MECHANICAL DESIGN
AND MANUFACTURE OF
HYDRAULIC MACHINERY

MEI ZU-YAN

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Mechanical Design and Manufacturing of Hydraulic Machinery

Mei Zu-yan, Editor

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Preface

The publishing of this book series on Hydraulic Machinery, organised and edited by the International Editorial Committee for Book Series on Hydraulic Machinery (IECBSHM), marks the results of successful cooperation between the Committee, the authors and the editors of each volume.

The Editorial Committee consists of 35 scholars from 20 countries. More than 100 academics and engineers from 23 countries have participated in the compilation of the book series. The volumes reflect the latest developments, gained from many countries, in concepts, techniques, and experiences related to specific areas of hydraulic machinery. This is a great joint exercise by so many experts on a world wide basis that will inevitably bring impetus to technical achievement and progress within the hydraulic machinery industry and promote understanding and cooperation among scholars and professional societies throughout the world.

The authors have devoted considerable time and energy to complete the manuscripts and even more time was occupied by the editors in revising and correlating the individual volumes. Dr A P Boldy, Secretary IECBSHM, contributed greatly to the overall editing and preparation of the final manuscripts. Mr J G R Hindley, of Avebury Technical, offered many suggestions and remained helpful in every phase of the editorial and publishing work.

Great assistance in the preparation of the manuscripts from numerous persons in different parts of the world have been received, without which the publication of the book series would not have been possible. I would like to express appreciation both from myself and on behalf of the Editorial Committee to these people, the list of names being too lengthy to include here.

Duan Chang Guo
Chairman IECBSHM

Foreword of the Editor

This book is one of the nine volumes in the *Book Series on Hydraulic Machinery* organised by the International Editorial Committee. The subject for this volume is *Mechanical Design and Manufacturing of Hydraulic Machinery*. This is a topic that concerns the varied functions of design offices and workshops of all manufacturers. Experiences gained in these organisations are so numerous that they can hardly be outlined and compiled into one book. Besides, designs and manufacturing practices are so varied among firms that it is difficult to select any ones to be representative for description in this book. Therefore a large number of authors, fourteen from six countries, have been invited to contribute to the chapters of this volume, each contribution based on the author's extensive experience.

The question of reader level of this series of books was the major topic for discussion at the initial organising meeting. It was agreed that the book series would not primarily be used by college students as textbooks or by engineers as design handbooks. Rather it purports to convey to the profession the present status and latest developments in the hydraulic machinery field.

The structure of a hydraulic machine is evolved principally to satisfy the requirements of the fluid flow, therefore in a volume where the main interest is in mechanical design and manufacturing it is still necessary to constantly refer to the hydraulic characteristics of the machines. In many chapters of this volume, the authors very deftly illustrated the arrival of the best choice in mechanical construction from assessment of the hydraulic characteristics.

For the specific purpose of writing this book series, Prof. P. Henry of the Ecole polytechnique federal de Lausanne was entrusted to prepare a unified nomenclature of symbols for use in the various volumes. The nomenclature system proposed is based on the one that had been in use for many years within the Hydraulic Machinery and Fluid Dynamics Institute of the EPFL and by several Swiss manufacturers. Formulas and symbols in most parts of the manuscripts are expressed in conformity to the recommended system, but some drawings and curves were originally done in conventional symbols and are difficult to be converted.

The compilation of a volume on such a comprehensive subject within such a short time span and contributed by so many authors is altogether a new experience to all of us, perhaps more difficulties had been encountered by every author than if he is given more time, more space and also more freedom. For my part as editor of the volume, I shared with all the authors the labours of putting scattered information into one organised text and the expectation that these material be useful to our readers. I helped to revise and correlate many parts of the manuscripts and generally polished the English language. For all six chapters written by Chinese authors, I

did the translation from Chinese into English. Through our joint efforts in nearly two year's time, this volume was finally completed in good form and in reasonably good time.

Contributions to this volume fall in two main categories, namely, hydraulic turbines (Chapter 1 through 11) and pumps (Chapters 11 through 16). Chapters 1 and 11 present general pictures on mechanical design of turbines and pumps respectively by giving specific examples of typical construction of each kind of machine.

Chapter 2 concerns the mechanical design of Francis turbines. The text on this most widely used type of turbine is arranged in a general form as the Francis turbine is the first major type of machine presented in this volume. The chapter covers general construction features of the turbine, determination of dimensions of major components and the sequence of assembly and dismantling of the machine.

Chapter 3 deals with axial-flow and diagonal-flow turbines, with particular interest in the Kaplan and Deriaz turbines. A major feature of these machines is the blade-adjusting mechanism that allows runner blade angles to be changed during operation. Design considerations of the mechanism, and examples of stress calculation of its component parts are given.

Chapter 4 explains the design feature of tubular turbines that are widely used in low-head applications. Although the runner of a tubular turbine is similar to that of a Kaplan turbine, the overall arrangement of the flow passage is quite different such as the placing of the generator inside of a bulb or a pier, the guide vanes that are set on a conical surface and the inlet and draft tubes. Description is also made on the straight-flow turbine which places the generator rotor on the rim of the turbine runner allowing a more unobstructed passage through the machine.

Impulse turbines that operate on a different principle of energy exchange is the subject for Chapter 5. Essential relations in hydraulic layout of the Pelton turbine nozzle and bucket are explained. This is followed by a detailed description of the mechanical construction of Pelton turbines of both the horizontal and vertical types. Problems of scale effects and cavitation related to impulse turbines are also discussed.

Chapter 6 concerns the pump-turbines used in pumped-storage power stations with emphasis on the reversible pump-turbines. These machines, based on more than 30 years of development, are capable of offering satisfactory performance in both modes of operation. However, vibration induced by interaction of hydraulic forces between the runner and guide vanes is a special problem that must be carefully analyzed in the design stage. Merits of the reversible machine as against the multi-stage reversible and the tandem pump-turbines are compared.

Valves and gates used in conjunction with hydraulic turbines are de-

scribed in Chapter 7. A main point of this chapter is on the sealing capability of valve seals since they are vital to the successful operation of the turbines.

Chapter 8 deals with the general topic of structural design of all types of hydraulic turbines. The question of growth rate of fatigue crack and allowable size of defects is examined in detail. Methods of stress and strain analysis are then explained and followed by description of numerical methods now widely used as computer-aided design tools.

Manufacturing methods of hydraulic turbine parts are the subject for Chapter 9. Production processes for the major components of various types of turbines such as the runners, shafts, guide apparatus and embedded parts are dealt with in detail. Emphasis is placed on the manufacturing of large turbines as it represents the major progress made in turbine production in recent years.

Small turbines which operate on the same principles as large ones do involve special problems in mechanical design. Chapter 10 describes the essential features of small reaction turbines (tubular, axial-flow and Francis) and small impulse turbines (cross-flow and inclined jet) as well as the selection procedures of these machines.

Chapter 12 discusses various aspects of mechanical design of centrifugal pumps with respect to conditions dictated by their hydraulic characteristics. Detailed descriptions are given on the construction of suction and discharge chambers, pump casing (particularly for multi-stage pumps) and the bearing, seals and balancing devices.

Chapter 13 is concerned with three types of pumps used in the lower head ranges, that is the axial-flow, mixed-flow and tubular pumps. As the performance of low-head pumps are more dependent on the structure of the pumping station, questions of pump installation and design of intake structures are treated in detail. Examples are also given for low heads pumps with concrete volutes.

Various forms of corrosion and erosion which constitute the major damage to metallic material are analyzed in Chapter 14. Since most cases of pump material failure are from incorrect material selection and not from material defect, a thorough understanding of the corrosion and erosion mechanism is essential to proper selection of materials for pumps.

Chapter 15 explains the casting and machining requirements of pump parts and the balancing procedures for the rotating components. Importance of quality control is discussed.

Chapter 16 deals with the problem of selection of pump drives and compares the merits of the many types of pump drives in use today.

Mei Zu-yan,
Editor

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Chapter 1

General Concepts of Hydraulic Turbine Construction

R.K. Turton

1.1 Hydroelectric Generating Unit Layouts

Hydroelectric stations may be classified into high, medium and low head categories, so that it is possible to class the types of machines involved by referring to head and flow as shown in Figure 1.1. Figure 1.2 illustrates the types of runner used: from the impulse (Pelton) turbine for high head; the Francis turbine for medium/low head; and the axial-flow (Kaplan) turbine for low head installations.

High head and most medium head units are driven by water accumulated in dams through long tunnels and penstocks, and some medium and low head machines are placed in dam power houses or run-of-river stations which form part of barrages in rivers and estuaries. A further way of classification is by power output, with generating units of large outputs of $100MW$ or more, medium-size units of 25 to $75MW$, and small or micro hydroelectric stations of limited outputs.

1.2 Typical Construction of Turbines

1.2.1 Impulse turbines

These machines may be of either vertical or horizontal shaft design, with the pressure head converted into high velocity jets by specially designed nozzles. The jets impinge on a runner provided with buckets as shown in Figure 1.3. The head of a recent installation, for example, is $1200m$ and the generated

Figures 1.1 Typical ranges of application for turbines
(Drawing courtesy Sulzer Escher Wyss)

Figure 1.2 Comparison of efficiency characteristics of different types of turbines
(Drawing courtesy Sulzer Escher Wyss)

output is 260MW , which is typical of the latest high specific output schemes.

Figure 1.3 Typical vertical shaft multi-jet Pelton turbine
(Drawing courtesy Sulzer Escher Wyss)

Small Pelton turbines may be installed where there is enough head, and units of 100kW or more are in operation. Many hydroelectric power stations use small Pelton turbines for station stand-by power.

1.2.2 Francis turbines

Figure 1.4 illustrates a large Francis turbine layout, the spiral case directs water through guide vanes (wicket gates) into the runner and out through the draft tube to the tail water. The turbine shown is a medium head machine that generates 715MW under 113m head. A Francis turbine is a mixed-flow machine, the characteristic shape of the runner varies with head and specific speed, as shown in Figure 1.5.

1.2.3 Axial-flow turbines

An axial-flow turbine may have fixed runner blades or variable-pitch blades, the former is commonly called a propeller turbine and the latter a Kaplan turbine. Figure 1.6 shows a typical Kaplan turbine layout. This machine with an output of 103MW under a head of 24.4m has a runner diameter of 8.4m . This turbine is typical of low head axial-flow machines and has a

Figure 1.4 Large capacity medium head Francis turbine
(Drawing courtesy J.M. Voith)

(a) Low specific speed (b) Medium specific speed (c) High specific speed

Figure 1.5 Characteristic profile of Francis runners

spiral case of near rectangular shape and stay vanes made up of separate columns.

Figure 1.6 Typical Kaplan turbine with rectangular spiral case made of concrete (Drawing courtesy Escher Wyss)

A variation used in small, river barrage and estuary installations is the bulb turbine. Here water flows around the generator bulb, through the guide vanes which are set in a mixed-flow annulus section and into the axial-flow runner. The entire unit is effectively tubular in shape as there is no spiral case, hence it is also called a tubular turbine. The bulb turbine shown in Figure 1.7 has an output of 25 MW under a 7 m head, a runner diameter of 7.7 m and a rotational speed of 62 min^{-1} .

1.2.4 Pump-turbines

Early pumped storage power stations used a *four machine* layout, with a turbine and generator as one set and a pump and motor as a second set.

Figure 1.7 Cross-section of a large bulb turbine
(Drawing courtesy Sulzer Escher Wyss)

The turbine generates at high grid demand times, and the pump uses surplus power from the grid at non-peak demand times, to refill the supply reservoir for the turbine. Later the two electrical machines were combined into one to form a generator-motor with the turbine and pump connected one on each end of it. The aggregate is called a tandem set, or a *three machine* layout.

Present-day pumped storage power stations use a reversible pump-turbine which rotates in one direction as a pump and in the other direction as a turbine. A pump-turbine closely resembles a Francis turbine, as shown in Figure 1.8, but all components of the flow passage are designed to work in both directions of flow.

The most recent machines typically deliver over 100MW power with a head of $400\text{--}500\text{m}$.

1.2.5 Micro hydroelectric units

Hydraulically the micro units may be Francis, axial-flow or bulb turbines, and are often laid out with the shaft either horizontal or inclined, the latter is used with the intent of saving civil engineering work. Typical arrangement of a micro hydroelectric unit is shown in Figure 1.9, where output may be $100\text{--}700\text{kW}$ with heads of $3\text{--}5\text{m}$.

- 1: runner
- 2: guide vanes
- 3: lower guide bearing
- 4: thrust bearing
- 5: generator-motor
- 6: upper guide bearing

Figure 1.8 Typical Francis pump-turbine layout
(Drawing courtesy J.M. Voith)

Figure 1.9 Layout of a low head micro hydro power station
(Drawing courtesy Sulzer Escher Wyss)

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