Proceedings of the 8th International Symposium on Cavitation
CAV2012 – Abstract No. ##
August 14-16, 2012, Singapore

ABSTRACT
Keynote paper

Cavitation (damage) strips with span-wise regularity on the guide vanes of Three Gorges turbines (Phenomenon and hypothesis)

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SUMMARY

Damage with an appearance entirely different from the well-known sponge-like cavitation erosion has been identified in 2006 from the Three Gorges turbines. Until then this phenomenon had never been reported in literatures, thus puzzling investigators.

Owing to its multidisciplinary nature, this page-limited abstract can only introduces very briefly the observed phenomenon and the hypothesis of the underlying mechanism. The causes of failures in preventing this problem in the first place by means of model tests and CFD simulations together with the ways forward for huge turbine development are presented as well. For detailed analysis and derivations, see the full length paper.

INTRODUCTION

Cavitation and its damage as a scientific subject as well as technical issues in particular relating to turbine development have been intensively studied for over a century, referring to reviews, e.g. [1, 2, 3 and 4]. However, immediately after commissioning a very unusual and strange pattern of damage never reported and studied before has developed on the guide vanes of the cutting-edge Three Gorges turbines. Owing to its appearance entirely different from any type of known damages including cavitation erosions, confusion arises about its nature. Against all suggestions[1] from the manufacturers [5], the author identifies it as a new type of cavitation damage. The significance of this issue lies in the fact that the Three Gorges turbines developed by leading suppliers have all developed more or less the same pattern of damage although no cavitation was detected during their model tests and CFD simulations. Therefore, it is not an isolated technical problem but a fundamental scientific challenge [6 and 7]. The damage details were obtained by the author from a site visit during a very short stoppage of the machine in the generating season; and based on multidisciplinary knowledge a hypothesis of its mechanism has been built up. Suggestions with update information for verifying this hypothesis are also following.

[1] They proposed such as particle impact, galvanic erosion, erosive/corrosive damage by river-water and material defects etc but not cavitation.

OBSERVED PHENOMENON

The damage[2] occurs on the pressure surface (not the suction surface) of the guide vanes (Figure 1) in the form of stream-wise strips[3], starting from the zone of favourable pressure gradient (FPG) and extending into the zone of adverse pressure gradient (APG) as shown in Figure 1.

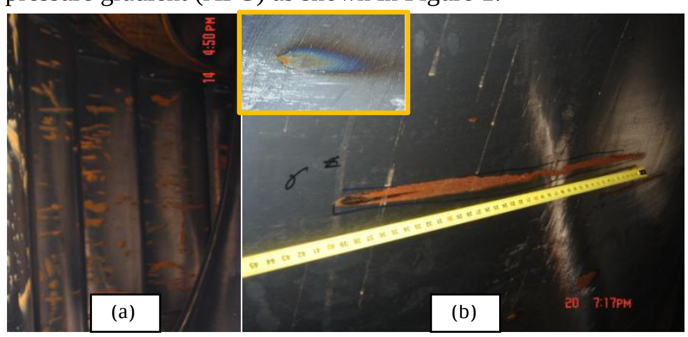

Figure 1. (a) Guide vanes with damage visible on their pressure surface; (b) A representative damage-strip showing the wedged head (inset: a typical heating sign)

These long strips, with almost equal width (approximately 10~20 mm), all have a wedged head as shown in Figure 1(b). They appear with a span-wise regularity of average spacing $\lambda_{strip}\approx0.100$ m. The damage depth is much less than 1 mm (touch feel only) and with a corroded rough surface. Signs of heating are also observed. These features are notably different from commonly observed cavitation damage, which usually develops a sponge-like eroded surface. The damaged strips observed on the guide vanes are all such long and narrow shaped and distributed regularly in span-wise. This reminds the author of searching for a delicate flow-structure most likely from the boundary-layer that fits all these features[4].

[2] These machines of cutting-edge technologies are the world largest Francis turbines. Only 10^3-10^4 hour operations, 14 machines in the left-powerhouse have all developed this type of damage on the guide vanes. The damage on No 4 guide vane of No 11 unit is representative, which is cited here.

[3] That is the direction of main flow there.

[4] This was exactly what triggered author's mind while conducting the examination inside the machine in 2006.

METALLURGICAL ANALYSIS

The multi-colour zones observed (termed as 'bluing' in heat-treatment) indicates a temperature rise to the range of 250°C-600°C. The only possible hydrodynamic mechanism capable of generating temperatures at or above this range is cavitation[5]. Single bubble luminescence [8, 9 and 10] has proven a heat source in the order of $10^3 K$ and so to be expected from the work on hydrodynamic (bubble) cloud luminescence [11].

The material used for the Three Gorges turbines is X3CrNiMo13-4 (EN-1088), which is close or equivalent to martensitic stainless steel *CA6MN* (12.9% Cr, 4% Ni and 0.04% C), commonly used for turbine fabrication [12]. The corrosive appearance of the damage in particular its very shallow depth (touch feeling only) readily tempts one to conclude corrosion being responsible for the damage. The analysis in the full paper will show corrosion is merely a consequence of cavitation attacks through a process of *Sensitisation* that is a phenomenon relating to heat induced inter-granular corrosion [13].

FLUID DYNAMIC ANALYSIS

The machines were operated mostly at lower head conditions (i. e. at reduced inlet circulation condition) making the pressure surface, instead of the suction surface, of the guide vane (hydrofoil) vulnerable to cavitation.

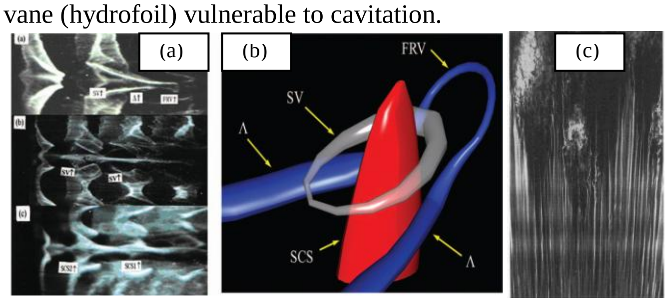

Figure 2 Streak structure & breakdown: (a) photos of typical hydrogen-bubbles in laminar streak formation illuminated by a laser sheet at different horizontal heights. SCS, the secondary closed vortex; SV the secondary closed vortex and FRV the first ring vortex [20]; (b) 3-D structure reconstructed from these detailed photos [20]; and (c) Streak observed through smoke visualization in a laminar boundary layer subject to 2.2 % free-stream turbulence [23]

The narrow and shallow strip damage suggests a delicate structure of cavitating flow involved. The wedged head of strips indicates that the triggering of this cavitation is likely associated with the formation of turbulent spot during the boundary-layer transition that is also featured with wedge head [14]. Convincing evidences thus point towards the boundary-layer transition and turbulence production. The analysis in the full paper will develop a logic flow along this direction using available knowledge in particular the relation with the span-wise stochastic characteristics of the damage strips. That is, there must be a flow structure in the boundary-layer capable of creating such negative pressure drops lasting long enough time for nuclei to cavitate [15]. The breakdown of K-mode streaks [16] and associated turbulence production is just such an ideal flow environment if the free-stream pressure *there* is also sufficiently low (but not necessarily down to the vapour pressure). Such a flow structure is shown, e.g. by Figure 2.

The parametric analysis of the span-wise regularities does support that the damage strips stem from the K-mode instability because their span-wise regularities match each other well reflecting the stochastic characteristics of the turbulence production from the breakdown of these boundary-layer K-streaks[6]. Finally the analysis will lead to a reasonable hypothesis. That is, the cavitation inception is triggered by boundary-layer K-mode transition and associated turbulence production. Once the first damage spot created, a *dynamics process* follows: The first damage spot will serves well as a roughness spot[7] creating a subsequent cavitation (damage) immediate downstream. This dynamic and sustainable process progresses stream-wise, resulting in such a horizontal and equal width damage-strip with a wedged head. Their span-wise distribution is thus a reflection of the span-wise stochastic characteristics of the turbulent spots.

FAILURES IN MODEL TESTS AND CFD PREDICTIONS

The reasons that manufacturers all failed in the first place to detect this problem by their model tests and CFD simulations were[8]: (a) there was absolutely no boundary-layer similarity for model and prototype, making the prototype much more susceptible to turbulent transition owing to its much higher boundary-layer based Reynolds number; (b) the free-stream turbulences were also not similar, subsequently affecting the boundary-layer dynamics particularly its K-mode instability through the receptivity mechanism [6]. For background knowledge, see e.g. [17 and 18].

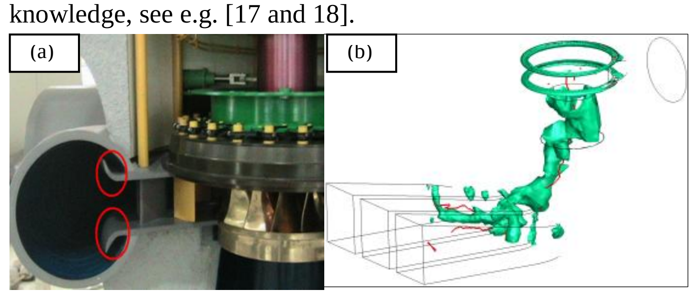

Figure 3 (a) Wrongly designed guide-plate (circled) on 3-Gorges (left power plant) turbines [6]; (b) This guide-plate inducing a huge vortex structure occupying whole flow passage. It is responsible for a gust-like dominating turbulence of extremely low frequency (0.336 Hz) in free-stream that has the highest receptivity to boundary-layer, promoting K-mode instability [6]. Referring to [24 and 25] for background information.

[5] Indeed, Hansson and Mørch have also observed such colouring resulting from high temperature and free radicals produced at cavity collapses very close to or directly on the specimen surface from their study [22]. Unfortunately, it was not reported in their article (Private correspondence with K A Mørch, 1st Nov2007)

[6] The resultant turbulent spot spacing is $\lambda^*_{spot} = 86\times10^{-3} \sim 129\times10^{-3}$ m approximately equivalent to the observed damage-strip spacing $\lambda^*_{srtip}(\approx 0.100\mathrm{m})$.

[7] For effect of surface roughness on cavitation inception, see e.g. [19].

[8] Details in the full paper will show: why the model turbine is cavitation free whereas the prototype suffers from cavitation?

For extremely large turbines with high prototype-model ratio (such as 28 for the Three Gorge turbines), these two scale effects are all extremely manifested, presenting a real challenge for giant hydro schemes, referring to Figure 3.

CONCLUDING REMARKS

All available evidence convincingly suggests a hypothesis for this type of cavitation (erosion). Its inception is likely triggered by the breakdown of the boundary layer K-mode streaks. The resultant damage patterns reflect well the features of the turbulent production from the breakdown of these streaks. The corrosion is not the cause but a consequence.

Though the phenomenon is identified from a technology development, the analysis offered explores a new scientific topic in the multidisciplinary domain open to cross fertilization of sciences.

Verifying this hypothesis requires the recreation of this phenomenon under controllable conditions for thorough investigations. Such a follow up programme is being carefully devised and conducted[9]. A new wave of modifications to the design of this part of turbines is already underway though a full understanding of this phenomenon is far from achieved yet[10].

ACKNOWLEGEMEN

UK EPSRC Grants (R.ESCM.9001 and R.ESCM9004) and Royal Academy of Engineering Grant (R.ESCM3021); and China CTGPC financial & technical support.

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[9] Details are to be shown in the full length paper.

[10] Following the identification of this damage from the Three Gorges turbines, manufacturers are now racing in modifying their turbine designs for new hydro schemes (such as Wu Dong De， Xi Luo Du， Xiang Ja Ba and Bai He Tan, total 43GW installation in China). However, without full understanding of the underlying mechanism, modifications on these giant machines (even larger units of 10,000MW also proposed) are indeed questionable. More discussions are in full paper.

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