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Vibration of Hydraulic Machinery

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Foreword

It is a privilege to be asked to write a prefatory note for this monograph reflecting the latest advance in the field of vibration of hydraulic machinery. Working on this book with Prof. Yulin Wu, a good friend and colleague for decades, and his outstanding team members was an enjoyable experience.

A jointly authored book like this has a root back to the last century. It began in the early 1980s when for the first time I heard about Yulin, a fast-rising scholar from Prof. Zuyan Mei. Indeed in the late 1960s, with Prof. Mei and scholars from the Beijing Institute of Hydropower, a monograph *Transient Process of Hydraulic Turbine* (in Chinese) initiated by me was written but cancelled for publication in 1969. Nevertheless, it inspired the *Book Series on Hydraulic Machinery* in 1986. Yulin and Prof. Mei were actively participating in the writing of this book series meanwhile they extended their work into the new field of numerical simulations for turbines including pump-storage turbines. After Prof. Mei deceased in 2003, Prof. Wu continues leading and developing this team at Tsinghua, producing remarkable numerical works. The excellence of their work on vibration simulations made him an ideal candidate for writing a continuous volume of the title *Vibration and Oscillation of Hydraulic Machinery* published two decades ago, emphasizing on numerical predictions. Being thus invited, he discussed the scope and set up the framework with me in late 2003. Then he started preparing the manuscripts together with Prof. Shuhong Liu who joined later. During the summer of 2008, while Yulin and Shuhong visiting me at Warwick, the first draft manuscript was proposed by Yulin with my contributions mainly to Chaps. 1, 6 and 7. Later on Profs. Zhongdong Qian and Hua-Shu Dou, both former team members of Yulin at Tsinghua, joined in 2011 and 2012 respectively.

Now I am pleased to witness the completion of this book reflecting such a collective willingness and effort across decades.

Personally, I would like to thank all the supports received to my research programmes and involvement in this book. These are the UK ESRC/EPSRC grants, the 10-year support from the UK EPSRC WIMRC grants and the generous support from the UK Royal Academy of Engineering; and the Open Fund of Tsinghua University (State Key Laboratory of Hydroscience and Engineering) and the financial and technical support from the Three Gorges authority.

In particular, it is a great honour to receive the award of Chinese Global Recruit Programme of Peking University that enables me to work in Beijing closely with authors during the final stage of the book writing. The support from Prof. Cunbiao Lee of Peking University is thus highly appreciated.

20 October 2012

Shengcai Li
Zhong-guan Xin-yuan
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Preface

The present book *Vibration of Hydraulic Machinery* deals with the vibration problem which has significant influence on the safety and reliable operation of hydraulic machinery. It provides with the new achievements and the latest development in these areas in the community including those by the authors, even in the basic areas of this subject.

The prediction for vibration of hydraulic machinery is currently an important subject since vibration has a major effect on the performance of hydraulic machinery. In the last 10 years, progress has been achieved in theory, modeling, and mathematical analysis, as well as monitoring of vibration of hydraulic machinery. With hydraulic turbine capacities getting increasingly larger and pump speeds ever higher, there have been many research achievements in these areas published in symposiums, journals, and books.

This book covers the fundamentals of mechanical vibration and rotordynamics as well as their main numerical models and analysis methods for the vibration prediction. The mechanical and hydraulic excitations to the vibration are analyzed, and the pressure fluctuation induced by the unsteady turbulent flow is predicted in order to obtain the unsteady loads. This book also discusses the loads, constraint conditions, and the elastic and damping characters of the mechanical system, the structure dynamic analysis, the rotor dynamic analysis, and the instability of system of hydraulic machines, including the illustration of monitoring system for the instability, and the vibration in hydraulic units. Solutions of all the problems are necessary for vibration prediction of hydraulic machinery.

The authors of the present book are as follows: Chap. 1: Shengcai Li, Chap. 2: Shuhong Liu, Chap. 3: Zhongdong Qian, Chap. 4: Leqing Wang and Dazhuan Wu, Chap. 5: Shuhong Liu, Chap. 6: Shengcai Li, Chap. 7: Shengcai Li, Chap. 8: Dazhuan Wu and Yulin Wu, Chap. 9: Zhongdong Qian, Chap. 10: Hua-Shu Dou, and Chap. 11: Lei Jiao and Yulin Wu. Professor Hua-Shu Dou made final reviewing and compiling of the whole contents of the book.

The authors would like to thank the National Natural Science Foundation of China (NSFC) for main key project grants (contracts No. 59493700) on the key technology of hydraulic turbine generator unit of three gorges projects (1994–1999), and for key project grants (contracts No. 90410019, 2004–2007 and 10532010, 2006–2009), as well as other five projects, i. e., China Yangtze Three

Gorges Project Development Cooperation (CTGPC) for project grants (contracts No. CT-02-04-04 and CT-03-04-01); China Longtan Hydropower Development Company Ltd. for project grants (2001–2002); Harbin Institute of Large Electric Machinery & Hydraulic Turbine for project grants (contracts No. 2002158 and 2006429).

Many thanks to Fujian Electric Power Test & Research Institute, Beijing Huake Tongan Monitoring Technology Co. Ltd., Tianjin Tianfa Heavy Machinery & Hydro Power Equipment Manufacture Co. Ltd. for their supporting to the cooperative research on hydraulic machinery.

Sincere thanks to Hitachi Ltd including both Hitachi Industries Co. Ltd. and Hitachi Works, Mitsubishi Heavy Industries Co. Ltd., the Institute of Fluid Sciences of Tohoku University, and Kyushu Institute of Technology, for long time of cooperation.

The authors would highly appreciate the help of Profs. Naixiang Chen, Hongyuan Xu, Zhenwei Wang, Shuliang Cao, Yangjun Zhang, Jing Ren, Xianwu Luo, Baoshan Zhu (Tsinghua University), Profs. Jianzhong Xu (Academician), Jiezhi Wu, Cunbiao Lee, Qingdong Cai (Peking University), and Professors from China and other universities Sheng Zhou, Xingqi Luo, Shouqi Yuan, Zhenyue Ma, Fujun Wang, Guoyu Wang, Qingguang Chen, Lingjiu Zhou, Xuelin Tang, Jiandong Yang, Fengqin Han and Chao Yan. Drs. Jiang Dai, Zixiang Sun,Weizhang Wu, Jianming Yang, Wei Zhang, Zhaohui Xu, Liang Zhang, Yu Xu, Yuzhen Wu, Yong Li, Hongfen Tang, Shangfeng Wu, Penghui Xia, Xiaojing Wu, Jie Shao, Daqing Zhou, Wei Yang, Fan Yang, Guangjun Cao, Gang Chen, Zhaofeng Xu, Zhiping Li, and Jinwei Li have been long cooperated with the authors, their supports are gratefully acknowledged.

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Finally, thanks to the UK EPSRC's Warwick-IMRC for their financial support (R.ESCM.9001 and R.ESCM9004) on turbine technology and cavitation.

Yulin Wu

Contents

Part III Hydrodynamic and Structural Analysis

Part I
Fundamental

Chapter 1
Introduction

In this book, a hydraulic machine is referred to a hydraulic turbine or a pump. Rotation of the turbine runner or the pump impeller is transmitted through a shaft supported on bearings to a generator or a motor that is connected with the electric grid. This whole assembly is called a hydraulic unit.

It is necessary to take vibration prediction into consideration since the vibration has a major influence on the performance of hydraulic machinery (Ohashi 1991). In this chapter, the main content of the vibration prediction of hydraulic machines will be briefly introduced. In the following chapters, detailed information will be given. First, the fundamentals on the prediction of mechanical vibration and rotordynamics will be briefly emphasized on their basic concepts, model, and essential equations in Chaps. 2 and 4. Chapter 3 introduces the main numerical methods used in structure and rotor dynamic analysis aspects, which are necessary for numerical simulation on the vibration prediction. Then mechanical excitations and hydraulic excitations as the source forces of forced vibration in hydraulic machinery will be analyzed in Chaps. 5 and 6 respectively. In Chap. 7, topics about pressure fluctuations induced by unsteady turbulent flow in turbine and pump will be presented in order to get the unsteady loads. Once information about the loads, the constrain conditions and the elastic and damping characters of the mechanical system is known, the structure and rotor dynamic analysis of hydraulic machines can be predicted as demonstrated in Chaps. 8 and 9 respectively. Chapter 10 focuses on the instability of hydraulic turbine system. Finally, Chap. 11 illustrates monitoring system of the instability and the vibration for hydraulic turbine units and pumps, including the sensor selection and system design. Some examples of large hydropower plants are also given in this chapter. This monitoring system is also used for checking the prediction results in hydraulic machinery.

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1.1 Hydraulic Machinery System

In this section, we introduce the concept of the mechanical systems of hydraulic turbines and pumps which is quite essential.

1.1.1 Hydraulic Turbine Structures

Most hydroelectric power comes from the potential energy of dammed water. The amount of energy stored in water depends on the volume and the difference in height between the source and the water's outflow. This height difference is called the head. The amount of potential energy in water is proportional to the head.

Hydroelectric plants with no reservoir capacity are called run-of-the-river plants, since it is not possible to store water.

With the increasing capacity and size of hydraulic turbines, vibration of the turbine structure and rotating system strongly influences the safety of the power house where turbines are installed. The dynamic analysis of the components, the rotor and its rotating system is therefore essential to design and operation.

The hydraulic turbine is a machine that converts the energy of an elevated water supply into the mechanical energy of a rotating shaft. All modern hydraulic turbines are fluid dynamic machinery of the jet and vane type that operates on the impulse or reaction principle and involves the conversion of pressure energy to kinetic energy. The shaft drives an electric generator, and the speed must be of an acceptable synchronous value. Efficiency of hydraulic turbine installations is always high, more than 85 % after allowances of hydraulic, shock, bearing, friction, generator, and mechanical losses. Material selection is not only a problem of machine design and stress loading from running speeds along with hydraulic surges, but also a matter of fabrication, maintenance, and resistance to erosion and corrosion, as well as cavitation pitting (Akahane and Suzuki 1996).

Storage hydro plants have employed various types of equipment to pump water to an elevated storage reservoir during off-peak periods and to generate power during on-peak periods when the water runs from the reservoir through hydraulic turbines. The principal equipment of the station is the pumping-generating unit. In most practices, the machinery is reversible and is used both for pumping and generating; it is designed to function as a motor and pump in one direction of rotation and as a turbine and generator in the opposite direction of rotation.

There are different types of turbines, such as, the Francis, Kaplan, bulb (or tubular) and impulse turbines, and their physical models need to be established for dynamic analysis of mechanical systems. There are three main categories of reaction hydraulic turbines: the Francis turbine (Fig. 1.1) and Kaplan turbine (Fig. 1.2), and bulb (or tubular) turbine.

In reaction turbines, pressure from working fluid changes as it flows through the turbine and thus the working fluid transfers energy to the turbine. A casement is needed to contain the water flow.

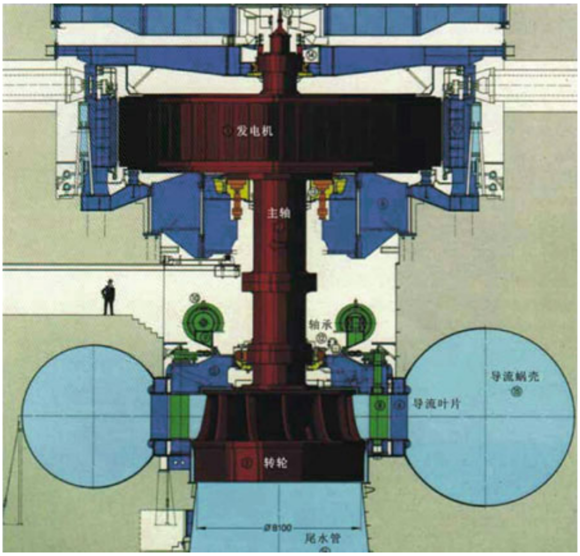


Fig. 1.1 Francis turbine (http://www.en.wikipedia.org/wiki/Kaplan_turbine)

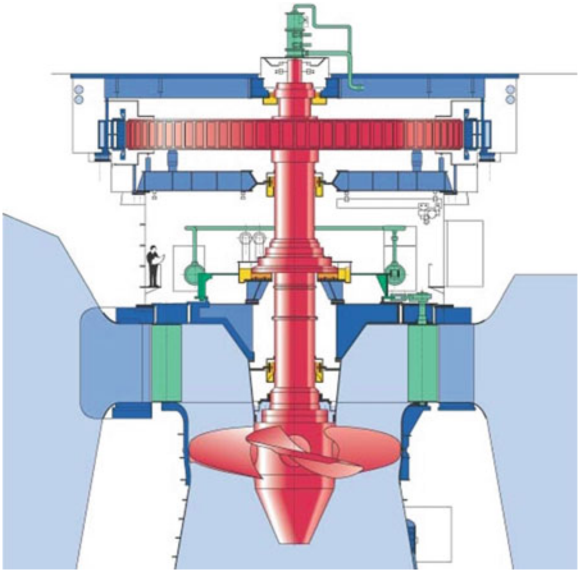
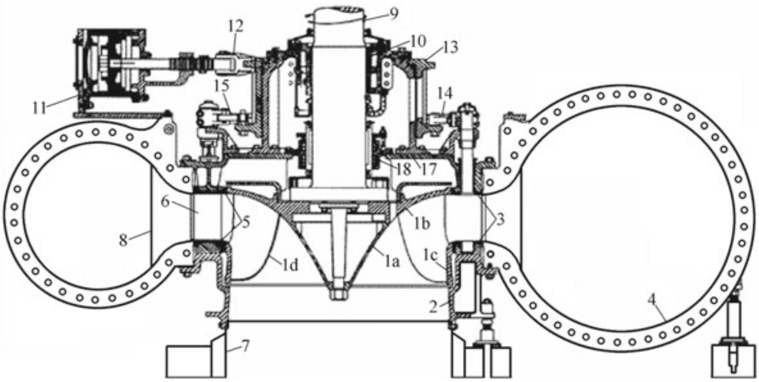


Fig. 1.2 Kaplan turbine (http://www.en.wikipedia.org/wiki/Kaplan_turbine)

The Francis turbine is located between the high pressure water source and the low pressure water exit, usually at the base of a dam. The inlet is spiral shaped. Guide vanes direct the water tangentially to the runner entrance. This radial flow acts on the runner vanes, propelling the runner to spin. The guide vanes (or wicket gate) may be adjustable to allow efficient turbine operation depending on the range of water-flow conditions (Fig. 1.3).



1	Turbine runner	8	Dischargering
1a	Runner cone	9	Turbine shaft
1b	Runner crown	10	Turbine guide bearing
1c	Runner band	11	GV servomotor
1d	Runner bucket	12	Servomotor rod
2	Wearing rings	13	GV opening ring
3	Facing plates	14	GV link
4	Spiral casing (SC)	15	GV arm
5	Stay vanes	16	Pacing box or stuffing box
6	Guide vanes (GV)	17	Head cover
7	Draft tube		

Fig. 1.3 Francis turbine structure components (from Wikipedia 2008a)

Large Francis turbines are individually designed for each site to optimize its operational efficiency, typically over 90 %. Francis type units cover a wide head range, from 20 to 700 m and their output varies from a few kilowatts to 1,000 megawatts. Apart from electrical production, they may also be used for pumped water storage.

The Kaplan turbine is another type of reaction turbine, i.e., pressure of working fluid changes as the fluid moves through the turbine losing energy. The inlet is a scroll-shaped tube that wraps around the turbine's wicket gate. Water is directed, through the spiral, on to the wicket gate, and then is turned from radial to axial direction before entering a propeller shaped runner. Different from the Francis turbine, the water is axially directed to the runner in the Kaplan turbine. The outlet is a specially shaped draft tube that helps decelerate the water and recover kinetic energy.

Variable Pitch angles of the wicket gate and turbine blades (often referred as "on cam" operation) allows efficient operation for a range of flow conditions. Kaplan turbine efficiencies are typically over 90 %, but may be lower in very low head applications. Kaplan turbines are widely used throughout the world for electrical power production. They cover the lowest head hydro-sites and are especially suitable for large flow rate conditions.

Propeller turbines have non-adjustable propeller vanes. They are used in situations where the range of water head is not large.

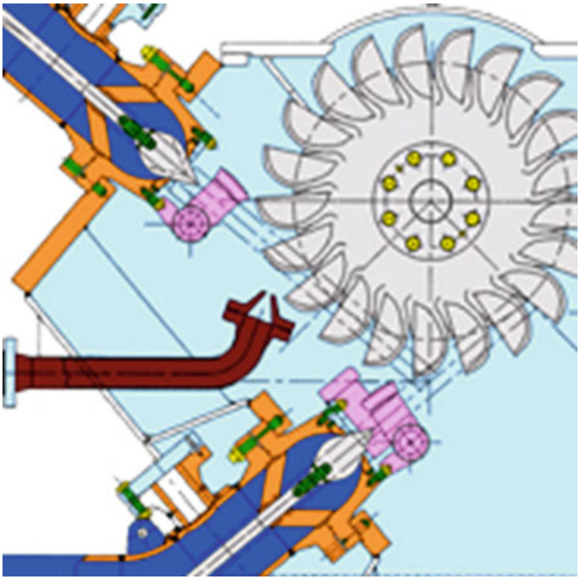


Fig. 1.4 Pelton turbine (http://www.en.wikipedia.org/wiki/Pelton_turbine)

Bulb or Tubular turbines are designed to allow the water flow directly into the draft tube. A large bulb is centered in the water pipe which holds the generator, wicket gate and runner. Tubular turbines are a fully axial design, whereas Kaplan turbines have a radial wicket gate.

The Pelton wheel is among the most efficient types of water turbines, and is an impulse machine which is designed to utilize the energy from a fluid jet (Fig. 1.4).

The water flows along the tangent to runner path. Nozzles direct forceful streams of water against a series of spoon-shaped buckets mounted around the edge of a wheel. As water flows into the bucket, the direction of the water velocity changes to follow the bucket contour. When the water-jet contacts the bucket, the decelerated water exerts pressure on the bucket as it flows out of the other side of the bucket at lower velocity. In the process, the water's momentum is transferred to the turbine. For maximum output and efficiency, the turbine system is designed so that the water-jet velocity is twice the velocity of the bucket. Often two buckets are mounted side-by-side, thus splitting the water jet in half. This balances the side-load forces on the wheel, and helps to ensure smooth, efficient momentum transfer from the fluid jet to the turbine wheel.

For detailed knowledge of fluid dynamics about these turbines, readers are referred to the volume titled 'Hydraulic Design of Hydraulic Machinery' (Krishna 1997).

1.1.2 Pump Mechanical Systems

A pump is a machine that draws fluid into itself through an entrance port and forces the fluid out through an exhaust port (see Figs. 1.5, 1.6, 1.7 and 1.8). A pump may

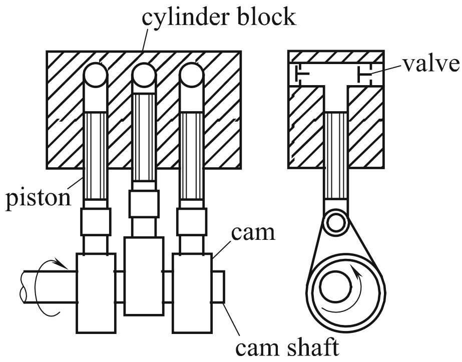


Fig. 1.5 Multi-cylinder reciprocating pump

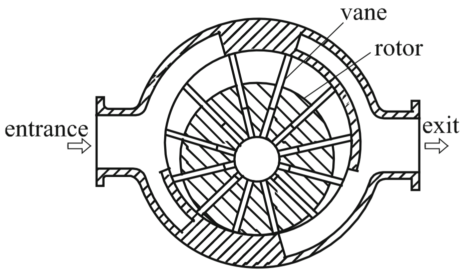


Fig. 1.6 Rotary pump (sliding type)

serve to move liquid, as in a cross-country pipeline; to lift liquid, from a well or to the top of a tall building; or to put fluid under pressure, as in a hydraulic brake.

A displacement pump is one that develops its action through the alternate filling and emptying of an enclosed volume. There are two basic types: reciprocating (Fig. 1.5) and rotary (Fig. 1.6).

Positive-displacement reciprocating pumps have cylinders and pistons with an inlet valve that opens the cylinder to the inlet pipe during suction stroke, and an outlet valve that opens to the discharge pipe during discharge stroke. Except for special designs with continuously variable strokes, reciprocating power pumps deliver an essentially constant capacity over their entire pressure range when driven at constant speed.

The purpose of a centrifugal pump is to move fluid by accelerating it radically outward. More fluid is transferred by centrifugal pumps than by all the other types combined (Fig. 1.7). As shown in Fig. 1.8, a centrifugal pump basically consists of one or more rotating impellers in a stationary casing which guides the fluid from one impeller to the next in the case of multistage pumps. Impellers may be single suction or double suction. Other essential parts of all centrifugal pumps are (1) wearing surfaces or rings, which make a close-clearance running joint between the impeller and the casing to minimize the backflow of fluid from the discharge to the suction; (2) the shaft, which supports and drives the impeller; and (3) the stuffing box or seal, which prevents leakage between shaft and casing.

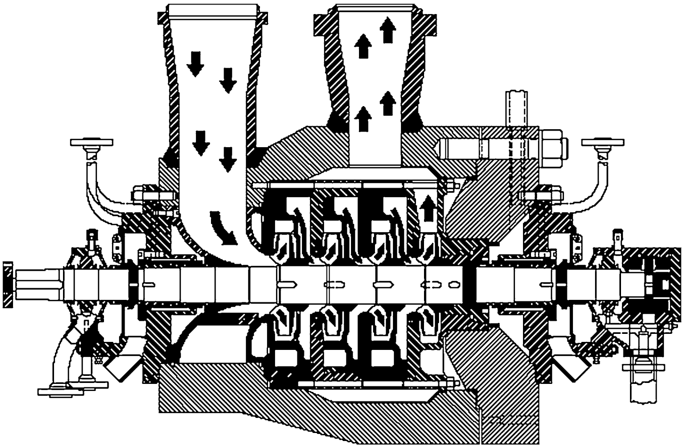


Fig. 1.7 Multi-stage centrifugal pump (http://www.architettisenzatetto.net/wp2/?cat=24)

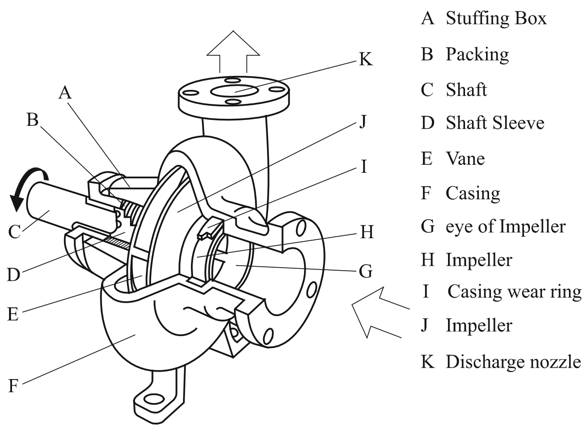


Fig. 1.8 Centrifugal pump assembly (http://www.pumpfundamentals.com/centrifugal_pump.htm)

1.2 Physical Model of Hydraulic Machinery as Mechanical System

Modern mechanical systems are often very complex and consist of many components interconnected by joints and force elements. These systems are referred to as multibody systems or continuous mass distributed systems. The dynamics of such systems are often governed by complicated relationships resulting from the relative motion and joint forces between components of the system. Figure 1.1 shows a Francis turbine generator unit, which can be considered as an example of a multibody system that consists of many components.

While most structures are stationary with respect to an inertial frame of reference, many machines contain rotating elements that may vibrate owing to their elasticity and inertia. Rotating bodies and structures are usually defined as rotors.

The dynamic analysis of vibration in hydraulic turbines has two aspects in engineering: (1) Dynamic analysis of the stationary structure's components (Structure dynamics analysis), which is performed for each component, such as a runner (even for a single runner-blade), a spiral casing and a draft tube, etc. The component is treated as a continuous mass object in the analysis. (2) Dynamic analysis of the rotating shaft system (shaft rotordynamics in hydraulic turbines), where the system is simplified as the lumped multibody system.

In each type of dynamic analysis, the following steps should be included:

(1) The first step is to establish the physical model of an analysis object.
(2) Secondly, it is important to determine which analytical approach should be used in the work. For example, in rotordynamics the Riccati transfer matrix (Garnett 1997), Newmark numerical integral method (Newmark 1959), or others should be adopted to calculate and analyze instantaneous non-linear response of the rotor system of hydroelectric units. In structure analysis, the finite element method (FEM) is usually applied to study the turbine components. The main analytical approaches from principle to their application in hydraulic machinery will be illustrated in following chapters, especially in Chaps. 8 and 9.
(3) The third step is to set up a grid system or other geometrical system of the analytical object. This process is determined according to the analytical approach and introduced in each calculation.
(4) The fourth step is to study the action forces and excitations which have impact on the analyzed objects, such as excitation induced by mechanical aspects, fluid flow (pressure distribution and pressure fluctuation) and by electric–magnetic effluences. Excitation will be covered in Chaps. 5, 6 and 7.
(5) The fifth step is to select the boundary and restrict conditions to each analytical object for numerical simulation.
(6) Afterwards, the numerical computation is carried out with different mathematical algorithms, and the computer resource and computation time is taken into consideration.
(7) The final step is to analyze the calculation results in order to apply them to an engineering design for enhance the performance of the machines.

The analytical procedure on pump dynamics is similar to that of turbines.

1.2.1 Physical Model of a Hydraulic Turbine Unit Shaft System

The hydraulic turbine unit is essential equipment to hydroelectric power generation, and shafts are an important component of these machines. Its dynamic characteristic is bound with the hydroelectric reliability, life-span, and economic

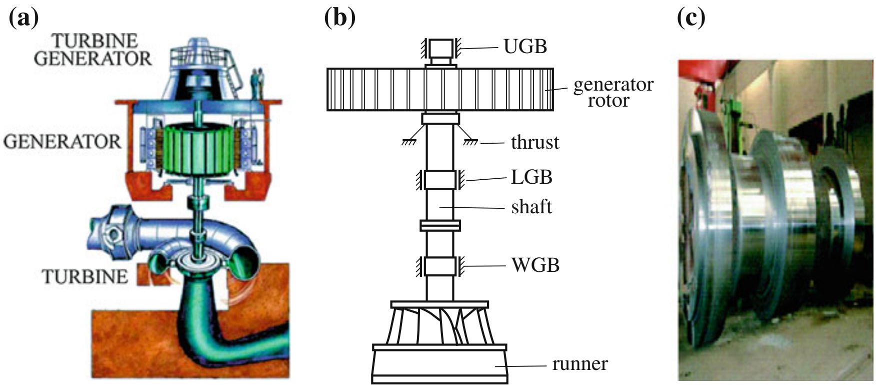


Fig. 1.9 Diagram of the umbrella-type shaft system of a Francis turbine unit. **a** Three dimensional diagram. **b** Meridional plane diagram. **c** Generator shaft

index of the entire machine. Therefore, it is necessary to analyze the large hydroelectric machines from this aspect.

The first step in rotor dynamic analysis of hydraulic turbines is to obtain the physical model from a real hydraulic turbine unit as shown in Fig. 1.9. The model is a simplified umbrella-type shaft system of a Francis turbine unit (http://www.rise.org.au/info/Tech/hydro/large.html).

The umbrella-type shaft system consists of a shaft, an upper guide bearing (UGB), a generator rotor, a thrust bearing, a low guide bearing (LGB), a coupling, a water guide bearing (WGB) and a runner (see Fig. 1.9b).

The shaft system of a real hydraulic turbine unit is a continuously distributed mass system with infinite degrees of freedom. Figure 1.10a and b show the mechanical models used for the analysis of shaft system. Figure 1.10a is a simplification of the shaft system that contains two-disc rotor system with

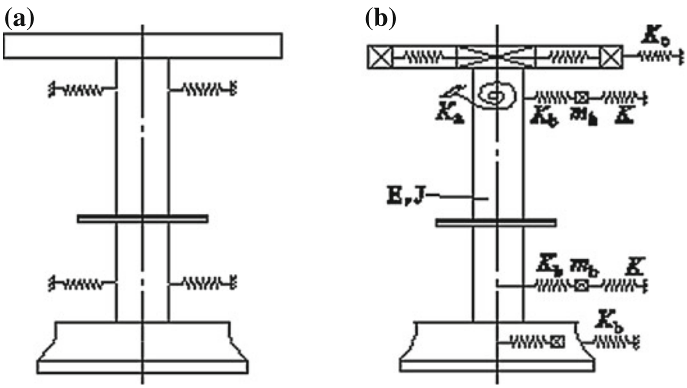


Fig. 1.10 Mechanics models of the shafts of the hydraulic turbine unit. **a** Simplified model. **b** Complex model

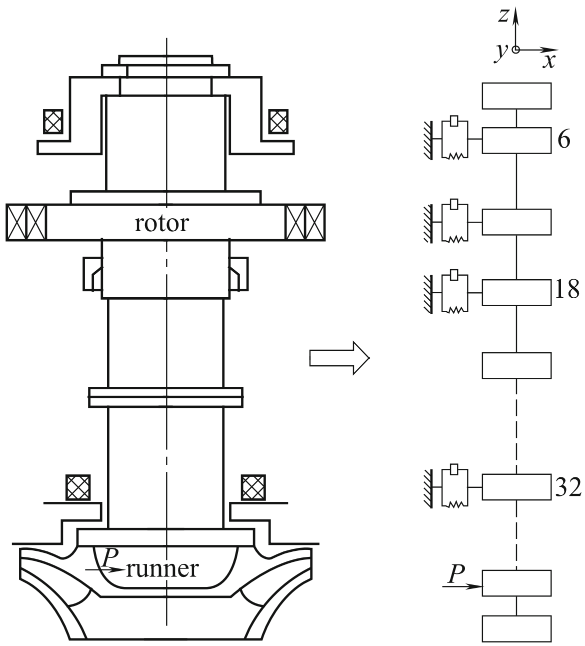


Fig. 1.11 Schematic drawing of a concentrated mass method in the shaft

multibearing supports; and Fig. 1.10b shows the rotor system with such effects, shear deformation, rotary inertia, gyroscopic moment, additional mass acting in the hydraulic turbine, and electromagnetic induction of instantaneous response in the rotor system. This model is necessitated because the diameter of the shaft is thick compared to its length (Fig. 1.9b). A non-linear oil film force on the bearing is identified and accounted by a factor in the calculation (Feng and Chu 2001).

Figure 1.11 shows a schematic drawing of the lumped mass method in a shaft using the Riccati transfer matrix method. In the model, the lumped parameters are set up from discrete treatment of the main assemblies contacting with the shaft (Feng and Chu 2001).

1.2.2 Physical Model of a Multi-Stage Pump Shaft System

A more effective approach to generate high pressure with a single centrifugal pump is to install multiple impellers on a common shaft within the same pump casing. Internal channels in the pump casing route the discharge of one impeller to the suction of another impeller. The illustration below shows a diagram of the impeller arrangement of a multistage pump. Water enters the pump from the top left and passes through each of the four impellers in a series, going from left to right. It goes from the volute surrounding the discharge of one impeller to the suction of the next impeller.

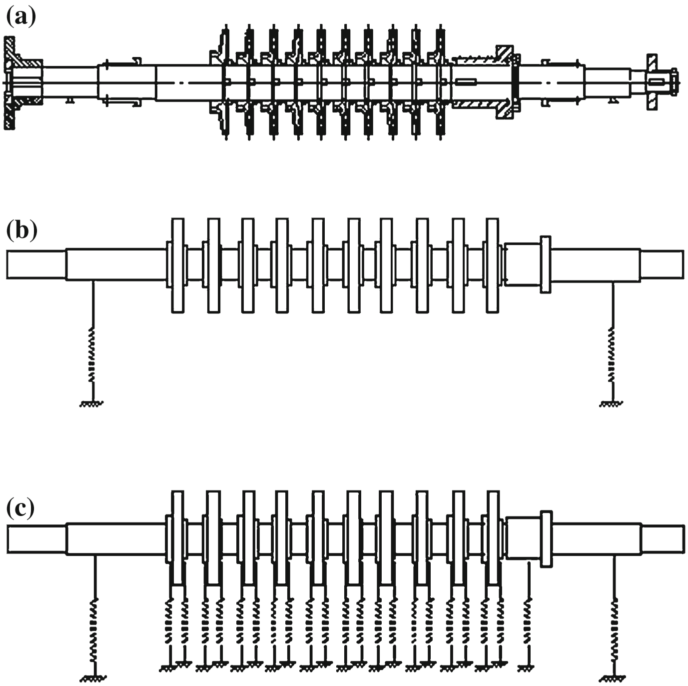


Fig. 1.12 **a** Model of multi-stage centrifugal pump. **b** Model of shaft operation in the air. **c** Model of shaft operation in the water

Now and then, centrifugal pumps are developed with larger capacity and higher head. The one shown in Fig. 1.12 has the head up to 3,000 m with power up to 3,000 KW, for the transportation of high pressure liquid in an industrial plant. For designing large rotating machinery, the values of critical speeds related to the desired operating range should be chosen carefully. For the rotor dynamic analysis of centrifugal pumps, the concepts of "dry" and "wet" critical speeds are introduced. The "dry" critical speed is one without consideration of the dynamic characteristics of seal as shown in Fig. 1.12b; The "wet" critical speed is when the pump is working in the power station with consideration of the dynamic characteristics of seal as shown in Fig. 1.12c (Chen et al. 2008).

1.2.3 Physical Model of Hydro-Turbine Structure Analysis

The physical model of hydro-turbine structure components for dynamic analysis is usually an exact geometric model of the components analyzed. For example, hydraulic excitation forces on Francis turbine runners (Fig. 1.13a and b) would increase due to higher heads and fluid velocities. A complete dynamic analysis of runner behavior is necessary for the prevention of vibration damage in a turbine.

Fig. 1.13 **a** Runner for three-gorges project. **b** Blade in machining of runner (http://www.xsrb.xsnet.cn/xsdaily/gb/content/2005-07/11/content_468089.htm, http://www.slsdge.com.cn)

Fig. 1.14 Geometric model of a runner

Since runners are submerged in water inside the casing, the effects caused by the presence of this heavy fluid inside a rigid wall must be considered in dynamic analysis (From Wikipedia 2008b).

Owing to the cyclic symmetrical nature of the runner structure (total 17 blades), a blade covering an angle of 360/17 degrees can be used in simulation for dynamic analysis. Then the model is expanded to cover the whole runner (shown in Fig. 1.14) and the analysis on mechanical vibration is performed. The complete model will also be used in the water simulation, that is, the physical model of the runner is surrounded by a cylindrical fluid domain shown in Fig. 1.15 (Liang et al. 2006). The fluid mesh should be generated using extension from the structure mesh so the same set of nodes is shared between both domains on the interface.