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Model Podded Propeller-Ice Interaction in Extreme Conditions using a Probabilistic Model

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ABSTRACT

Extreme ice loads acting on a model propeller blade during propeller-ice interactions are studied for input to the design and maintenance of ice class propellers. The main focus of this paper is to develop a framework for analyzing ice loads on a propeller blade using probabilistic methods based on experimental results. The Poisson distribution is used for the events of the propeller-ice interactions and the cumulative density function for extreme ice loads is modeled by a double exponential form (Gumbel Type).

Propeller-ice interaction experiments were conducted in the ice tank at the National Research Council of Canada Institute for Ocean Technology (NRC/IOT). A model podded propeller was used for the experiments and ice loads were measured with a six-component dynamometer attached to the root of the propeller blade inside the hub.

Based on the experimental results, extreme values are plotted with an exceedance probability. Some results for the maximum blade thrust, the maximum shaft thrust and the maximum out of plane bending moment are presented in this paper. The modeling of the extreme probability is also described briefly.

NOMENCLATURE

D Propeller diameter (m)
DOC Depth of cut (mm)
F_X Force in the direction of x-axis
$F(x)$ Cumulative density function
F_Y Force in the direction of y-axis
F_Z Force in the direction of z-axis
K_T Thrust coefficient ($T/(\rho n^2 D^4)$)
Pr Probability

T Thrust (N)
n Propeller rotating speed, rps
     (Revolution Per Second)
V_S Carriage velocity (m/s)
α_m Milling angle (*degree*)
γ Total expected number of events
μ Expected number of interactions (hits)
ρ Density of water
r Proportion coefficient of hits

1. INTRODUCTION

Most of the decisions regarding scantlings for an ice class propeller are made by various classification society rules, the Arctic Shipping Pollution Prevention Regulations (ASPPR) and the Finnish-Swedish Ice Class Rules (Bose et al., 1998). The ice class rules, however, were formulated on the basis of a prescribed ice torque. As the number of vessels capable of navigating in ice-covered seas is increasing, the need for the proper estimation of ice loads is becoming more important. Deterministic extreme ice loads on a propeller play an important role in the choice of the strength of the propeller at the initial design stage and the understanding of the interactions between the propeller and ice during navigation stage.

Generally, full-scale measurements are used for the evaluation of the maximum ice loads. The ice loads from full-scale measurements, however, have a high-level of uncertainties because of the non-uniform ice properties, the randomness of the interactions, uncertainties in the data acquisition systems, and discrepancies among the data analysis methods used. Also sampling rates are usually not high enough to capture the "real" peaks in the data. The cost of

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carrying out full-scale measurements for propeller-ice interactions is often prohibitive.

In order to overcome these difficulties, model tests with artificial/refrigerated ice were conducted (Jones et al., 1997; Searle, 1999; Moores et al., 2001; Akinturk et al., 2004; Wang et al., 2004; Wang et al., 2005). Model tests give more precise information in terms of the ice properties, the interaction conditions, and the data collected compared with full-scale measurements.

The objective of this work is to determine the maximum ice loads acting on the propeller blade using the extreme probability method. Model test data were used for the analyses.

The probabilistic analyses for propeller-ice interaction have been studied (Andruishin, 1993; Bose et al., 1998; Browne et al., 1998). Bose et al. (1998) introduced the probability method for determination of the full-scale ice loads during the propeller-ice interactions with two, and three parameter Weibull distributions and Gumbel distribution. The Gumbel distribution was used for structure-ice interactions (Jordaan and Maes, 1991; Maes and Hermans, 1991; Jordaan et al., 1993; Jordaan, 2001). In this paper, the probability method will focus on the Gumbel distribution because it can be applied to more general cases (Jordaan, 2004). The events of propeller-ice interactions assume a Poisson distribution and the extreme loads were simulated using an exceedance probability.

2. MODEL TEST

Model tests were conducted at the Institute for Ocean Technology ice tank with a model podded propeller. Wang et al. (2005) shows the test procedure and some of the results in detail.

2.1 Model Propeller

The propeller was designed to be similar to a general icebreaker propeller. It had a diameter of 0.3 m and four blades. Mean-pitch/diameter ratio (P/D) was 0.76 and expanded blade area ratio (EAR) was 0.669. The diameter of the hub at the propeller was 0.11 m.

2.2 Dynamometers

Ice loads acting on the propeller blade were measured by a blade dynamometer that was manufactured by Advanced Mechanical Technology Inc. (AMTI) and capable of measuring forces/moments in six degrees of freedom. It was mounted inside the hub and attached to one of the blades. The sampling rate was 5000 Hz. The transducer can measure forces up to 2224 N in x- and y- directions, up to 4448 N in the z-direction, and moments up to 56.5 Nm about all three

axes. The local coordinate frame for the blade dynamometer is shown in Figure 1.

Two dynamometers of the same type as the blade dynamometer were attached to the shaft bearings. The global dynamometer was on the top of the pod system, and measured the six degrees of freedom forces/moments in three orthogonal directions. Shaft torque was measured by a strain gauge system mounted on the shaft close to the propeller hub. Other measurements, such as carriage velocity, propeller rotating speed, azimuthing angle, and blade angular position were also taken.
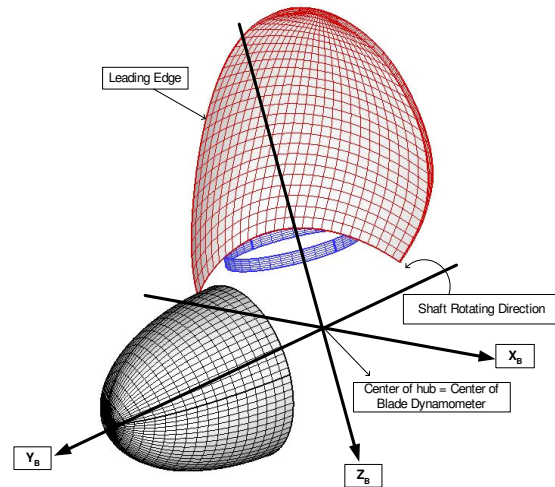

Figure 1: Axes for the blade dynamometer

2.3 Ice Tank

The tests were conducted in the ice tank at NRC/IOT (Jones, 1987). The useable area of the tank for ice testing is 76 m long, 12 m wide and 3 m deep. In addition, a 15 m long setup area is separated from the ice sheet by a thermal door to allow equipment preparation while the test sheet is prepared (Figure. 2). The range of the carriage velocity is from 0.0002 to 4.0 m/s. The carriage is designed with a central testing area where a test frame, mounted to the carriage frame, allows the experimental setup to move transversely across the entire width of the tank.
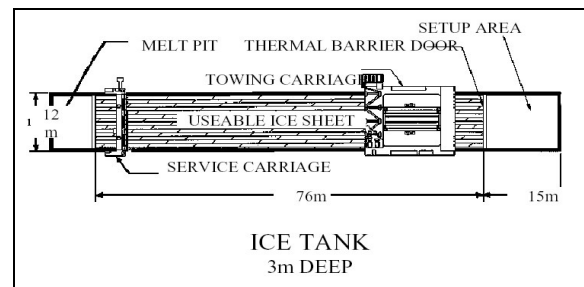

Figure 2: Schematic Diagram of the ice tank

2.4 Model Ice

EG/AD/S refrigerated model ice was used in these experiments (Timco, 1986, Spencer and Timco, 1990). The target flexural strength and thickness were 80 kPa and 60 mm, respectively.

2.5 Test Matrix

The tests were carried out at different depths of cut, propeller rotating speeds (RPS), ice conditions, and carriage velocity (V_s) (Table 1). The tractor (also called puller) mode was used in the present work. In this paper, "Case 1" shows the results when the azimuthing angle is between 180 and 150 degrees. "Case 2" shows the results when the azimuthing angle is less than 150 degrees.

	Azimuthing Angle (°)	Carriage Velocity	RPS	Ice Conditions
Case1	180, 150	0.2, 0.5, 0.8	5, 7, 10	Pre-sawn, Pack ice
Case2	120, 90, 60	0.2, 0.5, 0.8	5, 7, 10	Pre-sawn, Pack ice

Table 1: Test matrix for two different depths of cuts (15 mm and 35 mm DOC)

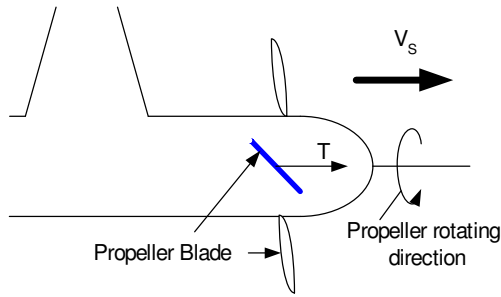Figure 3 shows the tractor mode with 180 degrees azimuthing angle.

Figure 3: Tractor mode with 180 degrees azimuthing angle

2.6 Data Analysis

Hydrodynamic loads were subtracted from total loads in the ice condition and only "ice-related" loads were used for the present work (Wang et al., 2005).

Total loads in ice = ice milling loads + "separable" hydrodynamic loads + "inseparable" hydrodynamic loads

"Ice-related" loads = ice milling loads + "inseparable" hydrodynamic loads

Total loads in ice can be obtained from ice tank tests, and *"separable"* hydrodynamic loads are the results of the open water tests. *"Inseparable"* hydrodynamic loads include the blockage/ proximity effects or cavitation due to the presence of the ice (Walker, 1994; Bose, 1996).

In the analysis, the depth of cut (DOC) is defined as the maximum depth that was penetrated by the propeller blade into the ice block (Figure 4). α_m is defined as the angle in which ice milling is thought to be occurring.
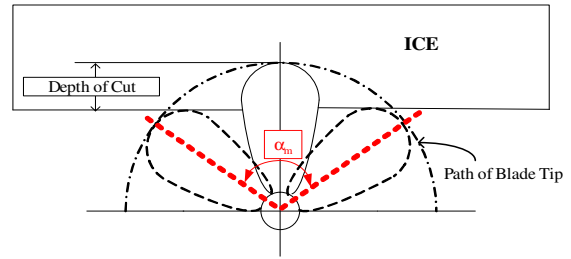

Figure 4: Depth of cut (DOC)

3. PROBABILITY METHOD

For extreme probability, there are three classical asymptotic models depending on the parent distribution. These are expressed as follows:

Type 1: $F(x) = \exp[-\exp(-x)]$
$$\text{for } -\infty < x < \infty , \qquad [1]$$

Type 2: $F(x) = \exp(-x^{-\alpha})$ with $\alpha > 0$,
$$\text{for } -\infty < x < \infty , \qquad [2]$$

Type 3: $F(x) = \exp[-(-y)^{\alpha}]$ with $\alpha > 0$,
$$\text{for } -\infty < x < \infty . \qquad [3]$$

Type 1, 2 and 3 are normally named as Gumbel, Frechet and Weibull distributions, respectively. For the maxima, the Type 1 distribution is the most useful because it is the natural extreme for most parent distributions (Jordaan, 2004).

3.1 Basic Concept

At first, all events are assumed to have independent and identically distributed random quantities. The set of random quantities is, for example,

$$\{X_1, X_2, X_3, ... X_i, ..., X_n\}. \qquad [4]$$

The extreme value Z can be defined as

$$Z = \max(X_1, X_2, X_3, \ldots X_i, \ldots, X_n). \qquad [5]$$

The cumulative density function, $F_Z(z)$, can be written as

$$F_Z(z) = \Pr(all\ X_i \leq z) = F_X{}^n(z). \qquad [6]$$

3.2 Application to propeller-ice interaction

Propeller-ice interactions can be explained by the Poisson process because, in an actual scenario, the interactions will not occur continuously. Also, propellers will more often experience ice pieces (pack ice) than level ice. For the extreme probability method, the only interesting region is the tail of the probability distribution and it may follow an exponential or double exponential form (Type 1, Gumbel distribution). In order to use the extreme statistics, the data set was ranked in descending order from order statistics (Castillo, 1988). The Weibull plotting position $[i/(n+1)]$ was used for the exceedance probability and double exponential form was used for the tail distribution. Therefore, the exceedance probability was defined as a double logarithm. In the Weibull plotting, n is the total number of interactions and i is the sequence number. The one percent exceedance probability (for example "100 year" load case if the distribution is based on one year), can be written as

$$-\ln(-\ln(P_e')) = 4.6. \qquad [7]$$

where $P_e' = 1 - P_e$, and $P_e = 0.01$.

When a propeller blade contacted ice, the "ice-related" loads were calculated, i.e. the total number of events was the same as the number of the ice contacts. The decision of a contact period was made by using blade angular position (Wang et al., 2005). Although blade angular position is within the target range of α_m, a non-contact may occur because of the shadowing of the blades or the irregularity of the ice feeding. Therefore, the number of interactions (hits) is counted only when the "ice-related" loads are larger than the maximum loads measured in open water tests (no ice case).

The Poisson distribution can be written as

$$P(n : \mu) = \frac{e^{-\mu}(\mu)^n}{n!}, \ n = 0, 1, 2\ldots \qquad [8]$$

where μ is the expected number of interactions (hits) per unit time for future estimation ($\mu = r\gamma$, where r is the proportion of hits and γ is the total expected number of events).

For most practical cases, the distribution of the tail can be represented by an exponential or double exponential form (Jordaan et al., 1993), which is

$$1 - F_X(z) = \exp(-[az + b]) \qquad [9]$$

A new Poisson process of tail for random quantities is:

$$\mu' = \mu(1 - F_X(z)) \qquad [10]$$

$$P(n' : \mu') = \frac{e^{-\mu'}(\mu')^{n'}}{n'!} \ n' = 0, 1, 2\ldots \qquad [11]$$

If n' is assumed to be equal to zero for the extreme case, then

$$F_Z(z) = \exp(-\mu') = \exp\{-\mu[1 - F_X(z)]\}$$

$$= \exp\{-\mu(\exp[-(az + b)])\}$$

$$= \exp\{-\exp(-[az + b] + \ln \mu)\}. \qquad [12]$$

Jordaan (2004, p. 501) shows the full derivation of equations with detailed explanation.

4. DATA RESULTS

In the calculations, the following assumptions are used:

1. All events are independent and identically distributed (*iid*).
2. Same contacting area: for a given test run, i.e. constant propeller rotational and advance velocities, the area of the blade contacting the ice during milling is assumed to be the same for each rotation of the propeller. Though, this area might vary during a test run.
3. Same pack ice condition: for all the tests in pack ice, the density of the ice distribution on the water surface is assumed to be the same, i.e. 9/10.

Figure 5 shows the total force distribution in time series; i.e. $\sqrt{F_X{}^2 + F_Y{}^2 + F_Z{}^2}$, acting on the propeller blade in pack ice condition.

In order to use the extreme probability method, an appropriate return period must be defined. For simplicity, it will be assumed that the return period is the time it took for the test run under consideration. This will be called a unit time for the sake of argument. For the purpose of illustrating the concept, number of hits will then be projected to a time scale equal to the 100 times of this unit time. This return period, however, can be controlled using a proper interaction scenario.

Figure 6 shows the total force on the blade, presented in Figure 5, against exceedance probability. If the "100 unit times" loads of the total force were considered, the exceedance probability value would be 4.6 from Equation 7. If the exceedance probability is determined, the design loads can be chosen.

Figure 6: Data in Figure 5 ranked and plotted with exceedance probability (Gumbel plot)
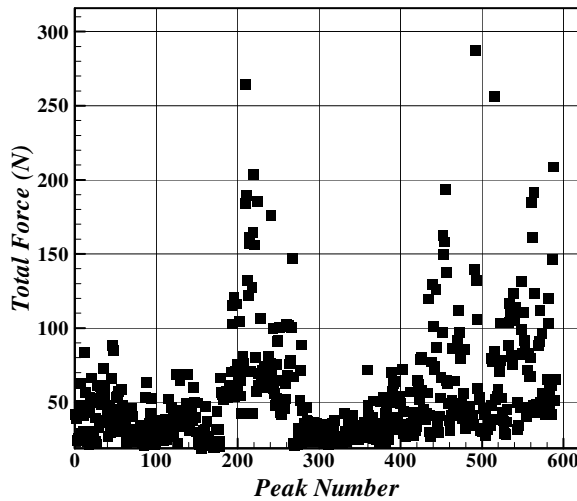

Figure 5: Measured maximum total force values for the assumed ice interaction segments in the time series for the selected test run

In Figure 7, shaft thrust coefficients are plotted for azimuthing angles of 150° and 180°. If we consider the "100 unit time" loads, the maximum shaft thrusts for 35 mm DOC and 15 mm DOC are 2.7 and 1.57, respectively. When the DOC is increased from 10 percent to the 23 percent of the propeller blade radius, the shaft thrust increased about 58 percent. The thrust coefficient (K_T) is defined as

$$K_T = T / (\rho n^2 D^4) \,,$$

where, ρ is the density of water, n is the propeller rotating speed and D is the diameter of the propeller.
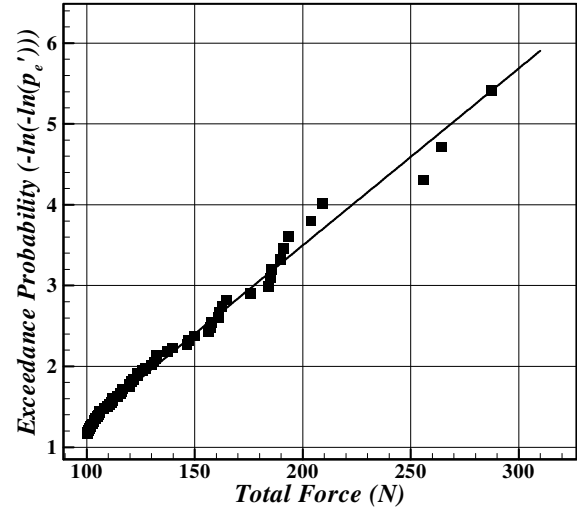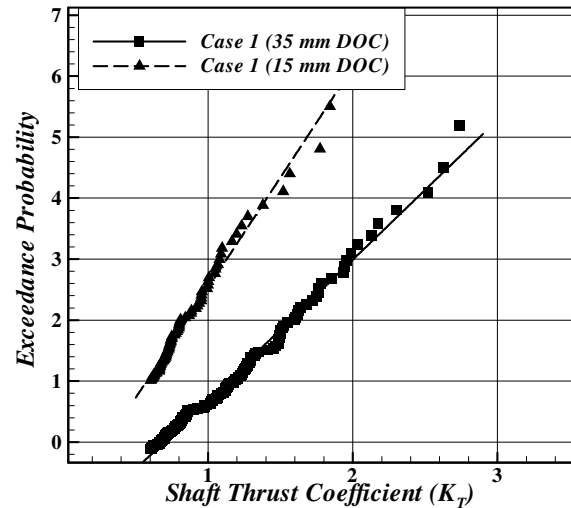

Figure 7: Shaft thrust coefficients with two different depths of cut against exceedance probability

Figure 8 shows the relationship between the shaft thrust and four times the blade thrust. Because the number of blades was four, four times blade thrust is assumed to be a good parameter to indicate the total thrust generated by the propeller. It is then compared to shaft thrust. In the case of 15 mm DOC, the four times the blade thrust compared well with the shaft thrust at the same probability (not shown in this paper). For 35 mm DOC, however, the shaft thrust, was much higher than four times the blade thrust values. It might mean that when the propeller blade penetrates deeper into the ice block, the rest of the blades might encounter accelerated broken ice pieces or dynamic ice loads.
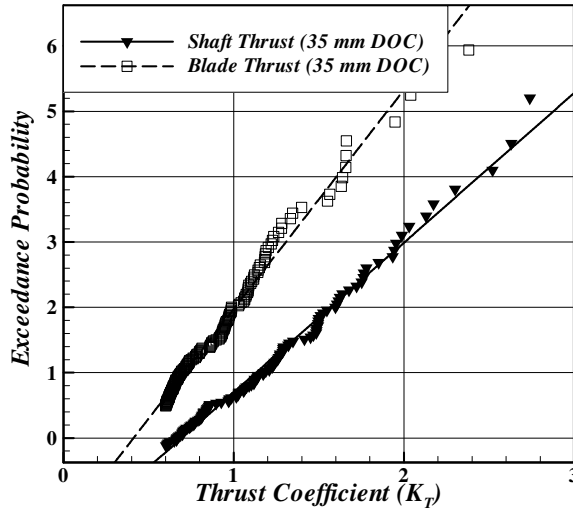
Figure 8: Comparison between shaft thrust and four times blade thrust

Out of plane bending moments of the propeller blade are plotted against the exceedance probability for 35 mm DOC in Figure 9. The largest out of plane bending moments can be expected when the azimuthing angle is less than 150° in pre-sawn ice conditions. From the "100 unit time" loads point of view, the maximum out of plane bending moment values for "Case 2" was 2.6 times higher than those of "Case 1".
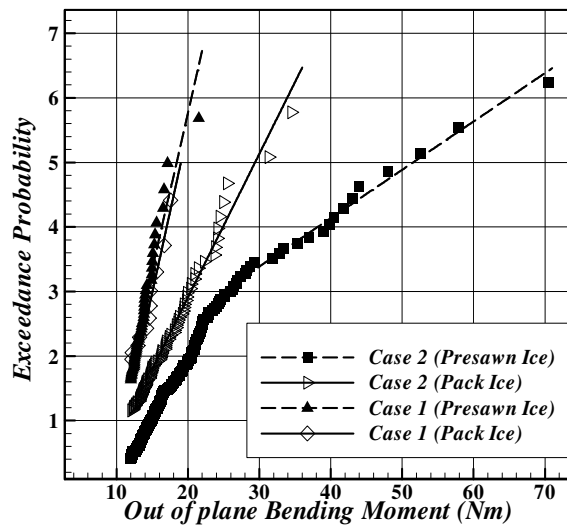

Figure 9: Out of plane bending moments with various operating conditions in 35 mm DOC

5. CONCLUSION AND REMARKS

The experimental test results were analyzed with extreme probability method. The extreme probability method is useful when deciding the ice loads in ice-class propeller design.

The thrust coefficient was selected as a case study to illustrate the concept. Of course, the same method can be applied to any other parameter, such as shaft torque, etc.

All the data used in this paper were the maximum ice induced loads that did not include separable hydrodynamic loads. The extreme values for the ice related shaft thrust, blade thrust, and out of plane bending moments were 9, 5.9, and 7.7 times higher than the maximum separable hydrodynamic loads as far as the estimated "100 unit time" loads are concerned. The corresponding maximum separable hydrodynamic loads were measured in clear water (no ice) at the same test conditions, i.e. advance coefficients, azimuthing angle, etc., as the ice tests.

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