tube flow at upper part-load pressure-fluctuation [16], which is regarded as a recent research topic [37, 38], should correspond to the flow regime II, though instabilities of runner and draft-tube flows might be related to the cause of pressure fluctuation.

4. Pressure Fluctuations Caused by Vortex Rope

An elbow draft tube is a key component of a Francis turbine to convert the kinetic energy of the flow from the runner into pressure for reducing the exit loss. However, due to a large pressure oscillation which is sometimes caused by the swirl flow in the draft tube at off-design condition, operation of a turbine is restricted. Thus, we should design the draft tube properly from both aspects [39, 40]. Though pressure measurement may be possible during the model acceptance test following the IEC code, how to utilize the result for designing improvement is still one of unresolved issues. As an elbow draft tube consists of three portions which are inlet conical diffuser (inlet cone), elbow and downstream diffuser (foot), clarification of hydrodynamic role of each portion is also expected.



(a) Shallow draft tube (mod A) (b) Deep draft tube (mod C)

Fig. 10 Test draft tubes

4.1 Shallow and Deep Draft Tubes

Component test results of pressure fluctuations caused by a spiral vortex rope in flow regime III are reviewed in this section. And two kinds of elbow draft tubes made of transparent plastic, which are shown in Fig. 10, were principally used to collect pressure data associated with *m* and *K*. One is a shallow draft tube (mod A), and the other a deep draft tube (mod C). As shown in the figure, two measurement stations 90 deg apart are arranged in one section ($1.12R_w$) of inlet cone for mod A, and three stations are arranged in each of two sections of inlet cone ($1.12R_w$ and $2.16R_w$) for mod C. Both of them have inlet diameter of 125 mm, inlet cone angle of 9 degree and exit-to-inlet area ratio of 4.1.

From a series of component tests, the following conclusions are found as the principal sources of pressure fluctuations measured at the wall of inlet cone.

(1) Sources of pressure fluctuation for a shallow draft tube

$$\tilde{p}(t) = \tilde{p}_{ro}(t)_{f=f_{ro}} + \tilde{p}_{sy}(t)_{f=f_{ro}} + \tilde{p}_{sy}(t)_{f=f_s} \tag{15}$$

$\tilde{p}_{ro}(t)_{f=f_{ro}}$: fluctuation due to precession of vortex rope in the measurement section ($f_{ro} = f_{ro\text{-}i} = f_{ro\text{-}b}$)

$\tilde{p}_{sy}(t)_{f=f_{ro}}$: pressure recovery fluctuation in the foot, having synchronous character

$\tilde{p}_{sy}(t)_{f=f_s}$: system fluctuation related to cavitation, having natural frequency f_s

<Features> Rotating frequency of vortex rope can be regarded as constant in the inlet cone.
Almost periodical pressure fluctuation is observed.
If $\tilde{p}_{sy}(t)_{f=f_s}$ becomes large in a certain K range, periodicity of pressure fluctuation is weakened, except the resonant condition.

(2) Sources of pressure fluctuation for a deep draft tube

$$\tilde{p}(t) = \tilde{p}_{ro}(t)_{f=f_{ro-i}} + \tilde{p}_{sy}(t)_{f=f_{ro-b}} + \tilde{p}_{sy}(t)_{f=f_s} \tag{16}$$

$\tilde{p}_{ro}(t)_{f=f_{ro-i}}$: fluctuation due to precession of vortex rope in the measurement section

$\tilde{p}_{sy}(t)_{f=f_{ro-b}}$: pressure recovery fluctuation in the foot, having synchronous character

$\tilde{p}_{sy}(t)_{f=f_s}$: system fluctuation related to cavitation, having natural frequency f_s

<Features> Rotating frequency of vortex rope tends to decrease in the downstream direction.
Irregularity appears in the fluctuation, excluding fluctuation at the resonance.

4.2 Cavitation Characteristics of Pressure Surge in Shallow Draft Tube

4.2.1 *Typical data* The cavitation characteristics of pressure surge at m_{th} = 0.97 in the case of mod A (shallow draft tube) is shown in Fig. 11, where $\Delta\psi_{rms}$ is root-mean-square amplitude of dimensionless pressure fluctuation and St is the surge frequency calculated from eq. (11). The following features are found in the results:

1. Similar cavitation characteristics of amplitude are observed in both measurement points L1 and L2, though the difference between them is not small.
2. If K_i decreases beyond 15, amplification of $\Delta\psi_{rms}$ occurs. $\Delta\psi_{rms}$ reaches the peak around K_i = 8.5 and it decreases with the decrease of cavitation parameter K_i.
3. The surge frequency is nearly constant in the range of high cavitation parameter, while the frequency gradually decreases with the decrease of K_i depending on the development of cavitation.

Selecting two typical cases of cavitation parameter, namely K_i = 25 and K_i = 8.5, time histories of pressure fluctuation at L1 and L2 are displayed in Fig. 12 [41]. In K_i = 25 case, amplitude and wave form are different each other to some extent, but the phase shift reasonably corresponds to 90 degree apart between L1 and L2. On the other hand, in K_i = 8.5 case, both pressures fluctuate in phase, though the amplitude and wave form are a little bit different between them. Based on these characters, the former is called QR type surge and the latter is QS type surge [36, 41].

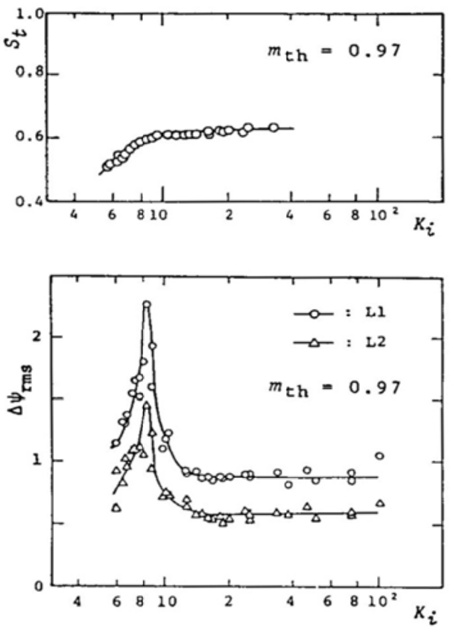


Fig. 11 Cavitation characteristics of pressure surge (mod A: flow regime III) [41]

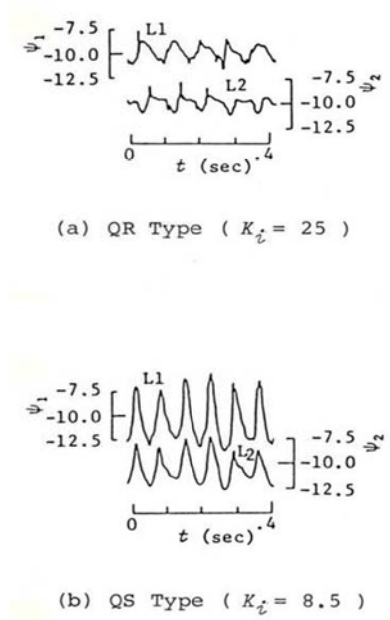


Fig. 12 Pressure wave forms (mod A: flow regime III) [41]

4.2.2 *Data processing based on Fourier analysis* Fluctuating components of pressures measured at the wall of inlet cone are mostly periodic character having a rotating frequency of vortex rope as the first harmonic so that they are approximated by the Fourier series. It indicates that $\tilde{p}_{sy}(t)_{f=f_s}$ in eq. (15) is negligible order in the higher K_i range. Thus, $\tilde{p}_1(t)$ for L1 and $\tilde{p}_2(t)$ for L2 are expressed as

$$\tilde{p}_1(t) = \tilde{p}_{sy}(t)_{f=f_{ro}} + \tilde{p}_{ro}(t)_{f=f_{ro}} \tag{17}$$

$$\tilde{p}_2(t) = \tilde{p}_{sy}(t)_{f=f_{ro}} + \tilde{p}_{ro}(t-\Delta t)_{f=f_{ro}} \tag{18}$$

where Δt is a quarter of time period T ($= 1/f_{ro}$) in the present phase difference between L1 and L2. From both equations, derived are the following relationships where subscript $f = f_{ro}$ is omitted:

$$\tilde{p}_{ro}(t) - \tilde{p}_{ro}(t-\Delta t) = \tilde{p}_1(t) - \tilde{p}_2(t) \tag{19}$$

$$\tilde{p}_{sy}(t) - \tilde{p}_{sy}(t+\Delta t) = \tilde{p}_1(t) - \tilde{p}_2(t+\Delta t) \tag{20}$$

If pressure data are processed using the above equations, we can have both $\tilde{p}_{ro}$ and $\tilde{p}_{sy}$ components separately. Thus, both rotating and synchronous amplitude Δp_{ro} and Δp_{sy} are calculated from the Fourier coefficients of $\tilde{p}_{ro}$ and $\tilde{p}_{sy}$ respectively. One note is that the first three harmonics in Fourier series are almost sufficient to represent the fluctuation [36, 42].

For our reference, this method was applied to the data shown in Fig. 11, and the dimensionless amplitude parameters $\Delta\psi_{ro}$ and $\Delta\psi_{sy}$ were correlated with the cavitation parameter K_i, which are shown in Fig. 13. Note that $\Delta\psi$ is the ratio of Δp to the dynamic pressure based on the area mean velocity at the draft tube inlet. It is seen that rotating component $\Delta\psi_{ro}$ is nearly constant in the test range, but it is seen that the synchronous component $\Delta\psi_{sy}$ amplifies in a certain range of cavitation parameter, where system oscillation becomes larger than variation of pressure recovery and both frequencies coincide at the maximum amplitude, i.e., $f_s = f_{ro}$, which might be the resonant condition.

This data processing might be usable as a diagnosis, since the sources of pressure fluctuations are evaluated directly associated with the draft tube geometry. Further, if you will be able to use two pressure sensors in one section of inlet cone, "90 deg apart" installation is the authors' recommendation [42].

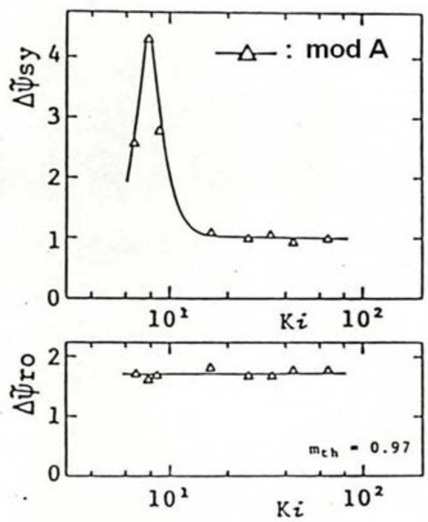


Fig. 13 Cavitation characteristics of amplitude parameters, $\Delta\psi_{ro}$ and $\Delta\psi_{sy}$

4.3 Cavitation Characteristics of Pressure Surge in Deep Draft Tube

4.3.1 *Cavitation characteristics* A typical example of cavitation characteristics of pressure amplitude is shown in Fig. 14, where dimensionless root-mean-square amplitudes $\Delta\psi$ measured at two locations, L1 and L2 (see Fig. 10), are plotted against cavitation parameter K_i. The characteristics are qualitatively similar to those of shallow draft tube shown in Fig. 11. However, if we observe the behavior of vortex rope in a deep draft tube by using a high speed video system, we might find the following difference comparing to the rope in a shallow draft tube: The rope at the inlet section has passed the last position when the rope at the elbow entrance arrives at the same position after a cycle. As the inlet cone is much longer than that of shallow tube, decay of the strength of swirl toward downstream may affect the behavior of vortex rope. It was found that the rope frequency (or rotating frequency) decreased by 25% at the test condition of $m_{th} = 1.4$ and $K_i = 12.6$ [43]. However, if we will be able to disregard the above difference and assume periodic pressure fluctuation, the same data processing method discussed in section 4.2.2 may be usable to evaluate $\Delta\psi_{ro}$ and $\Delta\psi_{sy}$ against the cavitation parameter [42].

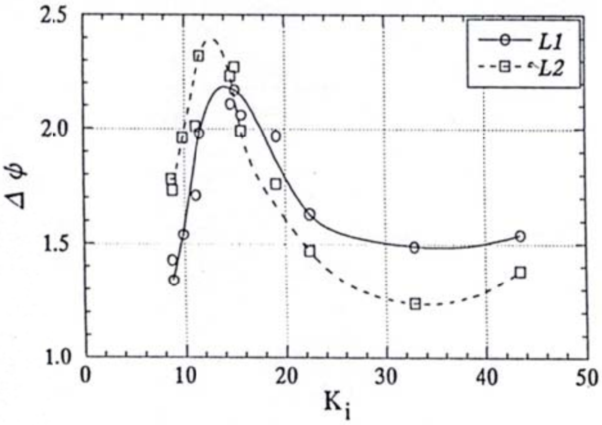


Fig. 14 Cavitation characteristics of $\Delta\psi$ at m_{th} = 1.4

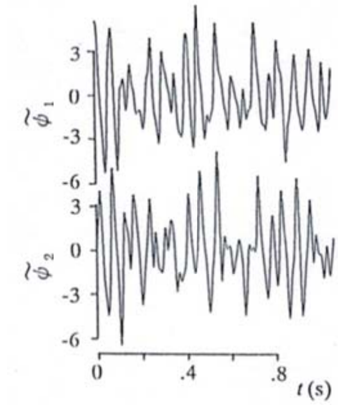


Fig. 15 pressure fluctuations [44]

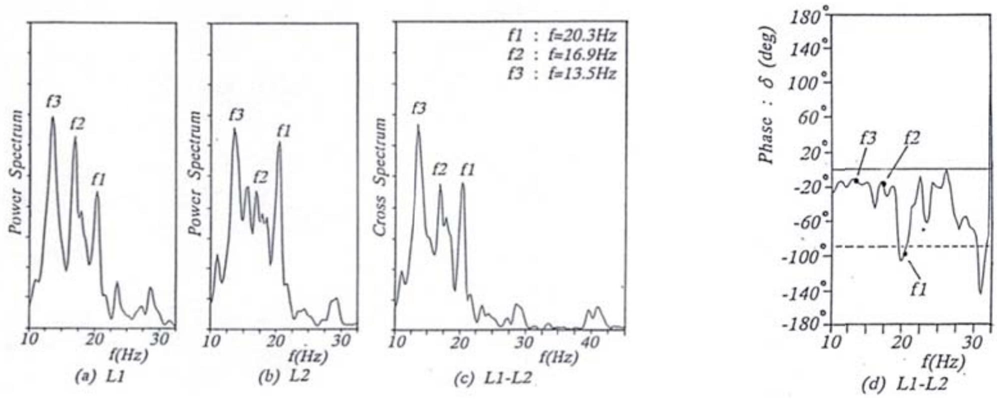


Fig. 16 Spectral analysis of pressure fluctuation at of m_{th} = 1.4 and K_i = 14.7 [44]

4.3.2 *Spectral analysis of pressure fluctuation* Figure 15 [44] shows a typical example of pressure fluctuations measured at L1 and L2 in the test condition of m_{th} = 1.4 and K_i = 14.7. It is seen that the fluctuations look irregular. In order to investigate the sources of irregular fluctuations, application of spectral analysis is desirable. Figure 16 (a)~(d) [44] show the results for the time series data in Fig. 15. In each power spectrum and cross spectrum, three kinds of dominant frequencies f_1, f_2, and f_3 are found. Each phase relationship between L1 and L2 for dominant frequencies is seen in Fig. 16 (d). All measured data for m_{th} = 1.4 were processed in the same manner, and their cavitation characteristics are shown in Fig. 17. The following characters are recognized:

1. St_1 (dimensionless form of f_1): it is nearly constant in the test range of K_i. And its phase shift is almost δ = -90 deg. Since δ corresponds to the angle between L1 and L2 stations, this frequency is $St_{ro\text{-}i}$, the rotating component in the measurement section.
2. St_2 (dimensionless form of f_2): This frequency decreases with the decrease of cavitation coefficient. And it corresponds to the synchronous fluctuation, since δ is nearly zero. Thus, this frequency is St_s, the natural frequency of draft tube system. It should be noted that the reason why this component appears in measured data might be due to the disturbance in turbulent swirl flow in a draft tube.
3. St_3 (dimensionless form of f_3): it is nearly constant like St_1. As this frequency coincides with the rotating frequency near the elbow obtained from the video data, this component corresponds to $St_{ro\text{-}b}$, the frequency of pressure recovery variation in the foot.

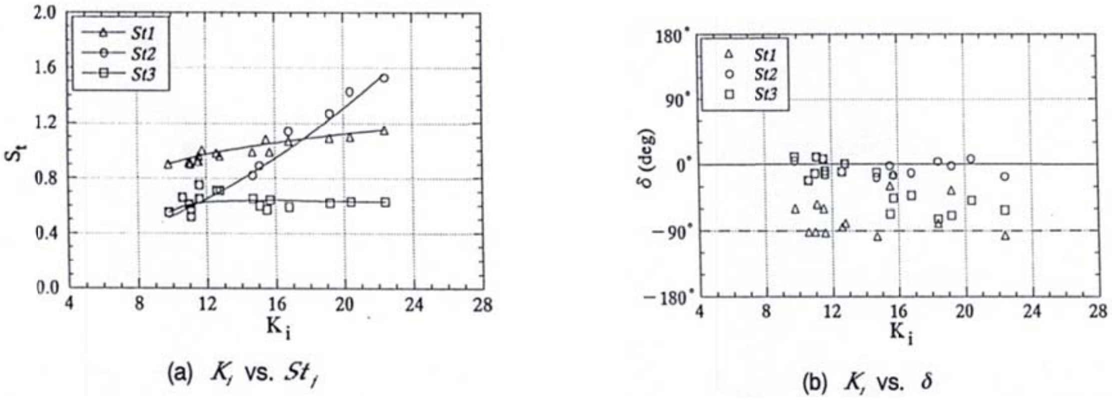
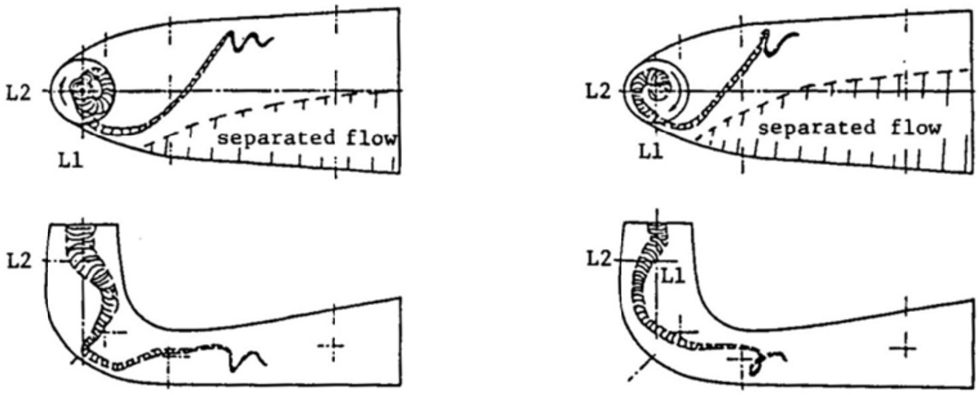


Fig. 17 Cavitation characteristics of dominant frequencies at m_{th} = 1.4

Further, an interesting note is that the maximum amplitude of pressure surge observed in Fig. 14 reasonably corresponds to the intersection between St_2 and St_3 curves. Therefore, the maximum surge might be interpreted as the resonance when the frequency of pressure recovery variation governed by a vortex rope precession in the elbow coincides with the natural frequency of draft tube system including the cavitated rope.

4.4 Natural Frequency of Draft Tube Vibration System

Figure 18 [24] shows sketches of spiral vortex rope at a resonant condition of mod A, where QS type surge occurs. (a) for the inlet pressure being minimum corresponds to the maximum pressure recovery and (b) for the maximum inlet pressure corresponds to the minimum recovery. We may suppose that the pressure recovery in the foot varies periodically depending on the location of vortex rope at the foot inlet, as the recovery is comparatively large in the foot for the case of strong swirling flow [45]. This assumption is supported by the following features seen in the sketches: Bold cavitated rope and its tip extended downstream in the foot are observed in (a) case, and slender cavitated rope and its tip near the entrance of the foot are the case of (b).



(a) at the minimum inlet pressure (b) at the maximum inlet pressure

Fig. 18 Sketches of vortex rope [24]

From this view, the draft tube vibration system may be represented by the one-dimensional spring mass model as the first order approximation [32]. The natural frequency is expressed as follows:

$$f_s = \frac{1}{2\pi}\sqrt{A_0\, p_C \,/\, (\rho\, L_{eq}\, V_C)} \tag{21}$$

where A_0 is area at foot inlet, p_C is pressure in the cavitated rope, ρ is water density, V_C is volume of cavitated rope, and L_{eq} : equivalent length (*f*: foot inlet, *e*: foot exit or draft tube exit).

$$L_{eq} = \int_f^e \frac{A_0}{A}\, d\ell \tag{22}$$

where A is area at distance ℓ from the foot inlet.

If there is a way to calculate V_C , we will be able to predict the natural frequency from eq. (21). An attempt was made by Wang, et al. [32]. Their result is shown in Fig. 19, where solid lines of their analytical result are compared with experimental data in St_S - K_i chart. Further, they challenged to predict the critical cavitation parameter K_{cr} at which the maximum pressure surge (QS type) due to the occurrence of resonance. Comparison of their prediction with experimental data is given in Fig. 20. Though the prediction is evaluated in the safety side, its improvement might be essential.

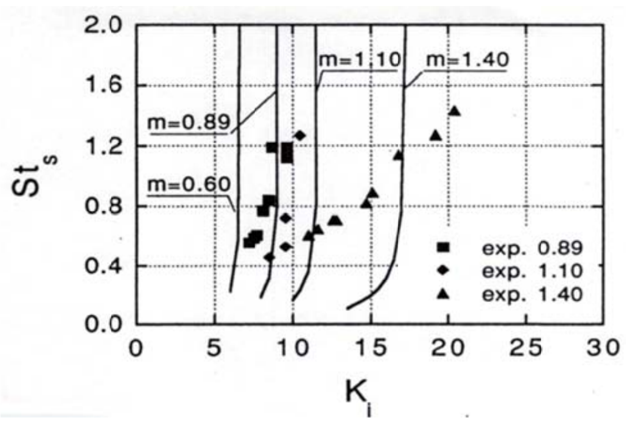


Fig. 19 Comparison of natural frequency [32]

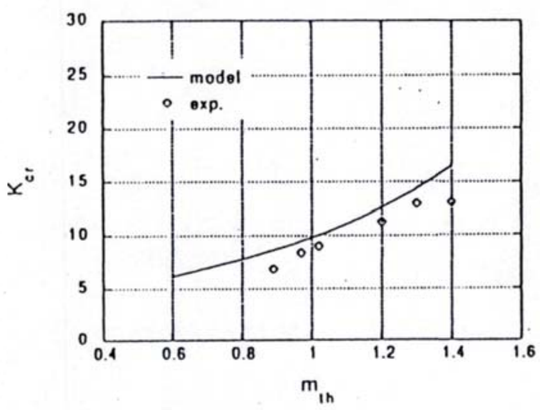


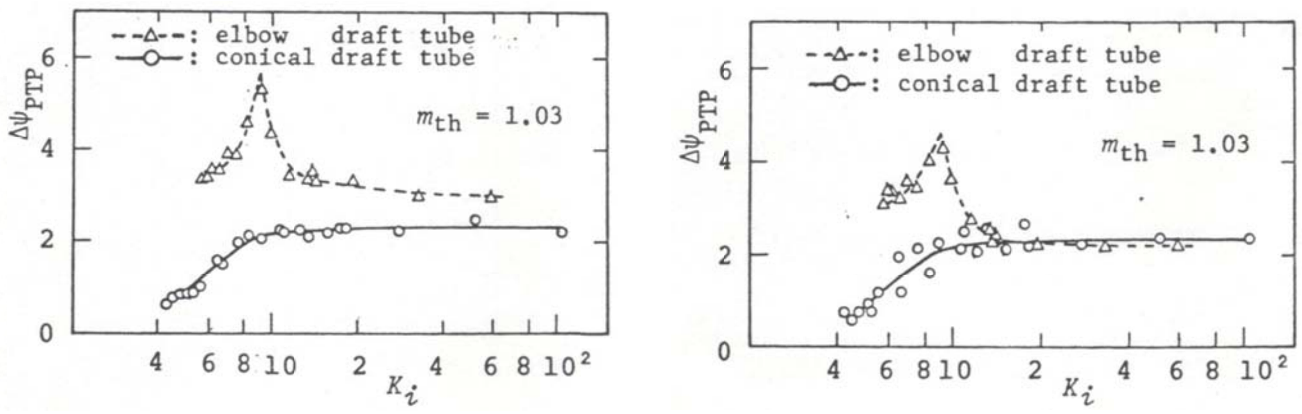
Fig. 20 Prediction of K_{cr} [32]

4.5 Alleviation of QS type Surge

Through a series of studies on pressure fluctuations in draft tubes, the authors have got the view that the flow in the foot governed by a vortex rope precession is the trigger of QS type surge in flow regime III. In order to validate this view academically, the following examinations to alleviate QS type surge might be desirable.

1. Larger inlet cone angle like 15 deg is selected so as to achieve sufficient pressure recovery up to elbow [36].
2. Area ratio of foot is reduced so as to minimize the variation of separated region in the foot caused by a vortex rope precession [41].
3. A conical diffuser (conical draft tube) is used eliminating elbow and foot components [41].
4. Fins are installed inside the inlet cone so at to weaken the swirl flow [46 - 49].

Here, No.3 attempt is briefly introduced. Namely, A conical draft tube without elbow, which has an inlet diameter of 125 mm, exit-to-inlet area ration of 4.1 and the cone angle of 9.5 deg, was prepared. Two pressure sensors were installed at L1 and L2 which were the same location as those of the mod A draft tube so as to compare the cavitation characteristics of pressure fluctuations directly. The results of amplitude characteristics at the test condition of m_{th} = 1.03 are shown in Fig. 21 [41], where dashed lines represent the characteristics of elbow draft tube and solid lines is that of conical draft tube. It is seen that the amplification of pressure surge didn't occur in the case of conical draft tube, though the cavitated vortex rope was observed inside it. Regarding the surge frequency, it is noted that both cavitation characteristics were almost the same [41].



(a) Measurement station L1 (b) Measurement station L2

Fig. 21 Comparison of cavitation characteristics between elbow draft tube and conical draft tube [41]

If we can suppress draft tube surge within the admissible level by using a certain technique [50 - 56], turbine operating range may be extended to much smaller load. Though the conventional techniques like air-injection were summarized by Grein [50], a new technique was proposed by Susan-Resiga, et al. [57], who utilized a water jet issued from the tip of runner cone axially in the inlet cone of a draft tube so as to eliminate the stagnation condition of swirling flow near the center. If replacement of turbine runner is possible, we will use an improved runner having such a character that sufficient meridional flow near the crown side is secured even at the partial load [58].

A note described here is regarding air-injection. Sufficient air supply to destroy the vortex rope is essential in this method, for the resonance may occur due to insufficient amount of air introduction in a draft tube since the natural frequency of the system decreases with increase of cavity volume with air in the rope.

5. From Component Test Stand to Numerical Test Stand - as Concluding Remarks

In the preceding sections, various flow physics related to the spiral vortex rope in a draft tube are discussed from a series of authors' studies based on the component tests mainly. This might be a useful approach, and deeper consideration of the model turbine test results may be possible from comparison with these basic flow natures. The other approach is the numerical analysis [59, 60, 61]. From such collaborative projects as Turbine-99 and FLINDT [62, 63], numerical analyses have really become a promising and powerful tool to solve abnormal phenomena occurred in the draft tube of a Francis turbine, though those important contributions are not discussed in this review. However, if we look back, the contribution made by Skotàk [64], who reported the reproduction of spiral rope in a conical diffuser by using LES successfully in 1999, greatly encouraged many researchers to be engaged in the simulation of vortex rope in a draft tube. In the 21st IAHR Symposium at Lausanne, Ruprecht et al. [65] demonstrated that the rope frequency was reasonably predicted from unsteady RANS calculation. And extensive contributions on the related subjects have been done and presented at the IAHR Symposiums held in the last decade [66 - 84]. One of challenging tasks at present may be prediction of natural frequency of draft tube system, examples of which are shown in Fig. 19. To accomplish this task, the cavitation model might be vital [85, 86]. If we refer to the 25th IAHR symposium held in Timisoara, an attempt to predict the cavity volume not in the part load but the over load case was reported by Dörfler, et al. [14].

Though it is true that further progress of numerical technique is still necessary, it may be possible to deepen our understanding of pressure surge and flow behavior in draft tubes of reaction turbines by using numerically simulated results in the present stage. In this sense, time has come to utilize a numerical test stand [87, 88] in place of a component test stand for solving questions of draft tube surge, which is an aged but fresh subject.

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Nomenclature

f	Frequency [Hz]	St	Dimensionless frequency
g	Gravitational acceleration [m/s^2]	St_{ro}	Dimensionless rotating frequency of vortex rope
K	Cavitation parameter	St_s	Dimensionless natural frequency of draft tube
K_{cr}	Critical cavitation parameter	t	Time [s]
K_i	Cavitation parameter defined at draft tube inlet	V_z , V_θ	Axial and circumferential velocity components
m, (m_{th})	Swirl rate (theoretical swirl rate)	$\Delta\psi$	Dimensionless pressure amplitude
n	Rotational speed [min^{-1}]	$\Delta\psi_{PTP}$	Peak-to-peak amplitude
n_s	Specific speed	$\Delta\psi_{rms}$	Root-mean-square amplitude
$\tilde{p}$	Fluctuating component of pressure [Pa]	$\Delta\psi_{ro}$	Rotating component of pressure amplitude
Q	Flow rate [m^3/s]	$\Delta\psi_{sy}$	Synchronous component of pressure amplitude
R	Radial distance [m]	δ	Phase [deg]
R_d	Radius of dead water region [m]	ρ	Water density
R_w	Wall radius of draft tube [m]	ψ_1 , ψ_2	Dimensionless pressure at location 1 and 2
r_d	Dimensionless radius of dead water region	$\tilde{\psi}_1$, $\tilde{\psi}_2$	Fluctuation of dimensionless pressure at 1 and 2

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