Proceedings of the 25th International Conference on
**Port and Ocean Engineering under Arctic Conditions**
June 9-13, 2019, Delft, The Netherlands

# Simplified ice impact load estimate for azimuthing thrusters

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## ABSTRACT

In winter navigation, a viable ice load scenario for azimuthing propulsor is an ice block impact to the propulsor structure. Such scenario is featured in the new Finnish-Swedish Ice Class Rules. This case can be considered as a dynamic process, where the ice contact and the structural deflection are contributing factors towards the net load on the propulsor structure.

The ice contact between the propulsor and ice together with the propulsor structure dynamics were implemented in a dynamic impact model. The model was validated with small-scale testing and full-scale reference cases.

With the dynamic model, the effect of operational and dimensional parameters to the ice impact load were studied. However, the use in ice class rules requires simplified formulation. This formulation should take easily understandable physical parameters as input, and provide a rule-of-thumb- results for ice impact load.

In this paper, the development of the simplified approach is presented, the simplified model is tested and its key parameters are identified.

KEY WORDS Ice; Impact; Load; Azimuthing thruster

## INTRODUCTION

For ships navigating in ice conditions, one needs to know how large loads is caused by ice blocks impacting ship's propulsor unit. For this reason, new Finnish-Swedish Ice Class Rules (FSICR) were developed (TRAFI 2017). First, a dynamic impact model was created and it was experimentally validated (Kinnunen et al., 2019). The dynamic impact model can be used when ice block hits the ship propulsor unit. The principle of the load scenario is shown in Figure *1*. To be used in the ice class rules, a more simplified method was needed. The background principles for the development of the more simplified method is presented in this paper.

First, the dynamic ice load model is introduced. Then, the simplified model was formulated with regression analysis from the results of the dynamic ice load model. Different non-linear model functions and the effect of different input variables were tested. Two and three variable models are introduced and discussed in this paper.

At the end, a review on few ice load calculation methods are presented to be able to compare the developed simplified model against other available methods.

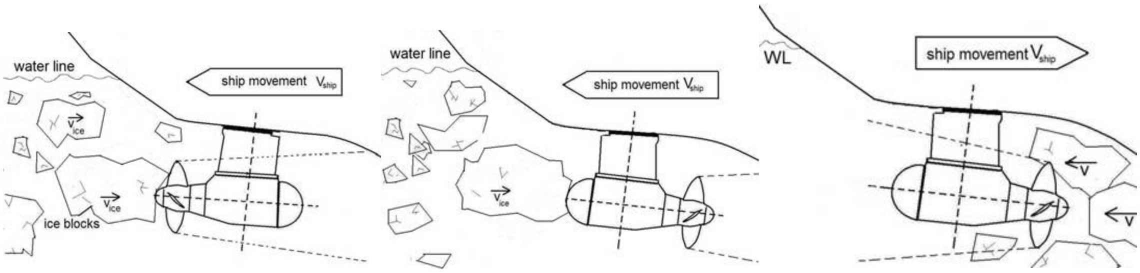


Figure 1. Ice impact load scenario

## DYNAMIC IMPACT LOAD MODEL

The impact load scenario was simplified by assuming that the ice block hits straight to the propulsor as shown in Figure *1*, and that the propulsor surface that is in contact with the ice is spherical. This approach was implemented into a dynamic ice impact load model and validated (Kinnunen et al. 2012, Kinnunen et al. 2014, Kinnunen et al. 2019) with experiments and full-scale references. In the following, the main equations of the model are presented.

The basic contact load principle is a pressure-area relationship (Sanderson 1988) joined with a dynamic structural model. The ice impact problem has been studied earlier (e.g. Popov 1967, Daley 1999, Daley 2009, Timco 2011) and the dynamic model introduces an approach to include structural dynamics.

In the dynamic model, the contact force $F_c$ is affected by the ice compressive strength (σ, or $p_{ref}$), the projected contact area $A$ determined by the thruster spherical surface radius $r$ and the indentation to ice, the initial impact velocity $v$, the ice mass $m_{ice}$, the thruster mass $m_{thru}$ and the structure flexibility, determined by the natural frequency $f$ in direction of the impact. The ship mass $m_{ship}$ is considered to be a large mass compared to the other masses in this context, but it is treated as a variable in the dynamic model as well. When the ship displacement is denoted with $u_0$, thruster displacement with $u_1$ and ice displacement with $u_2$, the model principles can be written as follows. First, the contact force as

$$F_c = p_{ref}\left(A_{ref}A\right)^{1/2} \tag{1}$$

where $A_{ref} = 1$ m$^2$ and the indentation-dependent projected area as

$$A = \pi(r^2 - (r - u_2 - u_1)^2)\ . \tag{2}$$

The equation of equilibrium for the ship, thruster and ice in principle can be written as

$$F_r = m_{ship}\ddot{u}_o \tag{3}$$

$$F_c - F_r = m_{thru}\ddot{u}_1 \tag{4}$$

$$F_c = m_{ice}\ddot{u}_2 \tag{5}$$

The thruster flexibility affecting the thruster response is

$$F_r = ku_1 + c(\dot{u}_1 - \dot{u}_0) \tag{6}$$

where the stiffness $k$ is determined from the natural frequency and the damping value $c$ is adopted from full-scale experience.

A constant value of $p_{ref} = 3$MPa was used, as it is considered representative for the ice conditions of the Baltic Sea.

## PARAMETER STUDY WITH THE DYNAMIC MODEL

With the dynamic model, a parametric study was done by calculating the impact load in time domain with a set of changing input parameters (thruster surface radius $R$, ice mass $m_{ice}$, thruster mass $m_{thru}$, initial velocity of impact $v$, natural frequency $f$) and recording the maximum contact load corresponding the input parameters. This way, the effect of initial values to the maximum load can be observed.

### Parameter selection and convergence towards simplified formulation

With the dynamic model, the effect of the input variable values to the maximum contact load was observed by calculating several cases with varying input values. This approach enabled drafting a few possible forms for the simplified model functions to be used in the regression analysis. For example, the effect of impact velocity and ice mass can be observed e.g. plots like Figure 2.

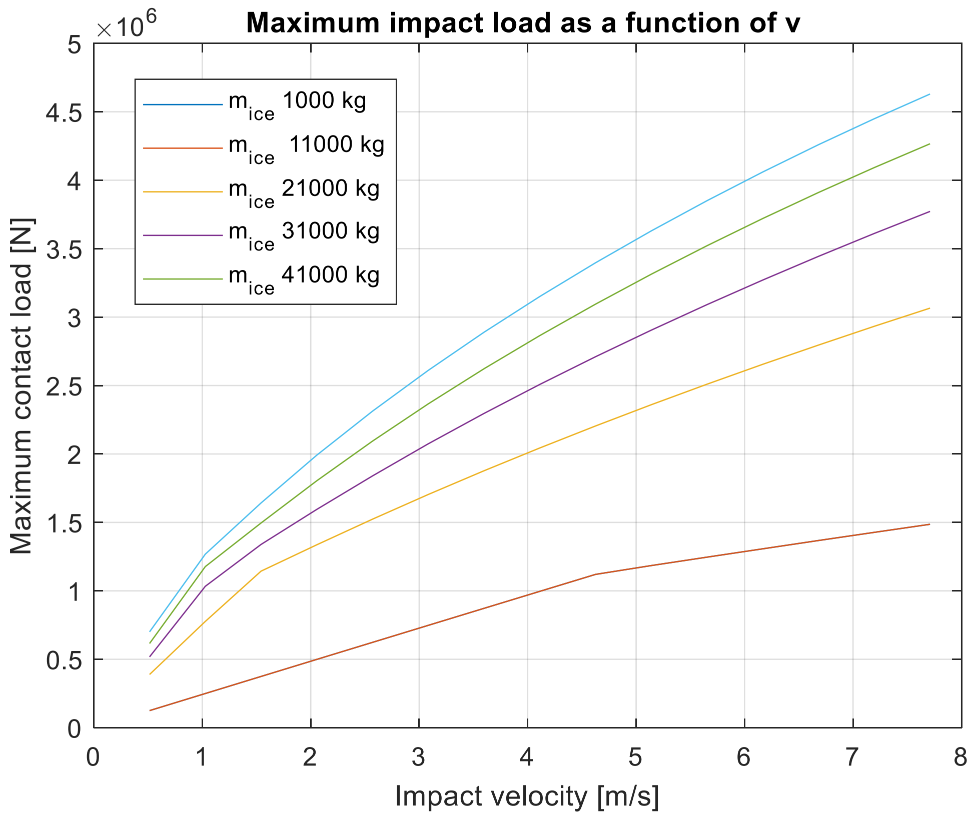


Figure 2. Maximum contact load from the dynamic model with varying impact velocity $v$ and ice mass $m_{ice}$. The impact speed is varied between 0.5m/s and 7.7m/s, and the ice mass between 1000 kg and 41000 kg. The thruster surface radius is 1.2m, the thruster mass is 50 tons, the natural frequency is 10 Hz, and the ship mass is 9500 tons

The variable space used to evaluate the effect of each variable in the dynamic model calculations and respective model fits is listed in Table 1. This variable space produces 1500 cases.

Table 1. Variable space for ice load calculation.

| R (m) | Ice mass (ton) | v (knots) | Thruster mass (ton) | Ship mass (ton) | Thruster natural frequency (Hz) |
|---|---|---|---|---|---|
| 0.1, 0.2, 0.3, …2,5 | 1 ,10,20 … 40 | 1,2,3… 15 | 50 | 9500 | 10 |

First, a two-parameter model was considered in the form of scaling the kinetic energy. This idea came mainly through the idea behind the dynamic model: when all the available kinetic energy is used in the impact, the indentation process stops. The initial two-parameter model was of form

$$F_c \sim b_1 (m_{ice} v^2)^{b_2} \tag{7}$$

The regression fit results $b_1$= 42579 and $b_2$= 0.31337 with the $R^2$ value of 0.694, that is not very encouraging. The comparison of the two-variable load function and the corresponding dynamic model maximum load is presented in Figure 3. It is clear, that the simplified model is grossly overestimating the load for many cases, compared to the dynamic impact load model.

The results of the comparison tell that there is apparently some lack in explaining capability of the simplified model. For example, the effect of the surface radius (thruster size) is not included at all in this approach. The maximum load from the dynamic model is plotted as a function of the thruster contact surface radius in Fig 4. Based on the figure, it is clear that the two-parameter model could be improved by including the thruster size as an input parameter.

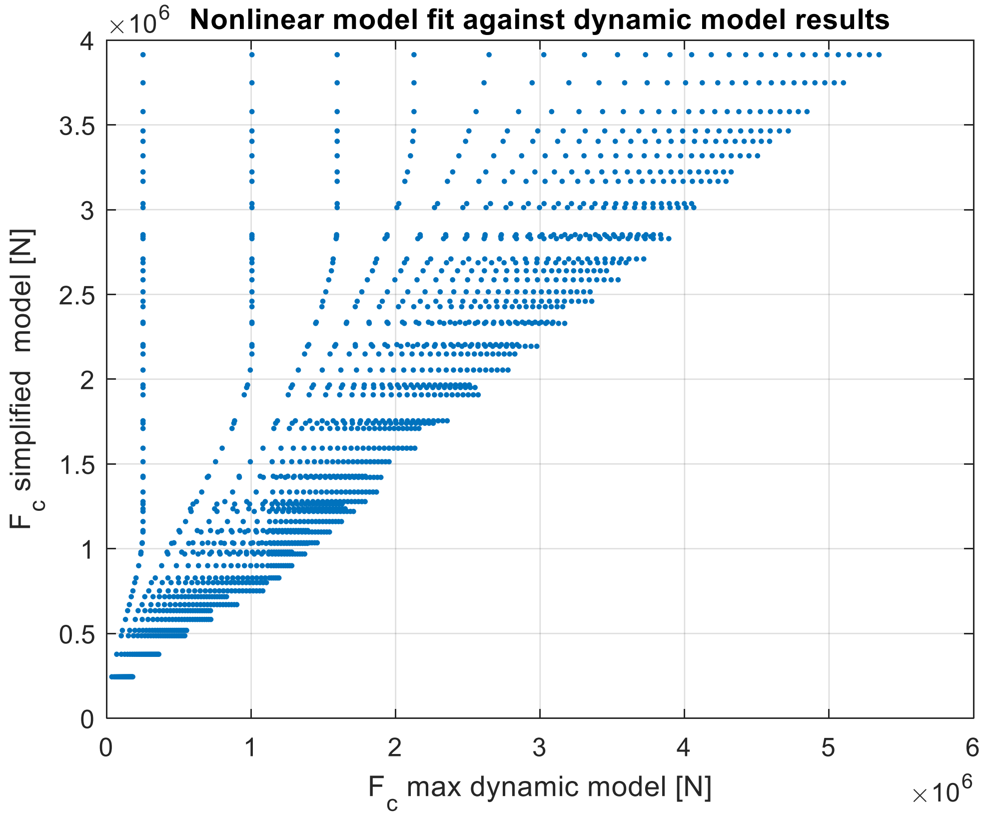


Figure 3. Two-variable simplified model results versus dynamic model maximum contact load.

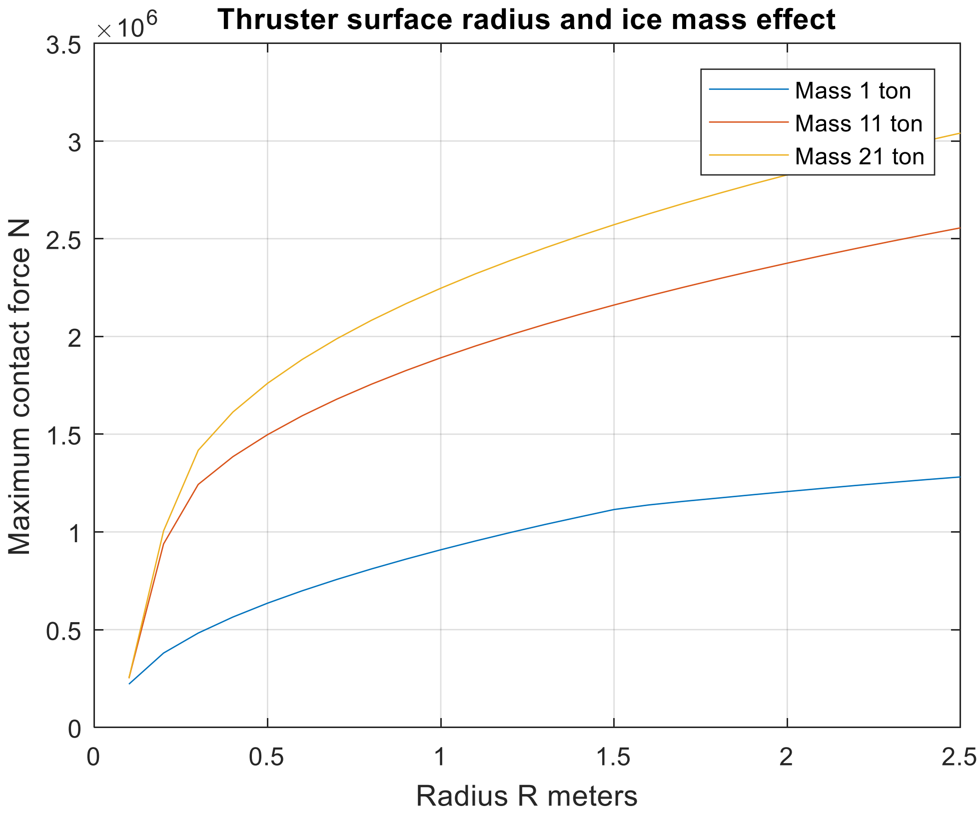


Figure 4. Maximum contact load from the dynamic model with varying radius $R$ and ice mass $m_{ice}$. Thruster mass is 50 tons, impact velocity 4.11 m/s (8 knots), natural frequency 10 Hz, and ship mass 9500 tons.

Based on this, exponential dependency of $R$ was added to the simplified model as

$$F_c \sim R^{b_1} b_2 (m_{ice} v^2)^{b_3} \tag{8}$$

Fitting the three-variable model (eq. 8) with a regression fit to the same variable space as the two-variable model, the model parameters were estimated as $b_1 = 0.42583$, $b_2$ = 38198 and $b_3$ = 0.31734. Now for this model formulation, the $R^2$ value is 0.981.

Contact load with the three-variable simplified model using the estimated parameters and the corresponding dynamic model maximum contact load are shown in Figure 5. It can be seen from this figure that the simplified model gives mostly load values of similar order of magnitude than the dynamic model.

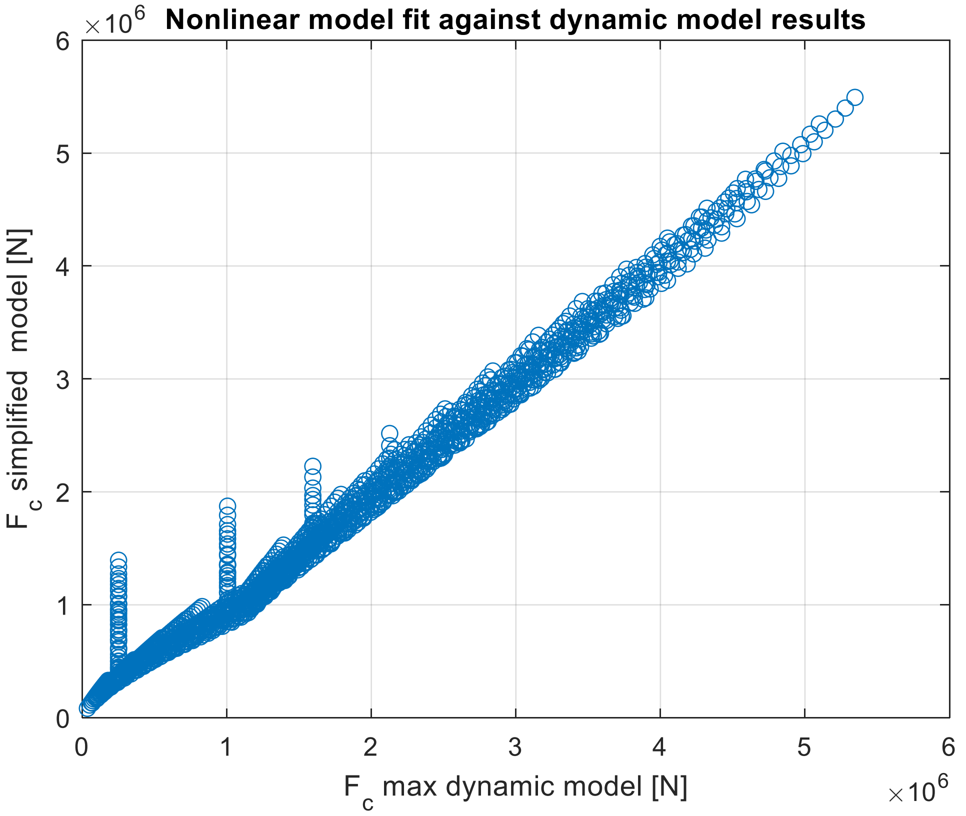


Figure 5. Three-variable simplified model versus dynamic model maximum load.

## Simplified formulation discussion and limitations

The quality of the regression model fit can be estimated with the results obtained in addition to the estimated coefficients. For the two-parameter model, the $R^2$ value was rather low 0.694, indicating that the resulting regression model is not very exact. For the three-variable model, the $R^2$ value was 0.981, which is rather good value. For this reason, the three-variable model was considered a good choice. For the actual ice class rules, the parameter values $b_1$, $b_2$ and $b_3$ were slightly tuned to be always at the safe side and to present the practical and experimental knowledge.

Even though the regression model fit can be very good with the given dataset, the underlying limitations and assumptions that the dataset is based on, are of importance. The dataset for this kind of model fit is to be considered to cover relevant values for the variables.

With respect to the dynamic model, the simplified formulation presented here is utilizing less variables, to provide a rather easily available estimate value for the impact contact load. For example, the effects of the thruster stiffness and mass are not involved in this study. In practice, these two are connected variables, to keep things interesting. With respect to the ice conditions, the limitation here is the background assumption of the Baltic Sea ice conditions, in terms of the used ice compressive strength value.

## COMPARISON BETWEEN ICE CLASS RULES

With the approach presented previously, the formulation for ice impact loads in Finnish-Swedish Ice Class Rules was developed (TRAFI 2017). The equation used for ice impact load in the rules is

$$F_{ti} = C_{DMI} 34{,}5 R_c^{0.5} (m_{ice} v_s^2)^{0.333} \ [kN] \quad (9)$$

The ice class defines the values for the dynamic magnification factor ($C_{DMI}$), design mass of the ice block ($m_{ice}$) and speed of the vessel ($v_s$).

It is interesting to compare the impact loads to other ice class rules. At least DNV GL (DNV-GL 2016) and ABS (ABS 2016) have guidelines to calculate ice loads for azimuthing propulsors. The methods in both of these differ somewhat from the impact load calculation adapted for the FSIC rules. For example, the speed of the ship and mass of the design ice block are not given. In both of these guidelines, the ice class only affects the design ice pressure and design thickness of the level ice.

The DNV GL formula for ice loads is

$$F = p_o^{0.8} (A C^{0.3})^{exp} C_1 C_2 C_3 C_4 \ [MN]$$

where $p_0$ is the ice pressure, A is the projected area exposed to ice pressure, exp is 0.3 or 0.85 depending on A, and C is the relation of projected area and ice thickness. Finally, coefficients from $C_1$ to $C_4$ depend on the propulsor position and the ship type.

The ABS formula for ice loads is

$$F = K_M K_{class} K_{loc} K_{LC} p_i A^{ex}$$

where $K_M$ depends on vessel category and operation mode, $K_{class}$ depends on ice class, $K_{loc}$ takes into account the position of the propulsor, $K_{LC}$ depends on load scenario, $p_i$ is the ice pressure and A is the area. Ex is taken as 0.5.

The DNV GL and ABS guidelines use Polar Class notation, but it can be assumed that the FSICR class IAS is compatible with the PC6 class and IA is compatible with the PC7 class. Because in all of these rules, the area exposed to ice block impact is a defining parameter, the following graphs give the loads as function of propulsor hull radius.

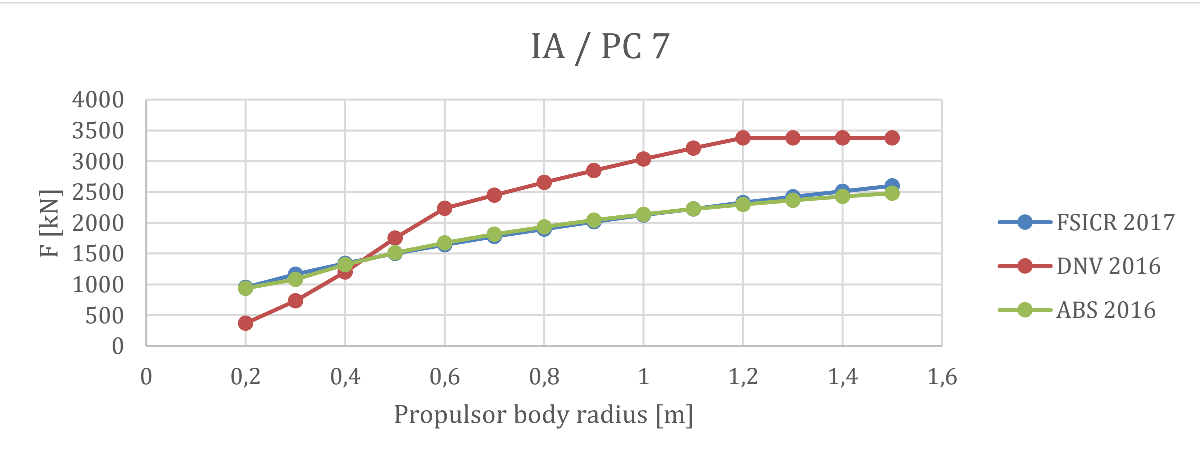

Figure 6 Comparison of impact ice loads FSICR IA / PC 7

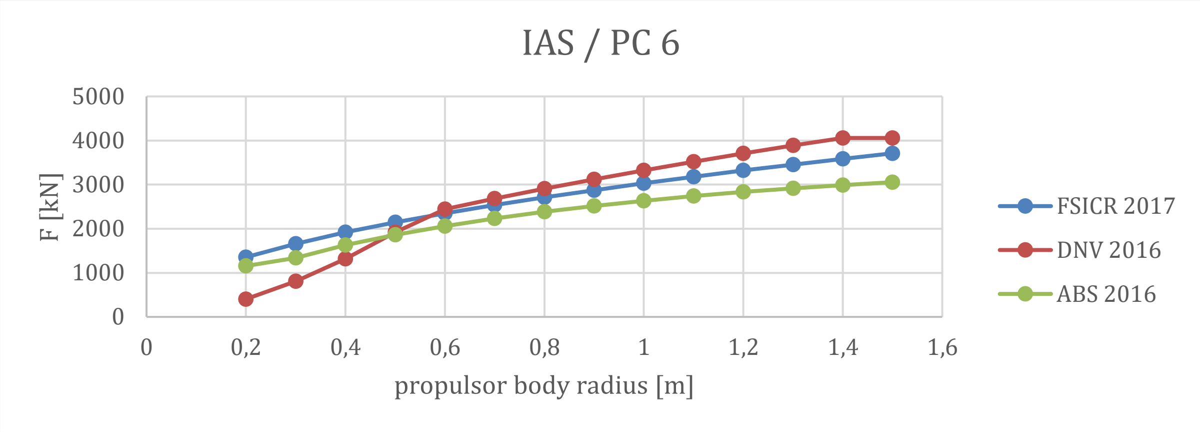


Figure 7 Comparison of impact ice loads FSICR IAS / PC 6

The comparison is not straightforward because all of the rules and guidelines have slightly different approach and parameters. For example, the position (deeply submerged or not) of the propulsor affects the parameters. However, this comparison is done with the most simple case of axial impact to the hub cap (opposite of propeller) of the propulsor and the propulsor is of pushing type.

The following parameters are used in the IAS / PC6 comparison. For ABS; $K_m = 0.75$, $K_{class} = 1.1$, $K_{loc} = 1$, $K_{LC} = 2$, $H_{ice} = 1.75$, $p_i = 1.4$. For DNV GL; $p_0 = 1.4$, $H_{ice} = 1.75$, $C = 1$, $C_1 = 1.5$, $C_2 = 1$, $C_3 = 1$, $C_4 = 1.2$. For IA /PC7 comparison parameters for ABS are same as used for IAS / PC6. For DNV-GL the parameters are ; $p_0 = 1.25$, $H_{ice} = 1.5$, $C = 1$, $C_1 = 1.5$, $C_2 = 1$, $C_3 = 1$, $C_4 = 1.2$.

It can be noted that for the very smallest propulsors ($R < 0.5$ m) the FSICR gives the highest ice loads. However, when the radius of the hull grows the DNV GL loads are the highest. ABS loads are quite identical to FSICR loads but slightly lower.

It should be noted that this comparison is only for axial impact case loads. Other load cases, such as ice ridge penetration cases, are not compared.

## CONCLUSIONS

The ice impact to azimuthing thruster was considered a reasonable load scenario. This is assumed to happen when ship is moving, and the thruster hits to an ice block at the ship speed. A straight hit of the ice block to propulsor was considered.

The loads occurring in this kind of load scenario are affected by the dynamics of the structure. The dynamical model for ice impact contact load developed earlier was considered reliable with respect to the validation data available.

The dynamic model was further used to study the effect of input parameters' effect to the ice impact load. For ice class rule type application, the key parameters were sought among physical, easily understandable and easily available parameters. The input parameters' effect to the maximum contact load was derived through running thousands of contact simulations with the dynamical impact load model. Then, with the input values and corresponding result sets, a regression analysis was performed with various simplified model hypotheses. This approach indicated that a fairly good set of variables for ice contact load estimation appeared to be the ice mass, impact velocity and the radius of the impacting part.

Along the route to the simplified model with a regression fit, the importance of the assumptions prior to the regression analysis became evident. Even though, the regression fit itself can work really well, the functionality and of the fitted model with respect to the problem itself, is to be checked and validated if possible.

A comparative study for ice loads obtained with ice class rules was done. ABS method and Finnish-Swedish ice class rule method indicate rather close to same load levels. DNV-GL estimates lower loads for the smallest azimuthing unit sizes, and highest loads for bigger propulsion units. The difference may be due to different level of inherent safety factor(s) included in the ice load estimation formula.

**ACKNOWLEDGEMENTS**

The financing for the research work contributing to the publication was provided by the Winter Navigation Research Board, which is joint research funding arrangement of TRAFI, The Finnish Transport Safety Agency, and the Swedish Maritime Administration, Sjöfartsverket.

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