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Indirect load case estimation for propeller-ice moments from shaft line torque measurements

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ABSTRACT

In order to estimate the forces exerted on ship propellers during ice navigation, the rotational dynamics of the propulsion system need to be accurately modelled. The blade measurements of ice loads on the propellers of ships during ice navigation is challenged by the harsh operating environment. Shaft line measurements are therefore performed inboard, and the required propeller loads are subsequently estimated through the use of a dynamic model and the solution of an inverse problem. The inverse problem is mathematically ill-posed and requires the determination of the ice-induced load on the propeller blade from shaft line measurements. The present study investigated full-scale torsional responses on the shaft line of a polar supply and research vessel during navigation through sea ice on a 68-day voyage between Cape Town and Antarctica. The vessel spent almost 11 days in ice with observed concentrations above 90% and a maximum thickness of 3 m. The aim was to evaluate the extreme ice-induced moments on the shaft line and thereby determine how sparsely published operational loadings compare to the design loads of an ice-going vessel. Ice-induced moments on the propeller were obtained from operational measurements through three previously published approaches to solving the ill-conditioned inverse problem. The regularization methods used included truncated Singular Value Decomposition, truncated Generalized Singular Value Decomposition and Tikhonov regularization. The maximum ice-induced external moment was found to be 941.5 kNm, which was just within the maximum allowed ice-induced torque on the propeller. The duration of ice impacts on the propeller ranged from 25 to 228 ms. A secondary peak was evident in torsional responses obtained from propeller-ice impacts which is thought to be a shear stress wave that propagates and reflects back in the shaft line. From the inversely determined ice-induced loads, the number of impacts, the duration, the shape and the damping of water on the propeller was identifiable. The results obtained were physically reasonable, indicating that the current methods are suitable for obtaining ice-induced loading on the propeller from shaft line measurements.

1. Introduction

Efficient and safe shipping in Arctic regions is an increasing requirement as maritime transport in ice-covered seas is expected to increase in future decades (Ikonen et al., 2014; Ansorge et al., 2017). The main source of excitation for polar class propulsion systems is attributed to propeller-ice interaction (Barro and Lee, 2011). The International Association of Classification Societies (IACS) (2016) which encompasses the Korean Register (2015), American Bureau of Shipping (2006), Det Norske Veritas (DNV) (2011), Lloyd's Register (Germanischer Lloyd, 2007) and Finnish-Swedish Ice Class Rules' Guidelines (Finnish Maritime Administration and Swedish Maritime Administration, 2005), amongst a few, has formulated rules for Polar Class (PC) ships intended for Arctic navigation. These regulations have been integrated to obtain the classification of ice going vessels (Barro and Lee, 2011). Detailed and reliable full-scale measurement data sets assist to improve such regulations, which lead to interest in the effect of ice loads on the propulsion systems of ships (Batrak et al., 2014; De Waal et al., 2017).

During ice passage, the first element of the propulsion machinery to interact with ice is the propeller. Subsequently, ice-related loads are transferred to other elements of the transmission system (Polić et al., 2014). In a year long study on Baltic shipping Hänninen (2004) reported that 35% of maritime-related accidents pertained to propeller damage (Hänninen, 2004). Ice navigation subjects the propeller to non-contact loads, which includes the hydrodynamic load on the blade

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experienced in open water conditions and contact loads, which comprise ice milling, crushing and ice impact (Barro and Lee, 2011). Ice milling is defined as the process during which multiple blades impact an ice floe (Riska, 2011). Crushing describes the situation where ice is pressed onto the blade until it crushes which results in high loads (Norhamo et al., 2009). Smaller ice debris that result in more moderate loads and which are passed through the propeller are referred to as ice impacts (Barro and Lee, 2011).

Propeller loads could ideally be determined directly from blade measurements (Ikonen et al., 2014). However, the challenges to this approach include the interaction of the blades with the working environment as well as ice impacts that damage the sensors (Al-Bedoor et al., 2006). Besides this, the installation costs involved are high due to the requirement of cable ducting through the shaft to the propeller blades (Ikonen et al., 2014).

Current full-scale measurements of ice loads rely on shaft line measurements through strain gauges, which are installed inboard, between the propeller and the engine (De Waal et al., 2017). With this approach ice-induced moments are not measured directly and include the dynamic response of the mechanical transmission elements (Polić et al., 2014). To determine propeller loads from shaft line measurements, the transfer function between the externally induced loads and the internal shaft line measured torque is to be determined. One of the most commonly used methods in torsional vibration analyses includes the simplification of transmission systems to lumped mass models as shown in studies by Ikonen et al. (2014), He and Du (2010) and Det Norske Veritas (2011). Inverse methods are subsequently required to perform indirect force determination of ice-loading on the propeller blades.

The complication with the discretization of inverse problems is that this leads to an ill-conditioned coefficient matrix for the system of linear equations, which require regularization methods to obtain stable solutions (Golub et al., 1999). Regularization is the procedure whereby a problem is modified to reduce the sensitivity of the response and obtain a robust solution (Jacquelin et al., 2003). Suominen et al. (2013) and Bekker et al. (2014) performed inboard shaft line measurements on the polar supply and research vessel, SA Agulhas II. Ikonen et al. (2014) proceeded to demonstrate the solution of an ill-conditioned inverse problem through three approaches including Truncated Singular Value Decomposition (TSVD), Truncated Generalized Singular Value Decomposition (TGSVD) and Tikhonov regularization. The findings indicated that these methods are capable of solving the ice moment function for a set of verification data and in load cases where up to four consecutive ice contacts were present. Myklebost and Dahler (2013) reported disturbances on the shaft line measurement system of the SA Agulhas II which inhibited the evaluation of full voyage data. This was rectified by De Waal (2017) who installed and validated a new measurement system on the same vessel, capable of gathering trustworthy data.

The aim of the present investigation was to verify the existing inverse estimation algorithm for ice-induced torque presented by Ikonen et al. (2014) and to use this algorithm to determine and publish propeller-ice loading from trustworthy shaft line measurements on an operational voyage of the SA Agulhas II to Antarctica. In particular, ice milling cases and associated ice conditions were investigated as well as the implications of different regularization methods on the interpretation of extreme loading conditions.

2. Full-scale measurements

2.1. SA Agulhas II

The polar supply and research vessel, SA Agulhas II (SAA II) (Fig. 1) is propelled by two Conver Team electric motors of 4,5 MW each. Each motor is connected to a propulsion shaft with four-bladed variable pitch propellers (STX Finland Oy, 2012). Four 3 MW diesel generators are used to supply propulsion power. The ship was manufactured in Rauma shipyard in 2012 by STX Finland (Bekker et al., 2014) with an ice-strengthened hull in accordance with DNV ICE-10. She is classified to Polar Ice Class PC-5 (Kujala et al., 2014) and therefore rated for year-round operations in medium first-year ice containing old ice inclusions (International Association of Classification Societies, 2016). Further specifications of the vessel are presented in Table 1.

2.2. Antarctic voyage

Full-scale measurements were performed during the 2015/2016 voyage of the SAA II from Cape Town to Antarctica. Shear strain and axial strain measurements were captured along with, machine control, radial bearing vibration, ice conditions and navigation data. The GPS track of the voyage is presented in Fig. 2 during the 2015/2016 voyage:

- The vessel departed Cape Town harbour (1) on 5 December 2015 and headed towards the Greenwich Meridian, along which she navigated to Antarctica (3).
- Ice was encountered on 11 December 2015 and continued until 16 December when she arrived at the shelf, Penguin Bukta (3).
- On 22 December she navigated to Akta Bukta near the German Antarctic Research Station, Neumayer.
- From Akta Bukta she headed through heavy pack ice towards the South Sandwich Islands and arrived at South Thule (4) on 24 December.
- After South Thule (4), she navigated out of the ice field and reached South Georgia (5) on 30 December 2015. On the same day she voyaged NE to rejoin her original cruise line towards Antarctica along the Greenwhich Meridian.
- She re-encountered ice on 11 January on route to Penguin Bukta (3).
- The voyage back to Cape Town started from SANAE IV on 1 February. The vessel left the ice field on 2 February and arrived in Cape Town on 11 February 2016.

The total voyage lasted 68 days, of which 10.7 days were spent navigating in ice, 40 days navigating in open water and 17.5 days stationary. The pie chart in Fig. 3 depicts the operational profile of the vessel. The ice conditions varied throughout the voyage and are summarised in Fig. 3.

2.3. Instrumentation

Strain gauges were installed on the port side intermediate shaft line, 25.9 m from the center of gravity of the propeller (Fig. 4), to determine torque loading from strain gauge measurements. The strain gauges were connected in a Wheatstone bridge configuration to reject axial strain, compensate for temperature variations and reject bending. This was achieved by installing two pairs of T-rosette strain gauges on diametrically opposing sides of the shaft. The gauges were inclined at ± 45° with respect to the horizontal mid-plane of the shaft in order to measure the maximum shear stress on the outer surface (Fig. 5a). A V-link lossless extended range synchronized (LXRS) system, produced by LORD MicroStrain, was installed to transmit the measurements wirelessly (Fig. 5b) to a HBM Quantum mobile data acquisition system. The HBM Quantum was connected to a laptop via an ethernet cable and recorded through Catman AP V3.5 software at a sample rate of 600 Hz.

The general equation used for a Wheatstone full bridge configuration (Hoffmann, 2001) is expressed in terms of U_E which is the supply voltage and U_A, the bridge output voltage as a result of operational shaft deformations. The gauge factor, $k = 1.99$, is supplied on the packaging and ε_i (where $i = 1,2,3,4$) represent the strain measurements from the gauges 1, 2, 3 and 4 of the Wheatstone bridge. When torque is applied as indicated in Fig. 5a, strain gauge numbers 2 and 4 will sense negative strain and strain gauges 1 and 3 will sense an equal but positive strain. Thus, the absolute value of the measured strains (ε_1 to ε_4) will be equal and additive.