Excitation Response Estimation of Polar Class Vessel Propulsion Shafting System

대빙 등급 선박 추진 시스템의 기진 응답 평가

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ABSTRACT

The prospect in opening the arctic trade transportation route on a year-round basis offers vast opportunity of exploring untapped resources and shortened navigational routes. In addition, the environment's remoteness and lack of technical experiences remains a big challenge for the maritime industry. With this, engine designers and makers are continually investigating, specifically optimizing propulsion shafting system design, to meet the environmental and technical challenges of the region. The International Association of Classification Society, specifically machinery requirements for polar class ships(IACS UR13), embodies the propulsion shafting design requirements for ice class vessels. However, the necessity to upgrade the various features of the unified rules in meeting current polar requirements is acknowledged by IACS and other classification societies. For the polar class propulsion shafting system, it is perceived that the main source of excitation will be the propeller - ice load interaction. The milling - and the impact load, in addition to the load cases interpreted by IACS, contribute greatly to the overall characteristic of the system and due considerations are given during the propulsion design stage. This paper will expound on the excitation load estimation factors affecting the dynamic response of the different propulsion shafting system design. It is anticipated that detailed understanding of these factors will have a significant role during propulsion shafting design in the future.

요 약

연중 운항할 수 있는 북극 항로 개설에 따른 전망으로 미개발 천연자원의 탐사와 짧아진 항로로 많은 기회를 부여하고 있다. 이는 환경과 거리가 먼 그리고 기술적인 경험 부족으로 해사 분야에서 커다란 도전으로 남아 있다. 엔진 설계자와 제작자는 이 지역에서 환경적 그리고 기술적으로 적합한 최적화된 추진시스템을 위하여 계속적인 조사를 하고 있고, 국제선급연합과 선급에서 인정하고 있는 대빙 등급 선박의 추진축계 설계를 위하여 통일된 규격의 여러 가지 특성에 대하여 개선할 필요가 있다. 대빙 등급 선박의

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추진축계 시스템에서 주 기진력은 프로펠러와 빙 하중의 상호작용으로 인식하고 있고 국제선급연합에서는 빙의 파쇄와 충격하중으로만 간주하고 있지만, 추진축계 설계에 있어 시스템에 대한 여러 가지 인자의 특징을 고려하여야 한다. 이 논문은 종류가 다른 추진 시스템의 동적 응답에 영향을 주는 인자들에 평가하고 있고, 추후 추진 시스템의 설계단계에서 이러한 인자들이 충분한 역할을 갖는 것을 감안 고려해줄 것을 기대하고 있다.

Nomenclatures

c	: Coefficient
C_q	: Impact effectiveness
d	: Propeller hub diameter[m]
D	: Propeller diameter[m]
D_{limit}	: 1.81 H_{ice} [m]
EAR	: Expanded blade area ratio
F	: Force
H_{ice}	: Ice thickness for machinery strength design
k	: Variable factor
m	: Mass[kg]
N_Q	: Number of propeller revolutions[rpm]
$P_{0.7}$	: Propeller pitch at 0.7 R[m]
$Q(\varphi)$	: Torque due to single blade ice impact [kNm]
Q_{max}	: Maximum propeller ice torque[kNm]
S_{qice}	: Ice strength index for blade ice torque
Z	: Number of propeller blades
$t_{0.7}$	: Maximum thickness at 0.7 radius
α_1	: Duration of propeller blade/ice interaction
ω	: Angular velocity[rad/s]

Subscript

b	: Backward
f	: Forward
i	: Ice strength
lim	: Limit
p	: Prime mover
f	: Flexibility of the system
φ	: Single blade phase angle impact
α	: Exponential coefficient for propeller diameter
β	: Exponential coefficient for ice thickness

γ : Exponential coefficient for angular velocity

1. Introduction

The prospects of energy and mineral resources availability in the Arctic area have continuously dictated a need for vessels with ice navigation capability. Further, the opening of the Northwest Passage, which ironically a beneficial result of the greenhouse effect and may allow routine transit in its receding ice, shortens transportation distances between Europe and Asia. As such, merchant vessels aimed to operate in ice-covered waters are adhered to comply in accordance with the Ice Class requirements of Classification Society and National Regulations^(1~4). Classification societies have recognized the fact that even though the Unified Rules on Polar Class vessels are in place, there is a need to address and meet the demands of current requirements through continuous updates⁽⁵⁾.

Propulsion shafting system is a complex structure considering the different loads and torque it is made to withstand. As such, much importance is given on strength, vibration, alignment and sag & gap component of the propulsion shafting system during the design stage⁽⁶⁾. Further, each propulsion shafting design will exhibit distinct characteristics. With the continual development of ice class vessels, not only is the hydrodynamic load is being considered but also the load brought about by the ice-propeller interaction wherein their variation is significant⁽⁷⁾. Under the LR Rules, it has identified the conditions and loading

to achieve a satisfactory understanding of the characteristics of the shafting design⁽⁸⁾. In addition, the interaction between the propeller and ice, i.e. ice milling and ice impact, results in higher load and exciting torque along the propulsion shafting system⁽⁹⁾. On the other hand, torque, together with power and the rotational speed of the propulsion shaft, is a dominating load and can exhibit the dynamic characteristics of the engine⁽¹⁰⁻¹³⁾. This torque will either be static or dynamic in nature and this harmonic torque will manifest as torsional vibrations⁽¹⁴⁾. Furthermore, classification rules on shafting diameter, being a factor in torque load, was said to have had neglected the alternating load and should be treated as a guide only⁽¹⁵⁾.

2. Propeller Load, Forces and Excitation Torque

The International Association of Classification Society(IACS) and classification societies i.e. Korea Register(KR), Det Norske Veritas(DNV), American Bureau of Shipping(ABS), and Lloyd's Register(LR) among others have laid the rules for Polar Class ships intended for Arctic navigation. In addition to this, state rules such as Finnish-

Swedish ice class rules' Guidelines for the Application of the Finnish-Swedish Ice Class Rules and Canada's Arctic Shipping Pollution Prevention Regulations(C.R.C., c.353) are also in co-operation with the societies and have been integrating their regulations for the classification of ships. Table 1 shows the main feature of IACS Polar Class Rule which is the range of ice classes.

When a propeller rotates in ice-covered water, it is subjected to contact loads, non-contact loads and generated forces. The non-contact loads refers to the hydrodynamic load on blade under open water condition⁽⁷⁾. The contact loads, then again, are differentiated as ice milling- and as ice impact-type load. Sodhi described ice milling taking place when an ice is large or is trapped between the hull, wherein the ice is crushed resulting to higher loads. Ice impact is referred to smaller ice pieces which are passed through the propeller and resulting to moderate loads⁽⁹⁾. Wang, J. Y., et al. also hypothesized in their paper the ice loads acting on a propeller as separable hydrodynamic loads, inseparable hydrodynamic load(ice-impact load) and ice contact load⁽¹⁶⁾. A representation of total ice loads was made as the sum of ice milling load, separable hydrodynamic load and inseparable hydrodynamic load. Ice related loads refer to the sum of ice milling load and inseparable hydrodynamic load occurring during the milling period. Another characterization of these loads was made by H Soininen. Accordingly, he stated that definition for milling load and impact-type loads is not very clear. He assumed milling load is when ice made contact with the leading edge of the blade while impact load is when ice hits the back or face of the blade⁽¹⁷⁾.

IACS have defined the forces acting on the propeller blade during the propeller-ice interaction. The forces are namely, F_b , being the force bending the propeller blade backwards when the propeller mills an ice block while rotating ahead

Table 1 Polar class descriptions

Polar class	Ice description
PC 1	Year-round operation in all polar waters
PC 2	Year-round operation in moderate multi-year ice conditions
PC 3	Year-round operation in second-year ice which may include multi-year ice inclusions
PC 4	Year-round operation in thick first-year ice which may include old ice inclusions
PC 5	Year-round operation in medium first-year ice which may include old ice inclusions
PC 6	Summer/autumn operation in medium first-year ice which may include old ice inclusions
PC 7	Summer/autumn operation in thin first-year ice which may include old ice inclusions

and, F_f , as the force bending a propeller blade forwards when a propeller interacts with an ice block while rotating ahead. Table 2 lists the design ice thickness and ice strength index to be used for the estimation of ice loads. H_{ice} refers to the ice thickness for machinery strength design, S_{ice} for the ice strength index for blade ice force and S_{qice} the ice strength index for blade ice torque.

Equations 1 and 2 are the given formula for maximum backward blade forces while Eqs. 3 and 4 refer to the maximum forward blade force.

$$F_{b-} = -27S_{ice} [nD]^{0.7} \left[\frac{EAR}{Z} \right]^{0.3} [D]^2 \quad (1)$$

when $D \leq D_{limit}$

$$F_{b-} = -23S_{ice} [nD]^{0.7} \left[\frac{EAR}{Z} \right]^{0.3} [H_{ice}]^{1.4} [D] \quad (2)$$

when $D > D_{limit}$

$$F_f = 250 \left[\frac{EAR}{Z} \right] [D]^2 \quad (3)$$

when $D \leq D_{limit}$

$$F_f = 500 \left(\frac{1}{1 - \frac{d}{D}} \right) H_{ice} \left[\frac{EAR}{Z} \right] [D] \quad (4)$$

when $D > D_{limit}$

where in D_{limit} is defined as

$$D_{limit} = \left(\frac{2}{1 - \frac{d}{D}} \right) H_{ice} \quad (5)$$

Table 2 Design ice thickness and ice strength index value in estimating propeller ice loads

Ice class	$H_{ice}[\text{m}]$	$S_{ice}[-]$	$S_{qice}[-]$
PC 1	4.0	1.2	1.15
PC 2	3.5	1.1	1.15
PC 3	3.0	1.1	1.15
PC 4	2.5	1.1	1.15
PC 5	2.0	1.1	1.15
PC 6	1.75	1.0	1.0
PC 7	1.50	1.0	1.0

Wang, in his paper, calculated the backward and forward forces and torque corroborated that ice loads per blade are much higher than hydrodynamic load of the whole propeller⁽⁷⁾. The response torque at any shaft component of Polar Class PSS should consider the following: the excitation torque at the propeller, the actual engine torque and the mass elastic system. Under the Korea Register of Shipping(KR), it established the maximum propeller ice torque applied for open propeller as:

$$T_{ice} = m \cdot D^2 \quad (6)$$

$$Q_{max} = 10.9 \cdot [1 - d/D] \cdot [P_{0.7}/D]^{0.16} \cdot [nD]^{0.17} \cdot D^3 \quad (7)$$

when $D \leq D_{lim}$

$$Q_{max} = 20.7 \cdot [1 - d/D] \cdot [P_{0.7}/D]^{0.16} \cdot [nD]^{0.17} \cdot D^{1.9} \cdot H_{ice}^{1.1} \quad (8)$$

when $D > D_{lim}$

being the D_{limit} given also as

$$D_{lim} = 1.8 \cdot H_{ice} \quad (9)$$

Likewise, KR also set the design loads on propulsion shafting system for Polar class vessels. Stating, the propeller ice torque excitation for shaft line transient torsional vibration analysis is described by a series of blade impacts which are half sine shape and occur at the blade. Equations 10 and 11 indicate the torque due to single blade ice impact as a function of the propeller rotation angle. Table 3 details the C_q and α_i parameters for the propeller ice torque excitation in shaft line analysis. The total ice torque is achieved by summing the torque individual blades taking into account the phase shift $360^\circ/Z$. The number of propeller revolutions during a milling sequence is obtained according to Eq. 12. The number of impacts is $Z \cdot N_Q$.

$$Q(\varphi) = C_q \times Q_{max} \times \sin(\varphi(180/\alpha_i)) \quad (10)$$

when $\varphi = 0 \cdots \alpha_i$

Table 3 Torque excitation parameters

Torque excitation	Propeller / ice interaction	C_q	α_1
Case 1	Single ice block	0.75	90
Case 2	Single ice block	1	135
Case 3	Two ice blocks(phase shift 45 degrees)	0.5	45

$$Q(\varphi) = 0 \quad (11)$$

when $\varphi = \alpha_i \cdots 360$

$$N_Q = 2 \cdot H_{ice} \quad (12)$$

3. Presentation of Case Study

Many technical challenges still loom ahead for Polar Class vessels. With the consideration of that not all aspects of design for cold climates are covered by Ice Rules⁽²⁾, continuous research has been dedicated to address this situation. The excitation loads on the ice class propulsion shafting pose a challenge due to unpredictable responses in some stage of propeller-ice interaction. On the assumption that during propeller-ice interaction, dominant torque stresses occur on the propeller and is transmitted towards the propulsion shafting. In this aspect, forces and torque response are represented by different functions and all propeller-ice loads. The representation of force in relation to damping coefficient and angular velocity can be given as:

$$T = -c \cdot D^\alpha \cdot H^\beta \cdot \omega^\gamma \quad (13)$$

The force in Eq.13 can be presumed as the forces during the ice-propeller interaction at different load cases. This dynamic response can be due to the relationships of ice thickness and strength, ship speed or shaft revolution to mention a few. Hence, considering the relationships of factors influencing the magnitude of loading, it can be assumed to take the form of Eq. 14. Equation 14 proposes the inclusion of the variables perceived

Table 4 Torque excitation factor parameters

Flexibility factor(k_f)		Prime mover factor(k_p)		Ice strength factor(k_i)	
Rigid	1.0	Diesel engine	1.2	PC 1 ~ PC 5	1.15
Diesel engine + flexible coupling	0.8	Motor	1.0	PC 6 ~ PC 7	1.0
Motor + flexible coupling	0.5	-----		-----	

to influence the overall dynamical characteristic of the propulsion shafting: ice load, prime mover, and system's flexibility.

$$T = -c_0 \cdot k_i \cdot k_f \cdot k_p \cdot D^\alpha \cdot H^\beta \cdot \omega^\gamma \quad (14)$$

Mainly, ice factor will consider the load on the propeller brought about by the ice-propeller interaction. This includes the milling and impact loading as well as the ice strength index. Secondly, the prime mover factor is influenced by the main excitation source of the system. Lastly, the system's flexibility variable will consider the propulsion shafting design. Rigid system, diesel engine – flexible coupling and motor – flexible coupling arrangement dictates the value for this factor. Exponential values are assumed as: $\alpha = 2$; $\beta = 1$ and $\gamma = 0.2$.

4. Analysis on Propeller Slippage Accident

Due to the limited availability of actual data for ice class propulsion shafting dynamic characteristics, this paper is supplemented with a propeller slippage accident. Figure 1 is MV Ricsun, a 138,500 DWT bulk carrier, which experienced a loss in propulsion during maneuvering.

Initial facts from this accident stated that the engine was operated normally but the propeller did not response. Sea condition during the accident was figured at -2 °C sea water temperature

Fig. 1 MV Ricsun experiencing loss in propulsion

Fig. 3 Propeller boss race showing wear and burn-down

Table 4 Propulsion shafting system specification for MV Ricsun

Main engine	B&W 6L80GFC4
Power	13,400kW @ 106 rpm MCR
	12,453kW @ 103 rpm MCR
Propeller type	Keyless solid 4-blade
Propeller diameter	7,100 mm / 23,330 kg
Propeller pitch	4,767 mm
Propeller shaft grade	Steel grade 2
Propeller material	Ni-Al-Be
Propeller shaft diameter	680 mm
Intermediate shaft diameter	550 mm

Fig. 2 MV Ricsun propeller shaft tapered 1/20

with a 10 cm floating ice block on the surface. At this temperature, many materials are assumed to increase their brittleness rather than decrease their toughness. Further, not considering the shallow draft of the vessel, the engine was operated

on full astern. This operation has resulted in higher torque and torsional vibration in the shafting system. Adding to the scenario, an impact was sensed on the propeller striking a foreign matter. This scenario was figured out later on with damages on the trailing edge of the propeller and thereby contributed to higher overall forces and presumed to be larger than designed contacting forces. Hence, with the whole scenario combined, it is presumed to be analogous with an ice class vessel design and environment. Table 4 details the propulsion shafting system specification for MV Ricsun. Figs. 2 and 3 show the damaged propeller shaft and propeller boss respectively. The damages are highlighted by scratches and malformation in shaft's surface while burn-down and wear are visible inside the propeller's boss race.

4.1 Shafting Material Characteristic in Low Temperature Condition

In general, most material's characteristic will reduce their toughness but instead increase their brittleness as the temperature decreases. The propeller shaft material is steel grade 2 while its chemical composition is carbon(C)=0.12 %, manganese(Mn)=0.60 %, sulfur(S)=0.05 %, phosphorus(P)=0.05 % and the rest is iron(Fe). KR rule requires the transverse average adsorption energy at 20 °C, 0 °C, -40 °C, and -60 °C must exceed 27J. This

Fig. 4 Manganese impact adsorption energy value

impact adsorption energy changes with the change of temperature. In Fig. 4, the impact adsorption energy change in Mn content in steel is shown. The impact adsorption energy at room temperature is around 130 J and 50 J at -2°C . Considering the shaft's Mn composition at max. 0.6 % for steel grade 2, the impact adsorption energy reduces further under 30 J. Under this condition, the propeller shaft material will lose its toughness about 75 % (30/130) and increase the brittleness.

In addition, the propeller material of MV Ricsun is Al-Ni-Be which is a high tensile copper base alloy, and the equivalent material under the KR rule is CU series or SHK#500SP. The heat expansion coefficient for this material is given as $2.0 \times 10^{-6}/^{\circ}\text{C}$. For the propeller shaft material, the carbon composition for steel grade 2 is 0.12 % and a heat expansion coefficient of $11.6 \times 10^{-6}/^{\circ}\text{C}$. Assuming the difference in sea water temperature of 0°C and room temperature of 25°C , and calculating the circumference of the propeller shaft/boss from propeller diameter to be 2,135.2 mm, the shrinkage can be calculated for both materials. Hence, for the propeller shaft will be $2,135.2 \text{ mm} \times 25^{\circ}\text{C} \times 11.6 \times 10^{-6}/^{\circ}\text{C} = 0.6 \text{ mm}$ while the inner propeller boss shrinkage will be $2,135.2 \text{ mm} \times 25^{\circ}\text{C} \times 2 \times 10^{-6}/^{\circ}\text{C} = 0.11 \text{ mm}$. The shrinkage differences can weaken the contact forces of the surfaces and slip is more probable at lower temperature.

Fig. 5 Approximate value for the propeller torsional stress

4.2 Load and Torsional Vibration Analysis

IACS requires that "the factor of safety against friction slip at 35°C is not to be less than 2.8 under the action of rated torque at corresponding power and speed plus pulsating torque due to torsional". MV Ricsun sea trial data indicated the resonance point at 60 rpm and the barred speed range at 56–63 rpm. The rated torque at full power on propeller shaft is 20.3 N/mm^2 , while the rated torque considering the factor of safety is 56.84 N/mm^2 . During the astern case, higher loads are predicted and the torsional stresses and delivery torque increasing by more than 30 %. Adding another 30 % load on normal case, torsional vibration stress will be 34.84 N/mm^2 and the delivery torque at 60 rpm is 9.3 N/mm^2 . Based on this calculation, the rated load during astern condition is increased to 12.71 N/mm^2 . Due to non-availability of actual torsional vibration data of MV Ricsun, Fig. 5 is the approximation graph for the propeller load and the resonance peak value is about 34 N/mm^2 at 60 rpm on ahead condition. Estimating the resonance peak value for propeller load at astern condition will yield 44 N/mm^2 .

As such, lower external load is needed for the propeller boss to slip. The scenario would then be when the propeller blade strikes a material; there will be an abrupt increase in torque and vibration. The external force may then exceed the contact

Fig. 6 Damage on the trailing edge of the propeller

force of the propeller shaft and propeller boss resulting in a slip. In Fig. 6, visible damage on the trailing edge of the propeller is shown. Assessment indicated one meter damage on the trailing edge with around twenty indentations measuring 7~8 mm at some points. The propeller damage condition implies a very high load and force have been translated to the propeller shaft and the propeller boss.

Figures 7~10 illustrates the torsional stresses response of the propulsion shafting system during crash astern condition. Facts have shown that during the astern condition, the reverse force tends to pull the propeller outwards from the shaft⁽¹⁶⁾. Figures 7 and 8 is the propulsion shafting dynamic response of a 6S70MC engine with an 18,660 kW $\times$ 91 rpm diesel engine. The passing time at dominant stresses is around 15 seconds (2565~2580 secs) being at the first node 6th order. Figure 9 and 10, on the other hand, is the propulsion shafting dynamic response of a 7S50MC engine with power rating at 11,620 kW $\times$ 127 rpm. Passing time at the dominant stresses is around 3 secs (477~480 secs) being the critical speed at the first node 7th order while the normal operation range is on the first node 4th order at 495 secs~498 sec (3 secs).

Hence from these data, the torsional stresses and the passing time can be said to be dependent of the power, speed and design of the propulsion shafting system. In relation to MV Ricsun, the

Fig. 7 Crash astern propulsion shafting dynamic response for the 18,660 kW diesel engine

Fig. 8 Highlighted dominant torsional stress during crash astern condition for the 18,660 kW diesel engine

Fig. 9 Crash astern propulsion shafting dynamic response for the 18,660 kW diesel engine

torsional load value phenomena may be com

Fig. 10 Highlighted dominant torsional stress during crash astern condition for the 11,620kW diesel engine

parable but taking into account the vessel's age, the passing time in the barred speed range can be estimated as 2~4 times longer.

5. Result of Case Study

This paper presented some contributing factors in the estimation of propulsion shafting system propeller load excitation calculation for Ice class vessels. Correlating these factors in MV Ricsun scenario, it was estimated that the torsional load at resonance peak during astern condition is about 44 Nmm while the factor of safety was given at 56 N/mm² for MCR. The values imply that smaller external load is needed to exceed the factor of safety value. Further, MV Ricsun data was simulated as an ice class PC 7 in the calculation of the maximum torque on the propeller using the IACS rule and Eq. 14. The value for the coefficient in Eq. 14 is 16. Figure 11 graphs the value of this calculation. IACS value for the propeller load at resonance peak is 2,132 kNm while at MCR is calculated as 2,701 kNm. On the other hand, the values using Eq. 14 was found to be 2,411 kNm at resonance peak and 2,701 kNm at MCR. The values of the proposed propeller load calculation yielded a 12~15 % margin compared to the IACS Rule. This higher margin is seen to

Fig. 11 Simulated value for maximum propeller load

compensate the factor of safety value and the propeller load value at resonance peak for MV Ricsun.

6. Conclusions

Equation 14 overviews the general concept of the authors. The variable factors presented in the equation will serve as a spring board for further study and understanding of ice class vessel propulsion shafting system dynamics and will be continuously developed. Initial outcome of this paper is summarized as:

(a) Calculation using Eq. 14 has a higher margin(15 % at MCR) compared to the IACS Rule for the calculation of the maximum propeller torque. This margin is seen to increase the flexibility of the propulsion shafting system specifically during the astern condition and likewise, the factor of safety is increased.

(b) Classification Societies Rule for the factor of safety against friction slip should not be less than 2.8 of the rated torque. Implying this value during the propeller/ice interaction, the propulsion shafting is believed to withstand the impact load on the propeller. However, analysis of the slip-page accident shows that material property and composition will influence this factor of safety.

(c) Ice class vessels may have to maneuver in astern condition during transit in ice-covered water. Under this condition, higher torsional loads are translated into the propulsion shafting system. As such, passing time at this barred speed range for two stroke low speed diesel engine with 4~7 cylinders should be made short as much as possible. Further, the propulsion shafting design should have the potential to dissipate the transient loading it may be subjected to.

(d) The different loads acting on the propeller can be defined as the total propeller-ice loads. On the other hand, different assumptions and definitions have been made on these loads – milling and impact load – and capitulates different experimental outcome. A definitive application of these loads can be implemented thereby a uniformity in experimental approach.

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