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Risk Analysis of Propeller Failure due to Wave-Induced Oscillation

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Abstract- In this paper, a risk analysis is carried out to identify the causes of propeller failure by wave-induced oscillations. Propellers need to be optimized for their actual operating condition rather than for calm water, hence a need to design the propeller to withstand all operating conditions. A first step would be to study the effects of wave-induced on propeller operation. Secondly, fault tree analysis is used to rank the risk identified and finally risk control measures are proposed. Changes in propeller performance in terms of cavitation, wake-induced forced oscillation of propeller blades, propeller wear, cyclic fatigues, propeller casting are also presented as addition factors that can lead to propeller failure. The result using an illustrative example, ranks propeller cavitation among the highest factors that can lead to failure of a propeller due to wave induced oscillation.

Keywords *- Propeller Failure, Propeller Thrust Deduction, Risk Analysis*

I. Introduction

Ship must be designed to be safe in all operational conditions hence a need for some flexibility in the design of ships especially its various critical components such as a propeller [1]. A ship in waves experiences severe modification in hydrostatic performance when engine propeller dynamics, wake variation and torque losses are taken into account [1]. To improve the propulsion performance prediction of ship's in all working conditions there is a need to study the effect of waves on the propeller. Also increased propeller load, added resistance and also reduce the ship motion have been identified by researchers as potential causes of propeller failure [2, 3]. Moreover, accidents occur due to unpredicted and rough sea states, which modify the sea keeping of the ship making the crew unable to keep the ship under proper control [3]. A propeller in service, regardless the designer and manufacturers endeavors cannot stop its performance to fluctuate due to unprecedented problems, arising from time to time [2]. In the same way, during the service life of the propeller a wide range of problems may occur such as accidental damage due to impact or grounding of the blades [2]. Other causes of ship propeller failure are cavitation, propeller casting defect, propeller grounding and propeller wear and induced-wave oscillations of propeller [3]. Induced-wave oscillations of ship propeller causes noise, thrust breakdown, vibration, relative rotative efficiency and reduce the overall propeller efficiency of the ship [3, 4]. The demand for high-efficiency propellers in the maritime industry is increasing therefore, identifying and preventing the effect of the induced-wave oscillation of ship propeller will ensure efficient operations of the ship [3]. The objectives these papers are; (1) to determine the causes of propeller failure by induce-wave oscillation, and (2) to present means of reducing the effects of induced-wave oscillation. Experienced marine engineers and surveyors in Tema port, Tema shipyard and marine engineers in the Regional Maritime University, Ghana were consulted for data input and relative expert judgments. No laboratory analysis or numerical modelling was used in this research hence the study may not be one hundred percent reliable and may yield different result using different method of analysis. Furthermore, the result of this research is limited to failure by wave-induced oscillation.

II. LITERAURE REVIEW

The maritime industries have been influenced by the marine environment through various operations, including induced-wave oscillation on ship propellers [3]. The wave-induced oscillation on ship propellers will result in vibration, noise, thrust breakdown, reduction in the relative rotative efficiency and erosion of the propeller blades [3]. Relative rotative efficiency is the ratio of the efficiency of the propeller operating in a uniform flow to the efficiency of the propeller operating with flow at an angle [5]. Current literature has demonstrated that the underwater noise can directly or indirectly affect marine livings in the short term [3]. The underwater noise is as a result of wave-induced oscillation having significant impact on the vessel's performance. Thrust breakdown, vibration and erosion affect the optimal operations of the ship therefore, identifying the wave-induced oscillation on marine propellers using risk analysis method (fault tree analysis) will help present effective measures for efficient ship propulsion [3].

A. Fault Tree Analysis

Fault tree analysis (FTA) is a system engineering technique, developed in 1961 that provides an organized illustrative approach for identification of high for quantitative analysis [6]. A fault tree (FT) diagram follows a top down structure and represents a graphical model of the pathways within a system that can lead to a foreseeable, undesirable loss event or a failure [6]. The pathways interconnect contributory events and conditions using standard logic symbols (AND, OR, etc.) [6]. If the occurrence of either input event causes the output event to occur, then these input events would be connected using OR gate [6]. On the other hand, if both input events must occur in order for the output event to occur, then they are connected using AND gate. Construction of a fault tree usually begins with the definition of the top undesired event (the system failure)[6]. FTA has been used to study industrial risk performed on a water supply system of an industrial facility to elucidate the causal relations leading to a given undesired event, and also in preventions of accidents [8, 9]. The causes are then indicated and connected to the top event by logic gates as follows, with detailed reading as referenced [7]:

AND gate general formula for occurrence probability calculation:

$$\mathrm{P(E_a)} = \prod_{\mathrm{i=1}}^{\mathrm{k}} \mathrm{P\ (Ei)} \quad (1)$$

OR gate general formula for occurrence probability calculation:

$$P(E_0) = 1 - \prod_{i=1}^{k}\{1 - P(Ei)\} \quad (2)$$

The propeller directly affects the safe navigation and running cost of the ship [3]. Propellers in operation undergo tension and stresses and various loads hence the need to carry out failure analysis. The concept of failure analysis is not new in marine engineering systems. It has been used to prioritize the expected cost associated with the system's actual failures [10, 11]. Other risk analysis methods used in engineering applications are the use of analytical hierarchical process, multi-attribute failure methods [12, 13].

B. *Description of Marine Propeller Operation*

The rotation of the propellers develops significant thrust that is used to propel the vessel at various operational speeds [14]. Propeller description and operations has been detailed in various research studies [14, 15]. The propeller is several blades sticking out of a shaft, which rotates with each of blade loading produces lift at right angles to the directions of water flowing to move the ship forward [14]. From the design stage, the propeller is optimized for at least 85% engine load, with 15% sea margin, at a draft of 8.5 m [14]. During operation of the propeller, the inflow velocity and pressure will change depending on the blade's angular position, and the efficiency of the propeller operation is primarily attributed to the reduction of the drag on vessel [14]. The Propellers are wake adapted for acceptable noise and vibration characteristics[15]. Several research has been carried out to identify wake adaption, wake criteria, wake gradients by using unsteady panel methods to study the effects of cavitation [15].

III. PROPELLER FAILURES

A. *Propeller Cavitation & Propeller Wear*

Cavitation causes a steady breakdown in the flow and consequent loss of thrust [2]. Fluid cavitation damage will occur in situations where the propeller is either working in a particularly onerous environment in terms of immersion or inflow conditions that cannot be accommodated in the design [2]. Cavitation also refers to as the formation and subsequent collapse of either gas or vapor bubbles in regions on propeller blades, where pressure has fallen below the vapor pressure of water this collapsed unstable bubble produces noise [2]. Cavitation damage can result in the wake of some mechanical damage such as a leading edge tear or bend, in which case the cavitation and erosion are secondary damage sources [2]. Methods for reducing cavitation effects on propellers are the submergence of propeller, proper ventilation, clearances from hull, use of skewed propeller, increasing developed area of blade and the use of appropriate propeller material [13]. A propeller in operation suffers wear due to physical damage, corrosive and erosive impact [3]. The wear by corrosive impact over the blade tip areas may increase by 4 to 5 times if the blade surfaces are rough and this increases the effect of drag [3].

B. *Wake-Induced Forced Oscillations on the Blades*

The propeller blade design optimization against failure is based on the evaluation of the circulation distribution along the span of the blade [3]. Considering a blade in incident wave of amplitude, the theories explained that the wave-induced motion and load amplitude on the blade are linearly proportional and can lead to propeller failure as researched by [3].

C. *Cyclic Fatigues & Propeller Casting Defects*

Propellers used on vessels undergo cyclic fatigues leading to cracks due to induced force on the blade [3]. The consequences are total loss of water craft, loss of performance or delay in time of operation [3]. Cracks mostly begin at the points of highest stress loads, such as sharp edges, thick to thin transition zones and areas where repair has occurred [3].

IV. CAUSES OF WAVE - INDUCED OSCILLATION

A. *Ship-Radiated Noise*

Wave-induced-based noise has been evaluated, and there exist empirical prediction models for ship noise [14]. The time-noise signature due to cavitation is dependent on many factors [14]. The application of the Bernoulli theorem to model, Fowc-Williams Hawking's equations, potential based flow solve numerical analysis has been use for research on noise prediction model and hydro acoustic properties analysis of marine propellers [14, 15].

B. *Reduction in the Thrust produced by Propeller*

Propellers facilitate the development of significant thrust that can be used to propel the vessel at various operational speeds [17]. Thrust developed by the propeller is transmitted to the ship's structure by the main shaft through the thrust bearing [17]. Sudden loss in the propeller thrust due to wave-induced oscillation, can cause a resistance increase on the vessel [3].

C. *Vibration in the Propeller Shafting*

Wave-induced oscillation affects the propeller performance and efficiency drastically [3]. It causes induced structural vibration through the thrust bearing [3]. Wave-induced oscillating propeller develops a no uniform wake during operation, which can result to a small variation in the propeller thrust and fluctuation in the shaft line [3]. The oscillatory thrust generated, acts on the shaft and causes ship structural vibration [3]. Table 1 presents the hierarchy structure of factors that can lead to failure of the propeller due to wave induced oscillation.

TABLE I. WAVE INDUCED OSCILLATION FAILURE

Propeller failure by wave induced oscillation (WIO)		
Propeller Cavitation (PC)	Wake Induced Forced Oscillation blade (WIFOB)	Propeller Wear (WW)
Cavitation due to sea water temperature (CAV-FAIL) Cavitation caused by half immersed propeller (FAIL-IP)	Propeller blades oscillation due to water circulation along the blade space (WIFOB –BS) Propeller blade oscillation due to thrust and torque vibration (WIFOB –LV) Propeller blades oscillation due to waves incident upon the propeller blades (WIFOB – WI)	Propeller failure due to propeller physical damage (PW-PD) Corrosive impact causing propeller failure wear cause by corrosion on blades (PP-PW-CI) Propeller failure caused by erosive impact of the blades (PP-PW-EI)

V. METHODOLOGY

The purpose of study identifies and proposes risk control measures in preventing the impact of wave induced oscillation of marine propellers. Marine engineering experts from the Regional Maritime University (RMU), Tema Shipyard, and the Ghana Ports and Harbor Authority (GPHA) were consulted for data collection. The nature of data collection was based on the expert judgment, only experienced marine engineers, maritime experts, and marine lecturers where selected from the target population of 50 participants. Data was collected using questionnaire and brief interview to validate the response on the questionnaires were experts were presented with the hierarchy structure of what can lead to a propeller failure due to wave induced oscillation. Considering the importance of the answer of respondent used as data for this study, the procedure for recruitment used was of extreme importance hence scouting carried out to ascertain which of the engineers, surveyors and maritime expert have high experience at sea and the field. In this study FTA was employed to rank the sequential event that can lead to propeller failure due do wave-induced oscillation. Construction of a fault tree began with the definition of the top undesired event (the system failure) as seen in Table 1. A FTA is constructed linking the intermediate events (propeller cavitation, waked induced forced vibration on the blades, and propeller corrosion). The causes were then indicated and connected to the top event by logic symbols (AND gate and OR gate). The probabilities of occurrence of intermediate events were run into risk control measure/options this was to rank the events that were more likely to occur in order of occurrence ranking. Figure 1 shows the participants working experiences contributed with dry dock engineer 29.6%, marine engineering lecturers 8.5%, and marine engineering surveyors 4.25%. Figure 2 and 3 represents the respondent input on the effect of water temperature and effect of propeller immersion on propeller failure respective. Out of 55 participants sampled, 47 participants responded.

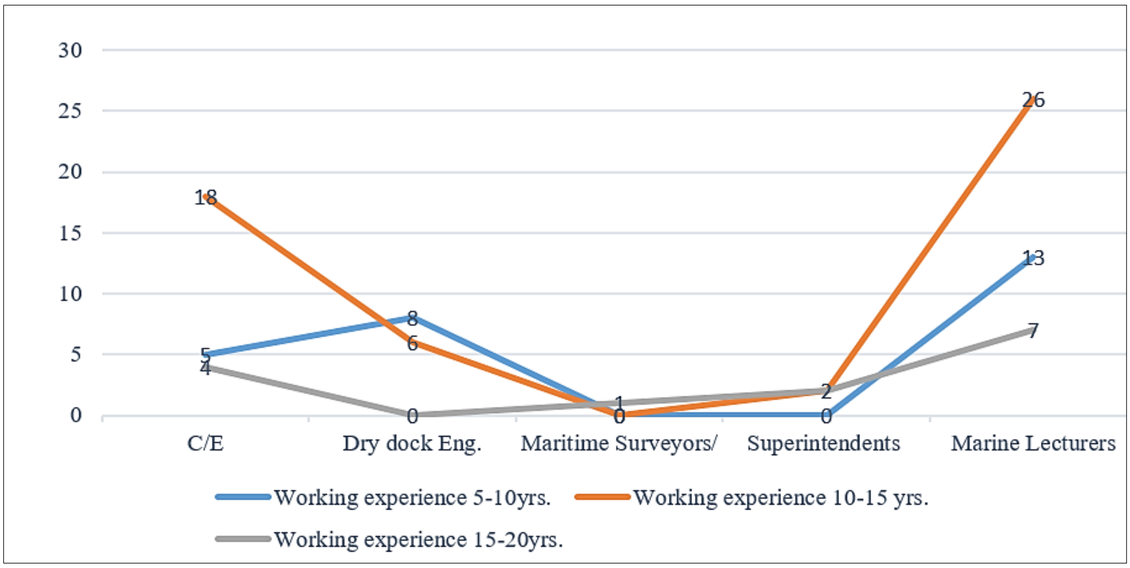

Figure 1. Participants working experiences

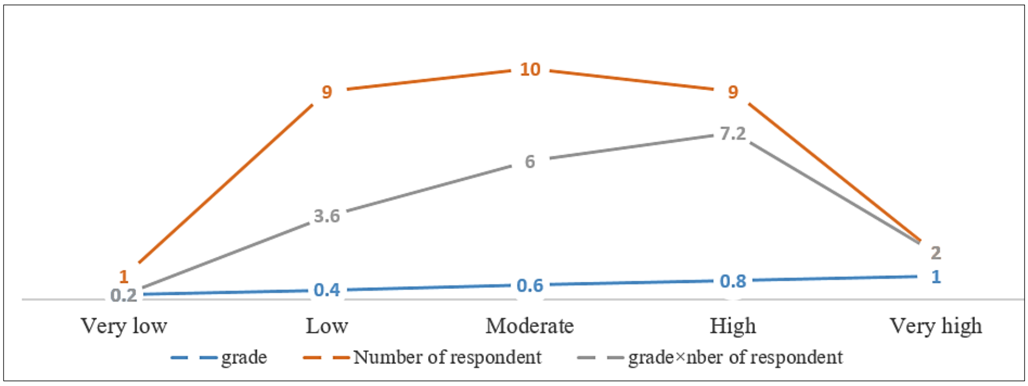

Figure 2. Respondent input on effect of water temperature

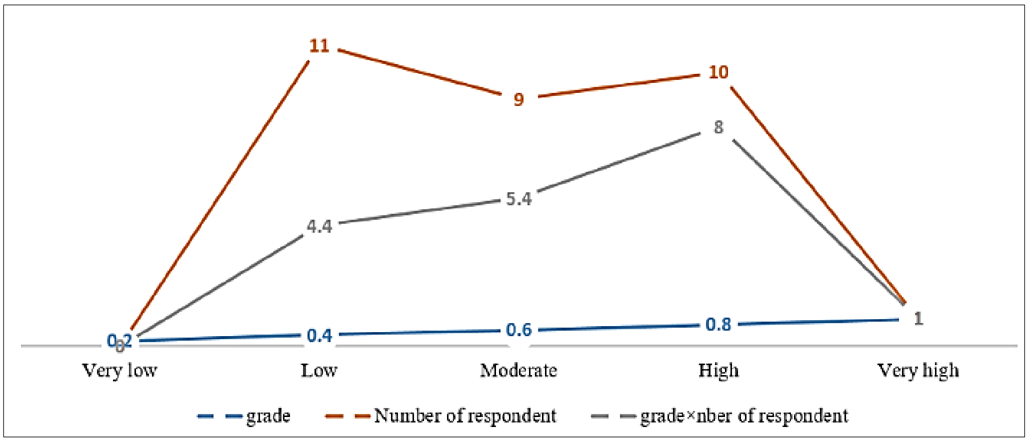

Figure 3. Respondent input on effect of propeller immersion

VI. ILLUSTRATIVE EXAMPLE AND DATA ANALYSIS

Probability of intermediate event "AND gate" is evaluated using Fault Tree "AND gate" general formula (1). From results obtained by mathematical computation, probability of occurrence of intermediate event propeller cavitation (PC) is the highest with a probability of 0.372, probability of occurrence of wave-induced forced oscillation of blades (WIFOB) and propeller wear (PW) have similar chance of occurring with a probability of 0.166 and 0.168 respectively.

The probability of occurrence of intermediate events is evaluated using the general formula:

$$P(E_a)=\prod_{i=1}^{k} P(Ei) \quad (1)$$

Probability of intermediate events

P (PC) = (WT) x (IP) = 0.613 x 0.605 = 0.372

P (WIFOB) = P (BS) x P (LV) x P (WI)

= 0.574 x 0.516 x 0.561 = 0.166

P (PW) = P (PD) x P (CI) x P (EI)

= 0.547 x 0.587 x 0.523 = 0.168

Probability of Occurrence of Top Undesired Event "OR" Gate

$$P(E_0)=1-\prod_{i=1}^{k}\{1-P(Ei)\} \quad (2)$$

P(WIOP) = P(PC or WIFOB or PW)

$P(PC) + P(WIFOB) + P(PW) - P(PC \cap WIFOP) - P(PC \cap PW) - P(WIFOP \cap PW) + P(PC \cap WIFOB \cap PW)$

$$P(WIOP) = [0.372 + 0.166 + 0.168]$$

$$-[(0.372\times0.166) - (0.372\times0.168) - (0.166\times0.168)]$$

$$+[0.372\times0.166\times0.168] = 0.564$$

The occurrence of any intermediate event causes the top undesired event (propeller failure) to occur since the intermediate events are connected to the top event by "OR gate". The occurrence probability of the top event (Wave-Induced Oscillation of Propeller) is evaluated using the "OR gate" Fault tree general formula (2). The result from mathematical computation reveals the probability to be 0.564 this means the 56.6% chances of the propeller to fail by Wave-Induced Oscillation. To determine the likelihood order of occurrence of each intermediate event by keeping two of three intermediate event probability constant and reducing the third one by 80% and run the result to find the percentage reduction.

Reducing the probability of propeller cavitation P (PC) by 80% and find the percentage reduction of the top event P (WIOP) keeping P(WIFOP) and P(PW) constant. Reducing the probability of Wake-Induced Forced Oscillation P (WIFOB) by 80% and find the percentage reduction of the top event P (WIOP) keeping P(PC) and P(PW) constant. Reducing the probability of Propeller failure by Wear P (PW) by 80% and find the percentage reduction of the top event P (WIOP) keeping P(WIFOP) and P(PC) constant as presented in Table 2.

The probability of propeller failure by Wave-Induced Oscillation reduced by 46.5% when the probability of propeller cavitation (PC) was reduced by 80% and WIFOB and PW were kept constant; the probability of propeller failure by Wave-Induced Oscillation was reduced by 13.9% when the probability of wake-forced oscillation (WIFOP) was reduced by 80% and probability of propeller cavitation (PC) and propeller wear (PW) were kept constant; the probability of propeller failure by Wave-Induced Oscillation reduced by 14.2%. The detailed fault tree analysis is shown in Figure 4 and the average probability of occurrence is seen in Figure 5. Propeller cavitation is the major thread to propeller failure by Wave-Induced Oscillation following by Wake-Forced Oscillation of propeller blades and finally propeller failure by Wear is at very low as in Figure 4, hence the need for relevant risk control measures to be put in place.

TABLE II. PERCENTAGE REDUCTION OF BASE EVENTS

Intermediate Events probability	80% reduction	Percentage reduction of the Top event (WIOP) (%)
P(PC) [0.372]	0.11	46.5
P(WIFOP) [0.166]	0.13	13.9
P(PW) [0.168]	0.13	14.2

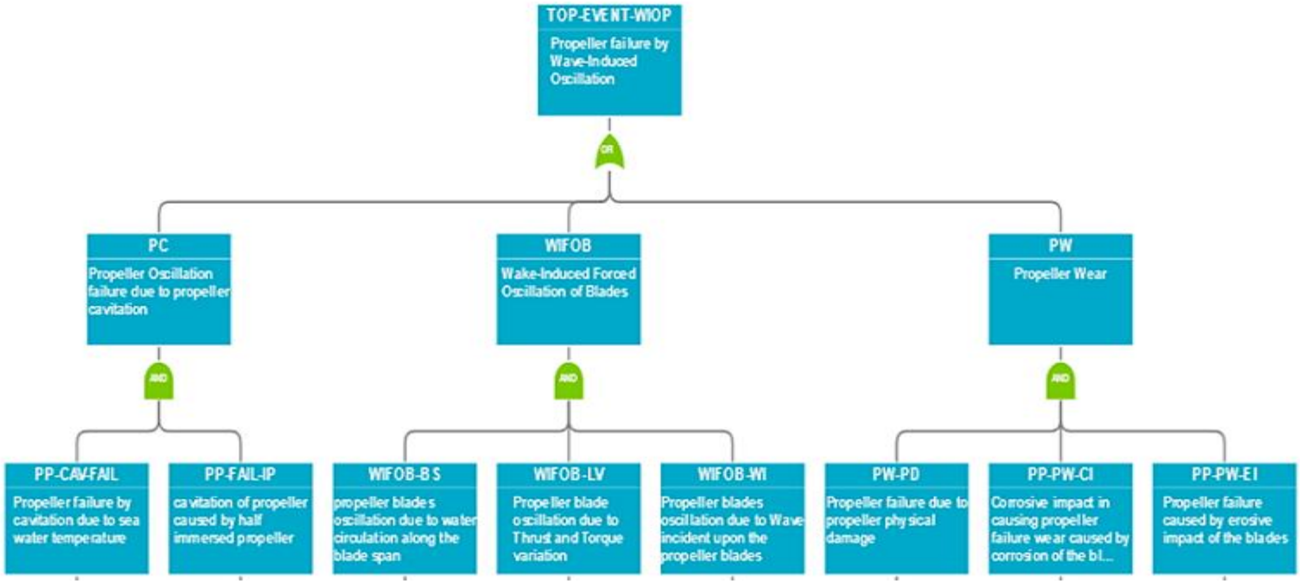

Figure 4. Fault tree analysis of propeller failure

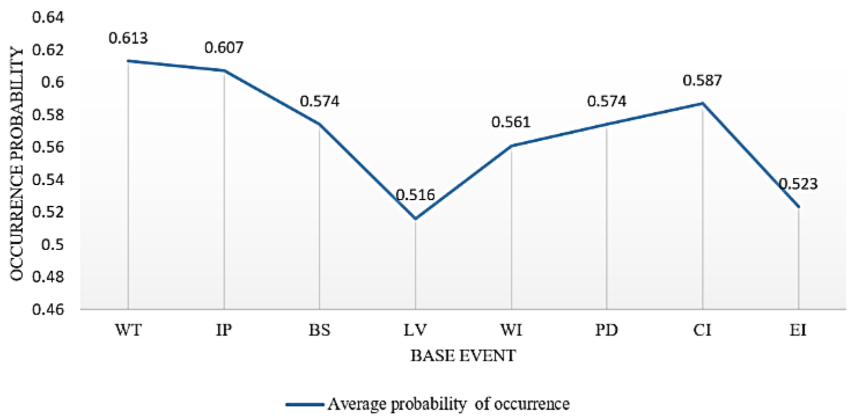

Figure 5. Average probability occurrences

VII. CONCLUSION

The results show that more attention should be paid to avoid cavitation of the propeller. Failure analysis of ship propeller operations has been addressed in this research work. Relevant failure modes of the ship propeller, such as PC, WIFOB and PW, have been identified and analyzed. FTA was used to estimate the various failure modes by maritime experts. The analysis using fault tree reveals that the PC is prone to cause ship propeller failure by Induced-wave oscillation than WIFOB and PW. The theory of ranking risk control measure/option was used to identify the failures that are more likely to occur than others. And the PC, WIFOB and PW are the highest and lowest, respectively, among other failure modes of the ship propeller operations. Therefore, propeller cavitation is a threat to effective operations of ship propeller operations. The result of this work can be beneficial to ship manufacturing companies, regulatory bodies and ship owners in decision making

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