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Evaluation, design and optimization for strength and integrity of polar class propellers

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ABSTRACT

An advanced 3D unsteady panel method was developed for the design and optimization of the strength and integrity of polar class propellers. Blade ice loading specification in both milling and impact cases, under the Unified Polar Class Rules (URI3), by the International Association of Classification Societies (IACS), was implemented. An optimization example and analysis were given for an R-class propeller. The strength of the R-class propeller was assessed for all 7 polar classes and 5 loading cases. Comparison was also made for all polar classes and ice loading cases. As the blade has little skew with a wide chord, both the spindle torque and the in-plane bending moment are small, so only out-of-plane bending failure is the key factor for strength. It was also found that by URI3, there is little difference in strength requirement between polar classes 1 (strongest requirement) and 7 (the weakest). An integrity design and optimization example showed a saving of 1.4 tonnes of blade material (22% saving) by decreasing the safety factor to 1.51 (the minimum safety factor under URI3 is 1.5), for which case the blade thickness is about 80% of the existing design.

Nomenclature

Symbol	Description	Units
6DOF	Six degree of freedom	[]
A	Area of rotor disk, $A = \pi R^2$	m^2
A_o	Area of blades	m^2
A_{IC}	Ice contact area on a single blade	m^2
NAB	Nickel–aluminum–bronze	[]
C_{my}	Maximum distance of the profile edge(s) to the y-axis (blade back to face) of the blade section	m
C_{mx}	Maximum distance of the profile edge(s) to the x-axis (trailing edge to leading edge) of the blade section	m
C_{mr}	Maximum distance of the profile edge(s) to the centroid of the blade section	m
CCGS	Canadian Coast Guard Ship	[]
D	Rotor diameter	m
$f_{thickness}$	Blade section thickness factor as multiplier to vary the thickness in design and optimization	[]
n	Rotor shaft speed, revolution per second	rps
N	Rotor shaft speed, revolution per minute	rpm
R	Rotor radius	m
V_a	Propeller shaft or ship advance speed	m/s
J	Advance coefficient	$J = \frac{V_a}{nD}$
ρ	Fluid density	kg/m^3

Nomenclature (*continued*)

Symbol	Description	Units
T	Propeller shaft thrust	N
K_T	Propeller shaft thrust coefficient, $K_T = \frac{T}{\rho n^2 D^4}$	[]
Q	Propeller shaft torque	N·m
K_Q	Propeller shaft torque coefficient $K_Q = \frac{T}{\rho n^2 D^5}$	[]
p	Blade pitch	m
p_D	Blade pitch diameter ratio	[]
$p_{D0.7R}$	Blade pitch diameter ratio at $r = 0.7R$	[]
EAR	Propeller expanded area ratio or rotor disk solidity $EAR = \frac{A_o}{A}$	[]
Z	Number of blades	[]
h_D	Hub diameter to rotor diameter ratio	[]
$F_{back\text{-}case1}$	Ice milling force on blade back (loading Case 1)	N
$F_{back\text{-}case2}$	Ice impact force on blade back tip (loading Case 2)	N
$F_{face\text{-}case3}$	Ice milling force on blade face (loading Case 3)	N
$F_{face\text{-}case4}$	Ice impact force on blade face tip (loading Case 4)	N
$F_{face\text{-}case5}$	Ice milling force on blade face moving astern (loading Case 5)	N
H_{ice}	Ice thickness specified by polar class rules	m
S_{ice}	Ice strength index for blade ice force	[]
S_{qice}	Ice strength index for blade ice torque	[]
$D_{\text{limit-back}}$	Intermediate variable for blade back force calculation	m
$D_{\text{limit-face}}$	Intermediate variable for blade face force calculation	m
σ_u	Ultimate tensile stress of blade material	N/m^2
$\sigma_{0.2}$	Proof stress at 20% elongation	N/m^2
σ_{ref}	Reference stress, $\sigma_{ref} = \{0.7\sigma_u, 0.4\sigma_u + 0.6\sigma_{0.2}\}$	N/m^2
f_{safety}	Safety factor, $f_{\text{safety}} = \frac{\sigma_{ref}}{\sigma_{\text{actual}}}$	[]
$f_{s\text{-}oop}$	Out-of-plane bending moment stress safety factor	[]
$f_{s\text{-}ip}$	In-plane bending moment stress safety factor	[]

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Nomenclature (*continued*)

Symbol	Description	Units
$f_{s\text{-}st}$	Spindle torque torsional stress safety factor	[]
I_x	Blade sectional profile moment inertia about the x-axis	m^4
I_y	Blade sectional profile moment inertia about the y-axis	m^4
I_r	$\approx I_x + I_y$, blade sectional profile polar moment inertia about the centroid	m^4
M_{st}	Blade spindle torque at a local section	Nm
M_{ip}	In-plane bending moment at a local section	Nm
M_{oop}	Out-of-plane bending moment at a local section	Nm
K_{st}	$=\frac{M_{st}}{\rho n^2 D^5}$, blade spindle torque coefficient	[]
K_{ip}	$=\frac{M_{ip}}{\rho n^2 D^5}$, blade in-plane bending moment coefficient	[]
K_{oop}	$=\frac{M_{oop}}{\rho n^2 D^5}$, blade out-of-plane bending moment coefficient	[]
σ_{oop}	$=\frac{M_{oop} C_{my}}{I_x}$, actual stress due to out-of-plane bending moment, either compressive or tensile, whichever is larger relative to material strength	$\mathrm{N/m}^2$
σ_{ip}	$=\frac{M_{ip} C_{mx}}{I_y}$, actual stress due to in-plane bending moment, either compressive or tensile, whichever is larger relative to material strength	$\mathrm{N/m}^2$
σ_{st}	$=\frac{M_{st} C_{mr}}{I_r}$, actual torsional shear stress due to spindle torque	$\mathrm{N/m}^2$

1. Introduction

Propeller blade damage due to ice collision or milling loading has long been a problem. Both ice-induced hydrodynamic load and ice contact loads (milling and/or collision), especially when acting in the same direction, are the major cause of blade failure of polar class propellers. The first attempt to predict hydrodynamic performance due to the proximity of an ice blockage, using a panel method, was presented by Bose (1996). Ice proximity effect on hydrodynamic performance and then cavitation performance under propeller–ice interaction were investigated experimentally by Walker (1996) and Walker et al. (1997). Experimental investigation of the ice blocked load for a nozzle propeller, Robert Lemeur, was conducted by Doucet (Doucet et al., 1997). R-Class model-scale and full-scale trial correlation was studied by Spencer and Jones (2001). These studies thoroughly examined the R-Class propeller shaft forces during propeller–ice interaction, in terms of K_T and K_Q.

One of the earliest propeller–ice interaction models, in terms of collision and cutting was established by Veitch (1995). A panel method code Propella was developed for the R-Class propeller study by Liu (1996a,c). For a number of ice class propellers, Propella was validated, enhanced and used to perform various investigations, for both propeller shaft forces (K_T and K_Q) and the 6DOF blade forces at local blade sections, in terms of in-plane bending, out-of-plane bending and spindle torque. Numerical predictions using Propella include three categories: ice-blockage (proximity) effect on hydrodynamic performance (Liu, 2000; Liu et al., 1999), transient loading from an approaching ice-block (Liu et al., 2001c, 2005, 2008), and ice-contact loading (Liu et al., 1999; Veitch et al., 1997), for which the ice-cutting model by Veitch was implemented (Veitch, 1995). These studies investigated the propeller–ice interaction induced forces in detail and provided scientific data for engineering design and codes and standards for regulatory bodies.

With the growing interest in polar navigation, polar class ships and their propellers become important. Prior to 2008, every classification society had its own rules and standards. The International Association of Classification Societies (IACS) established a set of unified requirements and rules for all polar class ships. These unified requirements, the Unified Rules I3 (URI3 for short) came into effect from March 2008. The current version is dated 2011 (IACS, 2011). They set machinery requirements, including for polar class propellers. Lee applied the URI3 with finite element methods and evaluated the strength of an ice class propeller (Lee, 2007) and a controllable pitch propeller (Lee, 2008).

Liu and Veitch (2012) developed a procedure to design and optimize rotor blade thickness and thickness distribution for both strength and integrity of tidal turbine rotor blades. The load for turbine failure was taken for the maximum harsh environment tidal speed of about 10 knots. The design and optimization procedure ensures safety controlled by a desired safety factor (strength) that is uniform across the blade span (integrity) with the maximum saving of blade materials. In the current work, the URI3 rules for all 7 polar classes and 5 ice loading scenarios were implemented in the code. The code was then used as a tool to perform a strength and integrity design and optimization by adjusting the blade sectional thickness, taking into account both hydrodynamic and ice loadings.

2. The panel method code and implementation of the URI3

2.1. The panel method code

Instead of displaying mathematical derivations and equations, a brief historical background of the panel code development is given here.

Panel methods are also called boundary element methods, or boundary integral methods. Lifting surface and panel methods have been widely used in research and development of aircraft wings, hydrofoils and both aerial and marine propellers. Hess and Vararezo (1985) probably made the first panel method computation for propellers. To deal with complete aircraft geometry, panel method codes, PMARC (Panel Method Ames Research Center) developed by Katz (Katz and Plotkin, 1991) and VSAERO by Maskew (1986) are early examples of panel methods for aircraft wings and propellers. Panel methods have also been used for marine propeller research and development and early examples among those are publications by Greeley and Kerwin (1982) and Hoshino (1989). A time domain unsteady panel method code OSFBEM (oscillating foil boundary element method) was developed by Liu (1996b) for oscillating propulsors of both chordwise and spanwise flexibility to simulate marine animal propulsion. To respond to the need in simulation of fluid–structure interactive hydrodynamics to predict ice blockage effects between sea ice and ice-class propellers, a panel method code, Propella (Liu, 1996a) was developed in 1996, based on OSFBEM. Since then, continued efforts were made to maintain and enhance the capability of the code. The capability for unsteady oblique flow and inflow wake were presented in early 1998 (Liu and Bose, 1998). Automatic body surface generation for propellers of arbitrary number of blades, and including nozzle, rudder, ice blockage etc., was presented in 2001, along with velocity profile downstream prediction and wake vortices roll-up enhancement (Liu et al., 2001a). Cavitation predictive capability via an empirical formulation was established for Propella and presented in 2001 (Liu et al., 2001b). A pre- and post-processor was developed for the code by using OpenGL and Visual C++ of Microsoft Foundation Class, as a 3D unsteady data visualization tool (Liu, 2002) to view the geometry motion and color blended results. A novel and robust numerical Kutta condition using

Table 1
The International Association of Classification Societies (IACS) unified requirements for polar class ice description (IACS, 2011).

Classes	Descriptions
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 multiyear 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.