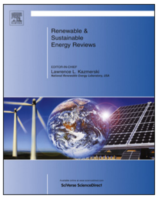
Renewable and Sustainable Energy Reviews 54 (2016) 1–14

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



A review on fatigue damage mechanism in hydro turbines

Xin Liu, Yongyao Luo, Zhengwei Wang*

State key laboratory of hydroscience and engineering, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form
2 June 2015
Accepted 18 September 2015
Available online 11 November 2015

Keywords:
Hydraulic turbine
Fatigue
Cavitation
Erosion
Ingested body

ABSTRACT

Well knowing a good-running hydraulic turbine has important operational and financial benefits to those who operate a plant. Fatigue damage is the most fundamental failure type of hydraulic turbines. Existing flaws due to fatigue and their risk limit the operating time of a unit. Some plants have been temporarily shut down for up to a month and sometimes longer to repair these fatigue-induced damage, which has resulted in enormous economic losses. Fatigue problems must be solved or effectively prevented to ensure that turbine units run safely and steadily within their design life. This paper reviews loading features and some key issues (e.g. different load operations, start-up, emergency shut-down, load rejections, and runaway) on the fatigue damage, and provides the latest information about different prediction approaches. At last, it also attempts to present an overview of the complete failure modes, therefore other types of failure including cavitation, erosion and ingested bodies are introduced briefly.

Contents

1. Introduction

Hydropower is a renewable energy source based on the natural water cycle, captures the kinetic energy of falling water that comes from a reservoir, a river, and waterfalls. Over the past century, hydropower has become a proven, extremely flexible, and well-advanced technology. The world's installed hydropower capacity in 2009 was 926–980 GW. By 2011, hydropower is the largest renewable energy in the electricity sector, and it contributed 17% of worldwide electricity supply and over 72% of the world's renewable electricity. China, United States, Brazil and Canada are the countries

---

* Corresponding author. Tel.: +86 10 51533279.
E-mail address: wzw@mail.tsinghua.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.rser.2015.09.025
1364-0321/

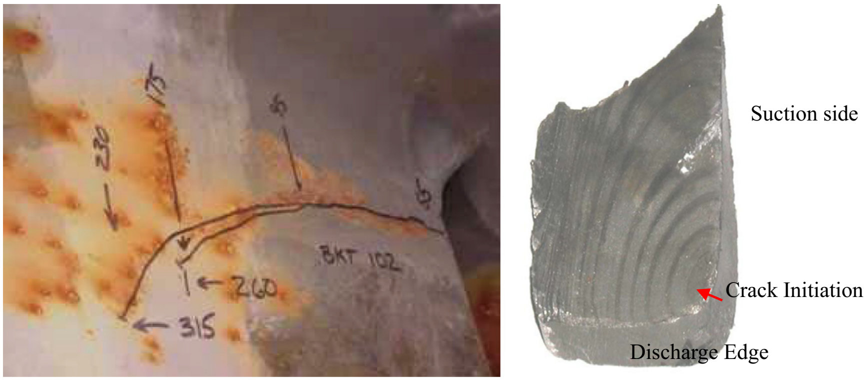


Fig. 1. Crack fracture surface.

Table 1
Failure information in some hydropower plants.

Plants	Country	Turbine type	Rated Unit Capacity (MW)	Failure location	Failure time	Shutdown (month)	Loss (million $)
Sayano-Shushenskaya	Russia	Francis	640	Bolts in #2, the plant destroyed	2009	Under repaired	13,000[a]
DaChaoShan	China	Francis	225	Runner	2001	4	63.71[b]
G.M. Shrum	Canada	Francis	261	Runner and wicket Gates	2002	14	258.67[b]
Porjus second	Sweden	Francis	240	Draft tube	2000	2.5	42.47[b]
XiaoLangDi	China	Francis	330	Runner	2001	4	93.44[b]
ErTan	China	Francis	561	Runner	2000	1	39.71[b]
ShuiKou	China	Kaplan	200	Piston rod	2006	1	14.16[b]
Khimti	Nepal	Pelton	12	Needle and buckets	2003	1	0.85[b]

[a] Direct economic loss from the official accident report. In fact, the indirect pecuniary loss is much large than this value.

[b] No data available in references. An approximate estimation based on 80% of effective generating period times unit capacity times residential retail price (12.29 cents/kWh) in the USA at February 2015. Maintenance costs are not included.

which have the largest hydropower generation capacity [1,2]. While current hydropower technology is very mature, there is still some room for further improvement. During operation, the acute interaction of turbine components occurs frequently and there are potentially severe consequences. For a majority of hydropower plants, turbines have operated for decades, and in many of these hydropower plants the operating conditions have changed significantly from the original conditions. These changes in operating conditions can lead to excessive vibration: in some cases, fatigue cracks have formed in parts of the turbines [3–5]. A typical blade crack due to fatigue cyclic loads is shown in Fig. 1. The formation and propagation of cracks may still lead to premature failure of or damage to key turbine components. Existing flaws and their risk limit the operating time of a unit. Some plants have been temporarily shut down for up to a month and sometimes longer to repair these fatigue-induced damage, which has resulted in enormous economic losses, as listed in Table 1 [6–12]. Compared with hydraulic performance issues (i.e. output, efficiency and cavitation), it is more difficult to assess the durability of the equipment [13]. Because of the aforementioned, fatigue problems must be solved or effectively prevented to ensure that turbine units run safely and steadily within their design life. In this paper, an overview of the fatigue damage, the most important failure mechanism of hydro turbines, will be presented in details, and other types of failure mechanisms such as cavitation, erosion, and ingested bodies will also be presented briefly.

2. Fatigue failure

There are different stages of fatigue damage where defects may nucleate in an initially undamaged section and propagate in a stable manner until catastrophic fracture occurs. For this most general situation, the progression of fatigue damage can be broadly classified into the following stages: (i) structural and microstructural changes which cause nucleation of permanent damage; (ii) the creation of microscopic cracks; (iii) the growth and coalescence of microscopic flaws to form ‘dominant’ cracks; (iv) stable propagation of the dominant macrocrack; (v) structural instability or complete fracture. The conditions for the nucleation of microdefects and the rate of advance of the dominant fatigue crack are strongly influenced by a range of mechanical, microstructural and environmental factors [14,15]. Fig. 2(a) shows a part of the crown detached from the runner while the machine was in operation. The detached part passed through the machine, causing further damage. Fig. 2(b) shows a close-up of the broken part of the runner. The analysis of the part revealed a fatigue problem. Beach marks can easily be identified in the crack, which was propagated from the T-joint between the runner blade and the crown [16].

Life estimation of turbine components require numerous intrinsic mechanical factors and extrinsic factors. Fig. 3 schematically summarizes these factors and their-relations [17]. These factors act in synergy to establish the turbine's static strength, cavitation resistance, erosion resistance, corrosion resistance, impact resistance, fracture toughness and/or fatigue resistance. But difficulties exist still in the design stage, model tests and even in-situ measurements. One tricky issue is to find out a proper fatigue criterion for hydro turbines. The general physical model is simple geometric structure under axial-loading. Contrarily, the hydraulic loading are complex and multi-axial. In general, failure behavior in hydro turbines is difficult to evaluate by experimental tests or is experimentally inaccessible. Because it needs to test a large number of materials and structural components in a very short time. The current work is to develop the general failure physical model by introducing the correctional parameters based the existing measurement data of hydro turbines. Another tricky issue is how to predict prototype loadings based on the model tests. It is related to a popular focus on similarity relationship between model and prototype machines. At present, lots of work have been carried out to establish the hydraulic similarity law through model test and prototype test. Even so, there is a debate in the extrapolation of model test results to prototype values [18].