Similarity research of Francis turbine draft tube pressure fluctuation

Y L Xu¹,², D Q Qin¹,², Y Zhao¹,² and X C Meng³
¹ State Key Laboratory of Hydro-power Equipment, Harbin City 150040, China
² Harbin Electrical Machinery Company Limited, Harbin City 150040, China
³ China Institute of Water Resources and Hydropower Research, Beijing 100038, China
⁴ HADONG National Engineering Research Center-Hydropower Equipment Company LTD, Harbin City 150040, China

E-mail: xyl20081001@sina.com.cn

Abstract. In this paper, it presented the similarity research of Francis turbine draft tube pressure fluctuation between model turbine and the corresponding prototype. First, a qualitative analysis was made by runner outlet triangle velocity. Then a comparison was made between popular method and the method recommended by this paper which based on relative discharge taken zero swirl discharge as reference and dimensionless pressure pulsation amplitude taken runner outlet blade velocity head as reference respectively on model and prototype. Also a comparison of draft tube pressure fluctuation was made between model test data and prototype data from 12 power plants based on this method respectively. It had shown some similarity between model turbine and homologous prototype and had given the similarity range by statistic method. At last, a method was given concerning prototype draft tube pressure fluctuation amplitude prediction and a comparison was carried out between prediction results and site test results. It fitted very well which can prove the feasibility of this method.

1. Introduction

According to statistics from the world-bank, the share of hydro-power has increased by 22% in the energy structure in the latest 10 years, 2/3 contribution of which is from china. Because of its adaptive of large variation of head and discharge, Francis turbine is powering 60% of the worldwide installed hydroelectric capacity. In china, the number of Francis turbine with unit capacity bigger than 200MW is more than 400 units. It normally has to operate at off design condition according to the grid requirements. The induced hydraulic stability is key topics in the industry and the draft tube pressure fluctuation is a main parameter to evaluate it.

For hydraulic turbine, the prototype performance is predicted by the test results of reduced scale model turbine according to IEC 60193. In which the amplitude of the whole passage is normalized and dimensionless by the formula \[ \tilde{p}_A = \frac{\tilde{p}}{\rho E} \] or \[ A = \frac{\Delta H}{H} \] for convenience. The advantage of the definition is simple and correct from basic assumption and dimension analysis [1]. However, with regard to the phenomena represented, this definition has two drawbacks: (1) it can transpose from model to prototype just only the same operating parameters for model turbine and the homogenous prototype. But the model test is normally carried out at several characteristic head and prototype is operating at a wide range. Thus it results in big uncertainty for prototype prediction; (2) the draft tube
pressure fluctuation amplitude is directly related to the swirl at the runner outlet and it is not reflected at this definition.

Peter Dörfler and Fisher, R. K had studied the similarity of Francis turbine draft tube pressure fluctuation since 1980 and recommend to normalized it by the velocity head based on runner outlet absolute velocity or relative velocity [2,3,4,5]. Their work and method had made foundation for draft tube pressure fluctuation investigation. Wang had investigated the relation between vortex characteristics and pressure fluctuation of Francis turbine draft tube based on combination of simulation and model test [6]. Qin had studied the influence of operation condition, Thoma number and vortex characteristics on pressure fluctuation by model test and site test [7]. At the present stage, the researches of Francis turbine draft tube pressure fluctuation mainly focus on two aspects: (1) CFD simulation of draft tube pressure fluctuation; (2) Experiment method by model test or site test. Both methods have qualitatively studied the characteristics of draft tube pressure fluctuation, but not involved the similarity between model and prototype and transposition method if possible. Precise pressure fluctuation data is very rarely for model turbine and homogenous prototype because of limitation of prototype measuring condition and technical confidentiality of the supplier. So the theory research results can’t be verified directly.

This paper was based on zero swirl discharge and runner outlet relative velocity head to predict Francis turbine draft tube pressure fluctuation. First it was analyzed by runner outlet velocity triangle. And then a comparison was made between model and homogenous prototype of different methods. At the same time, 12 typical big Francis turbine draft tube pressure fluctuation data was collected and directly compared. And the recommendation transposable range was given by statistics method. At last a comparison was made between predicted value base on model turbine and site measuring results. It fitted very well.

2. Theory analysis
When operating at off design condition, it generates swirl at the draft tube for Francis turbine, which strikes the draft tube wall and induces draft tube or even the whole water passage pressure fluctuation and also imposes periodic axial and radial force on the runner. It is a big hidden trouble of the plant safety operation. For presentation draft tube pressure fluctuation amplitude intensity, it normally expresses as the relation between relative amplitude $\Delta H$ based on test head $H$ and discharge $Q$. Model test as well as site test results indicate that it is a big difference for different head when expressing them as this method. And the higher the operating head, the bigger the relative amplitude. It is taken a big problem to predict the prototype performance and assess the level of hydraulic stability.

As we all know, the runner exit swirl circulation is determined by the discharge at a constant prototype head, and the draft tube pressure fluctuation characteristics is closely related with it. Figure 1 is a Francis turbine runner exit velocity triangle. $U_2$, $W_2$ and $C_2$ are the peripheral velocity, relative velocity and absolute velocity respectively, $C_{2m,0}$ is the absolute velocity at zero swirl condition. From the knowledge of hydraulic machine, turbine discharge is proportional with runner exit meridional velocity:

$$Q = C_{2m} \cdot \frac{\pi D_2^2}{4} \cdot F_e$$

Where $F_e$ is the effective cross section area, $C_{2m}$ is runner exit meridional velocity and $D_2$ is runner outlet diameter.

The test head and runner diameter is normally constant for model test or site test. And the unit discharge is defined as $Q_{11} = Q / (D_2^2 \sqrt{H})$, so

$$Q_1 / Q_{11,0} = C_{1m} / C_{2m,0}$$

Where $Q_{11,0}$ is the unit discharge at zero swirl circulation condition. Zero swirl discharge line is defined as fitting curve across every zero swirl discharge point. A schematic diagram is shown as figure 2.

According to the velocity triangle, then
\[
Q_{11}/Q_{11,0} = C_{2m}C_{2m,0} = (U_2 - C_{2u})/U_2 = 1 - C_{2u}/U_2
\]

From above formulae, we deduce that the ratio of peripheral component of absolute velocity and peripheral velocity is the same at the identical relative discharge \(Q_{11}/Q_{11,0}\). In addition, draft tube pressure fluctuation amplitude is related to vortex characteristics or physically the runner exit swirl circulation, the characteristics parameter of which is exactly \(C_{2u}\). So it is reasonable to normalized Francis turbine draft tube pressure fluctuation expressing as the relation between relative amplitude based on runner exit peripheral velocity head and relative discharge dimensionless by zero swirl circulation discharge, which is \(\Delta H/h_{\text{dyn,u}} \sim Q_{11}/Q_{11,0}\).

### Figure 1. Exit velocity triangle of Francis turbine runner

### Figure 2. Schematic diagram of zero swirl discharge

3. **Case studies**

3.1. **Introduction of case study plant**

The case study is a Francis turbine of giant hydropower plant on the Yangtze River in China. Its main parameters were listed as table 1.

| Parameters                        | Value |
|-----------------------------------|-------|
| Rated head \(H_r\) (m)            | 85    |
| Rated speed \(n_r\) (r/min)       | 75    |
| Rated output \(P_r\) (MW)         | 710   |
| Specific speed \(n_s\) (m-kW)     | 186.35|

In the table, the specific speed is defined as \(n_s = n \cdot P^{0.5}/H^{1.25}\) and it was calculated at the optimum point. Pressure fluctuation locations were recommended by IEC 60193 for model turbine and homogenous prototype. This paper investigated the location at the draft tube downstream from 1.0D2 the runner outlet.

3.2. **Comparison of model turbine test results**

Model turbine test was carried out at the hydraulic machine test rig of China Institute of Water Resources and Hydropower Research, which is international neutral test rig and its test parameters and test method meet the relevant IEC code. Pressure fluctuation test was executed at sigma plant for 7 prototype characteristic head and discharge varied from no load condition to 120% rated output or the maximum expected output if the prototype head lower than rated head. Figure 3a is the presentation method from relevant IEC code, in which X-axis is the unit discharge \(Q_{11}\) and Y-axis is the peak to peak pressure fluctuation amplitude in the time domain and at 97% confidential level. In contrast, figure 3b is the recommendation method, in which X-axis is relative discharge \(Q_{11}/Q_{11,0}\) and Y-axis is relative amplitude \(\Delta H/h_{\text{dyn,u}}\) dimensionless by runner exit peripheral velocity head. For technical
confidential consideration, all pressure fluctuation data is a relative value, which is the ratio of real results and the maximum value across the whole operating range.

![Graph](image1)

(a) Presentation method from IEC code  
(b) Recommendation method

**Figure 3.** Comparison of model turbine draft tube pressure pulsation results between different methods

From above figures, the lower the prototype head, the bigger the draft tube pressure fluctuation amplitude if using the IEC code method. And the curve moves toward to right direction. By contrast, the curves almost converge to one line if consideration of the test uncertainty when using the recommended method.

### 3.3. Comparison of prototype site test results

Prototype data was provided by site measurement. This paper presented the location of draft tube cone which is geometry similarity with the model turbine location. The test was carried out at 7 prototype operating head and load from no load to full load, which almost cover the prototype whole operation range. Figure 4a is the presentation results from relevant IEC code and figure 4b is the recommended method. Different colour represents different operating head.

![Graph](image2)

(a) IEC code presentation method  
(b) Recommendation method

**Figure 4.** Comparison of prototype draft tube pressure pulsation test results

From above figures, prototype draft tube pressure fluctuation amplitude is related with head and discharge if using standard method. And the lower the operating head, the bigger the amplitude, and the curve moves toward the right direction. By contrast, it is just related with the discharge or load if using the recommendation method. In a word, it showed some similar tendency with the model turbine.

### 3.4. Comparison of model turbine and the homogenous prototype

Normally the model test was finished at the plant design stage. And it is hard to make sure the
prototype operating condition exactly with the model test because of its random nature. So it is a big problem to make directly comparison between model turbine and prototype. Francis turbine draft tube pressure fluctuation is irrelevant with the model turbine unit speed or prototype operating head if using the recommendation method. And above problem can be fully avoided by transposition the parameters of model turbine and homogenous prototype to dimensionless value. Furthermore, this paper presented comparison results of draft tube pressure fluctuation amplitude from 12 big hydropower plants in China, which were shown in figure 5. In the figure, the dashed line represents the site test results and dotted line is for model turbine test results. For the 12 plant, operating head is from 50m to 230m and the unit output range is from 90MW to 812MW and the unit specific speed range is from 128m•kW to 233m•kW. And they were designed and fabricated by 5 famous hydraulic machinery companies across the world. So it is much more representative.

Figure 5. Comparison of draft tube pressure pulsation test results between model and homologous prototype
According to above comparison results, the draft tube pressure fluctuation amplitude showed good similarity between model turbine and homogenous prototype at the range of 0.6 \( \frac{Q_{11}}{Q_{11,0}} \) to 1.2 \( \frac{Q_{11}}{Q_{11,0}} \) if using the recommendation method. And it can cover the normal operating range if properly design according to figure 2. However, if the selection design is not reasonable or the operating condition is far from the design point, some other complicated flow pattern will appear such as the inter-blade vortex region at low discharge, the flow separation region at low or high speed range, cavitation region at large discharge and Von Karman vortex region and so on. In these complex flow region, it may be not fitted very well between model turbine and homogenous prototype because of interaction among several flow pattern or some not similarity factors between model test and site test. For specific plant, the transposable range can be determined according to model test and flow pattern observation. Besides the draft tube vortex, the inter-blade vortex, the leading edge flow separation and runner outlet cavitation as well as Von Karman should also be considered. In these complicated regions, it showed a bigger difference between model turbine and homogenous prototype.

On the other hand, it is difficulty to intuitively determine whether the model turbine and prototype shows some similarity because the unit speed of model turbine or prototype operating head has a big influence on the results when using the IEC code method. So it is hard to predict the prototype operating stability.

4. Prediction of prototype draft tube pressure fluctuation amplitude
By comparison of different presentation methods and analysis of 12 plant draft tube pressure fluctuation data, it is more suitable to use the relative amplitude based on runner outlet velocity head and dimensionless discharge based on zero swirl discharge to predict the prototype performance. For the 12 plants, the operating heads cover 50m to 230m, and the specific speeds vary from \( 128 \text{m} \cdot \text{kW} \) to \( 232 \text{m} \cdot \text{kW} \), which can include mostly Francis turbine operating in china. Based on this, it can predict the prototype performance. Firstly the normalized curves were obtained by model test at different unit speed covering the prototype operating range and which showed the relation between \( \Delta H/\Delta h_{\text{dyn,u}} \) and \( \frac{Q_{11}}{Q_{11,0}} \). And then draft tube pressure fluctuation amplitude nature curves of this turbine were determined by statistics method and were shown as figure 6. In the figure, the dotted lines were the model test results and red dashed lines were nature curve by statistic method. At last the prototype draft tube pressure fluctuation amplitude could be predicted according to prototype operating conditions. Figure 7 is the comparison between predicted performance and site test results at minimum head and maximum head of this plant.

![Figure 6. Determination of prediction curve](image-url)
Figure 7. Comparison between prediction value and site test value

From figure 7, the predicted performance and site test results were fitted very well at most operating condition. At the region nearby $Q_{11}/Q_{11,0}=0.75$, the divergence may be induced by the difference of Thoma number between model tests and site test.

5. Conclusions
For this paper, it presented a method to characterize Francis draft tube pressure amplitude based on relative amplitude normalized by runner exit velocity head and relative discharge dimensionless by zero swirl circulation discharge. It is irrelevant with model test unit speed or prototype operating head and can provide the convenience for prototype performance prediction.

From the statistic results, the prediction range is simple swirl flow region, and the corresponding range is from $0.6Q_{11}/Q_{11,0}$ to $1.2Q_{11}/Q_{11,0}$. For complicated flow region such as inter-blade vortex region, flow separation region and so on, the similarity between model turbine and prototype is not very well. So it pays more attention to investigate the mechanics and interaction among these multi flow pattern.

It showed some limitations because it just investigated the amplitude characteristics but not involved the frequency analysis.

Acknowledgement
This work was supported by China Electrical Equipment Industry Association (Project No.2016YFF0202805) and the General Administration of Quality Supervision (Project No.201510207). We thank Harbin Institute of Large Electric Machinery for its test platform.

References
[1] IEC 60193. (1999–2011). Hydraulic turbines, storage pumps and pump-turbines—model acceptance tests (2nd edition).
[2] Peter Dörfler.,Mirjam Sick.,André Coutu. Flow-Induced Pulsation and Vibration in Hydroelectric Machinery,163-197.
[3] Doerfler, P. (1982). System oscillations excited by the Francis turbine’s part load vortex core: Mathematical modelling and experimental verification (German text, English summary). Dissertation, Technical University Vienna (Austria), October 1982.
[4] Doerfler, P., Lohmberg, A., Michler, W., & Sick, M. (2003). Investigation of pressure pulsation and runner forces in a single-stage reversible pump turbine model. IAHR work group WG1 (the behavior of hydraulic machinery under steady oscillatory conditions) 11th meeting, Stuttgart.
[5] Fisher, R. K., Palde, U., & Ulith, P. (1980). Comparison of draft tube surging of homologous scale models and prototype Francis turbines. IAHR Section Hydraulic Machinery,Equipment, and Cavitation, 10th Symposium (Tokyo, 1980), Vol. 1, pp. 541–556.
[6] Wang Zhengwei, Zhou Lingjiu. Simulations and Measurements of Pressure Oscillations Caused by Vortex Ropes. Journal of Fluids Engineering. Vol.128, Transactions of the ASME, July 2006, pp.649-655.

[7] Qin Daqing, Zhao Hongtian, Zhao Yang. Some new views on Francis turbine stability, Large electric machine and hydraulic turbine [J], 1998 (3): 43-50