Chapter 1

Introduction

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1.1 Cavitation

1.1.1 Discovery

Although the word *CAVITATION* was originally coined by R.E. Froude and firstly cited by Barnaby & Thornycroft in 1895 [1.2], the phenomenon was suggested much earlier by Euler in his theory of hydro-turbines in 1754 [1.3]. However, actual cavitation was firstly discovered and investigated by Barnaby & Parsons in 1893 [1.1] when they found that the formation of vapour bubbles on blades was responsible for the propeller failure of a British high-speed warship (HMS *Daring* with a design speed of 27 *knots*). In 1895, Parsons established the first water tunnel[1] for cavitation study, and discovered the relation between cavitation and its damage on the propeller [1.8]. It was Rayleigh who laid the theoretical foundation for cavitation study by solving the problem of the collapse of an empty cavity in a large mass of liquid in 1917 [1.9].

Following the milestone work done by both Parsons and Rayleigh, more than ten thousand articles and several books on this subject have been published. Nevertheless, our knowledge of cavitation is still very limited.

1.1.2 Classification

Cavitation is normally defined as the formation of bubbles filled with vapour/gas or their mixture and subsequent activities (such as growth, collapse and

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[1] This tunnel with a 12 *in* diameter test section is now at the University of Newcastle upon Tyne, UK.

rebound) in liquids. According to the content of bubbles, cavitation can be classified as *vaporous cavitation* and *gaseous cavitation.* Cavitation differs from boiling by its generating mechanism. That is, it is a phenomenon directly related to the pressure reduction below a certain critical value. Usually, there are two ways by which the pressure reduction is caused. One is by a fluid flow, which is often referred to as *hydrodynamic cavitation.* The other is by an acoustic field, which is often referred to as *acoustic cavitation.* However, there are also other cavitations generated either by photons of laser light or by other elementary particles (e.g. protons in a bubble chamber). These cavitations are achieved in nature by local energy deposit rather than by tension in liquid. Therefore, they are often referred to as *optical cavitation* and *particle cativation* respectively. These two types of cavitation do not occur in hydraulic machines.

According to the mechanisms by which cavitations are generated, the classification by Lauterborn, 1979 [1.5], is shown in Figure 1.1. For more information, the review by Hutton, 1972 [1.4], is suggested.

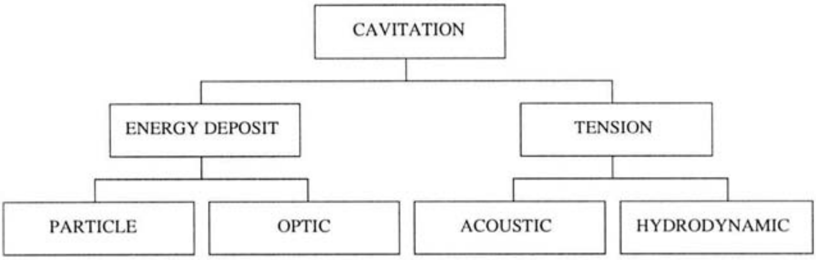

Figure 1.1: Classification of cavitations

Nowadays, cavitation study is being performed in various fields such as (single/multi/stochastic) bubble dynamics, acoustic cavitation, hydrodynamic cavitation, cavitation luminescence, cavitation noise and cavitation erosion etc.

1.2 Hydraulic Machinery and Cavitation

1.2.1 Problems Caused by Cavitation

Cavitation is almost always an unwanted phenomenon in hydraulic machinery although it has some favourable effects in other fields[2]. Actually, it is a main obstacle to the development of high-performance machines.

Cavitation will erode machine parts (e.g. Figure 1.2); deteriorate machine performance; cause noise, vibration and even entire system oscillation; and enhance corrosion/silt erosion through synergism mechanisms. As examples, such cavitation-damaged turbine and pump are shown in Fig. 1.3. The

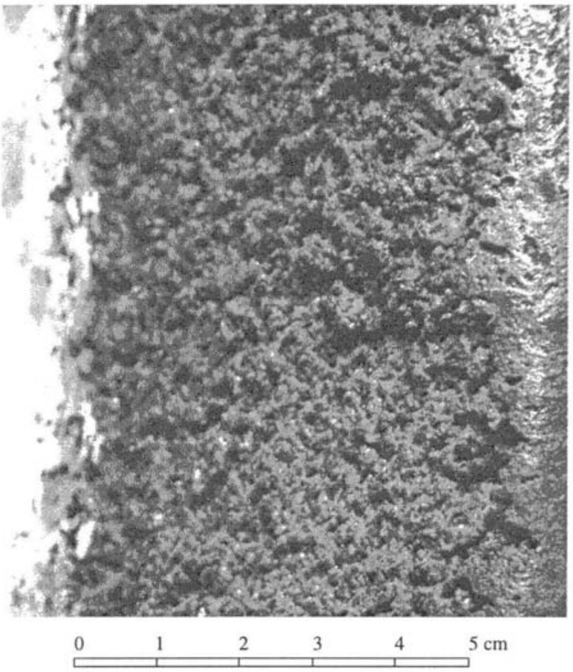

Figure 1.2: Typical sponge-like erosion-pattern caused by a severe leading-edge-cavitation attack (Li, 1987 [1.7])

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[2] They are used in some physical/medical/industrial applications. For, detail, see Young, 1989 [1.10].

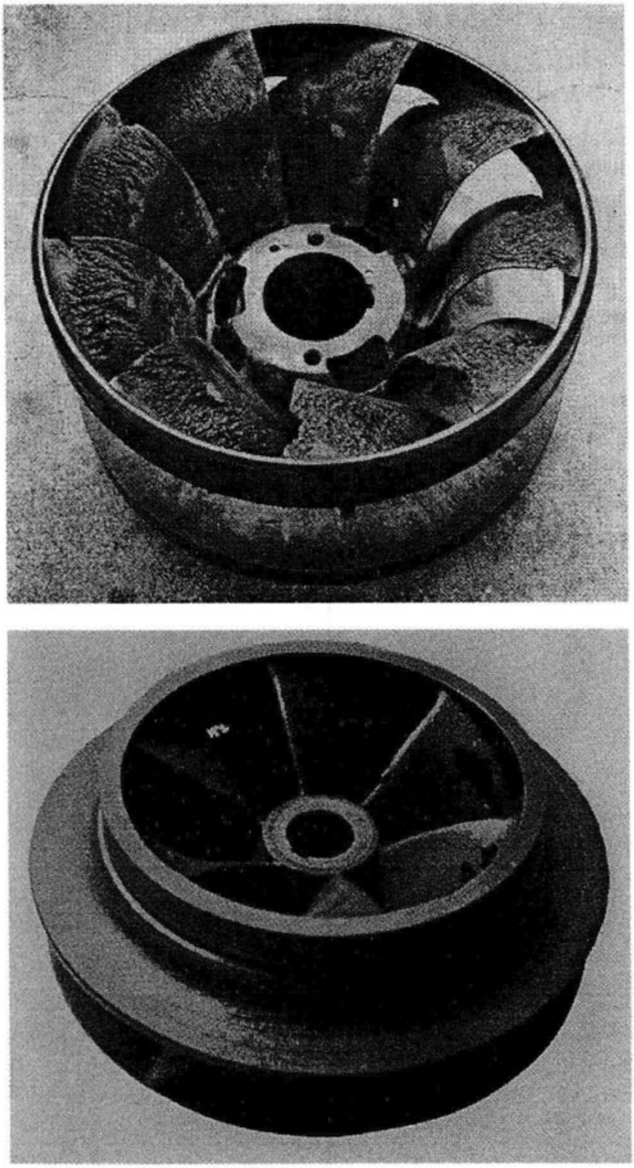

Figure 1.3: Cavitation damaged Francis-turbine runner (top) and centrifugal-pump impeller (bottom). (Courtesy of IMHEF, Lausanne)

repair of cavitation damage is a costly work, which reduces the capability-availability and the lifetime of machines.

1.2.2 Combating Cavitation

The past 100-year history shows that the discovery and study of cavitation is strongly associated with the development of hydraulic machinery[3]. Under a given application environment, the higher performance (e.g. higher specific speed, n_s) machines are more prone to cavitation and its damage[4]. Therefore, cavitation becomes a main obstacle in developing high-performance machines.

To combat cavitation, appropriate measures should be carefully considered and balanced throughout the planning of hydro schemes, machine selection and parametric design, machine (hydrodynamic) design and material selection, mechanical design, determination of machine setting level (i.e. the plant cavitation number, σ_p, for turbines and the required net positive suction head, $NPSH_{req}$, for pumps), and machine operating/maintenance/repair. Thus, a comprehensive and optimum anti-cavitation approach can then be developed for a given project, which requires a joint effort cutting cross many disciplines.

There are basically two concerns in combating cavitation. One is how to avoid cavitation in the first place. On the other hand, if cavitation is not avoidable, measures should be employed to minimise it to an acceptable level and to reduce future repair cost by easing the repair/replacement of the parts that are likely to be damaged.

When selecting or designing a machine for a given scheme, previous experience or databases should be used as a prime reference since theoretical calculation and prediction of cavitation occurrence in a machine, particularly for off-design operation, is not accurate and not always reliable. The advanced flow-simulation technique, such as the 3D $k-\epsilon$ turbulence flow model[5], should be employed to optimise the hydraulic design of machine.

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[3] In broad definition, any machines that use a fluid as the working medium either to change energy from one type to another or to transmit energy are referred as *hydraulic machinery*. Based on their functions, they can be further categorised as four types: hydro driving machines (e.g. hydro turbines), pumping machines, hydro transmissions and hydro propulsions (e.g. ship propellers).

[4] For example, the cavitation erosion rate increases with the 6th power of relative flow velocity.

[5] A complete simulation of a Francis turbine (i.e. from the inlet of the spiral case to the exit of the draft tube) with a $k-\epsilon$ turbulent model has been reported recently by

It is vital to avoid the most damaging cavitations (such as the vortex cavitation) and unsteady cavitating flows (such as cavitated vortex shedding and cavitated vortex core in the draft tube). A proper model-test technique should be adopted to detect critical flow structures prone to cavitation and, by using a precise scaling law, to predict possible cavitation inception and its development on the prototype. The proper selection of the machine setting level is vital to avoid blade cavitation but it has little effect on non-blade related cavitation. A safety factor is required for choosing the value of $NPSH_{req}$ or σ_p to ensure an acceptable degree of cavitation[6]. However, this will increase capital cost since a deeper setting of the machine requires more civil work. Therefore, a careful trade-off is needed. The use of materials with high-cavitation resistance and low cost (in terms of both the material itself and the machining/repairing process) in the areas prone to cavitation attack is effective in mitigating cavitation damage. From an operation view point, if possible (e.g. for the turbines providing base load), avoiding off-design operation is crucial. Besides, anti-cavitation devices such as air injection, blade fin (for Kaplan/propeller machines) are the effective measures often used. Novel designs are also sought for developing low-cavitation and high-energy machines. For example, the idea of using a double-row cascade runner was proposed by Li, 1964 [1.6], and has been proved successful in producing such machines[7]. As concerns maintenance and repair, appropriate inspection and maintenance programme and repair approach (which involves repair

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Keck et al (*Sulzer Technical Review* 1/97, pp26-29). This approach uses the technique of 'circumferential mixing plane interface' to simulate the interaction between the rotor and the stator so that it can produce a full hill chart of machine performance. It is claimed that for retrofit-turbine projects this approach can design new runners matching the existing components (for say, the stay ring) much better than the costly model test approach does.

[6] The machine value of $NPSH$ or σ is obtained by the test against a certain energy (e.g. efficiency, pumping head etc) drop which is caused mainly by blade cavitation. Indeed, at this stage, cavitation has already developed into a severe status.

[7] This idea was tested with favourable results on the Francis turbine (Yunfeng Power Station, China, in late 1960's) and on pumps (by Shanghai Pump Factory in early 1970's). Recently, a novel Francis turbine (unit capacity 150 MW) using such a double-row structure has been developed by Kvaerner Brug A/S (Norway) for the Lubuge Power Station, China. By using a double-row (the blade chord-length of the second row is shorter) cascade runner, particularly for low n_s Francis machines, machine cavitation number σ can be remarkably reduced owing to: (a) the favourable alteration of the pressure distribution on the main blades; (b) the postponement of boundary-layer transition and separation in some operating conditions which in turn delays cavitation inception; (c) the mitigation of secondary-flow formation during part-load operation. Apart from σ reduction, the high-energy (efficiency) zone becomes much broader owing to the better flow conditions achieved.

frequency, damage-cause analysis, repair method and material selection etc) are vital to the minimisation of cavitation and its damage. By an effective repair approach, cavitation problem on a machine can be minimised and even solved completely. Otherwise, the damage will become a progressive process. For a retrofit project, it is often seen that severe cavitation and damage is introduced by retrofitting because the desire for a higher energy performance (output and efficiency) often tempts one to overlook the risk of cavitation. For example[8], a retrofitted new Francis runner usually possesses a larger diameter, fewer blades and a much sharper corner of the bottom ring. This will create a flow environment prone to cavitation. Therefore, for retrofit design, precautions must be taken in balancing the energy gain and cavitation risk.

Having implemented an appropriate comprehensive anti-cavitation approach, such as mentioned above, it is possible to produce a virtually cavitation (damage)-free turbine of 60-year lifetime, capable of operating 30 years without major maintenance. For pumps, a ten-year lifetime may be possible if cavitation intensity is controlled below the material resistance.

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[8] See §6.6.4 Example.

References

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1.9 Rayleigh, Lord (1917), 'On the Pressure Developed in a Liquid during the Collapse of a Spherical Cavity', *Phil. Mag.* 34, pp94-98.

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