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Inverse ice-induced moment determination on the propeller of an ice-going vessel

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ABSTRACT

This paper presents inverse methods to determine the ice-induced moment on the propeller based on shaft line torque data. The following methods are applied: Truncation of singular value decomposition (TSVD), truncation of generalized singular value decomposition (TGSVD) and Tikhonov regularization. The dynamic behavior of the structure is modeled by combining an increment form of the governing equation of torsional vibration and Newmark-β method. Inverse methods are applied on model-produced verification data and full-scale measurement data. The verification indicated that the methods are capable to solve the ice moment function in loading events where multiple consecutive ice contacts are present. Results with full-scale data were physically understandable. The three presented loading events had 1 to 4 individual ice contacts. Durations of these ice-propeller contacts were mostly 60 to 80 ms. Ice contacts were observed to have a secondary peak that could be caused by a shear stress wave propagating back and forth the shaft line. After the ice contacts, the moment caused by the damping effect of water can be seen in the results.

1. Introduction

Maritime transport in ice-covered seas is expected to increase during future decades. A major concern related to ice is the load applied on the propulsion system during the ice-propeller interaction. The propulsion design in ice-going vessels is based on regulations defined by classification societies and their cooperative association, called International Association of Classification Societies (IACS). Regulations are defined based on various ice-propeller interaction models and measurements in full-scale and in ice tanks (Koskinen et al., 1996). In the following, only full-scale measurements are discussed. Extensive and realible data set of full-scale measurements from various types of vessels and conditions would improve the definition of propulsion regulations.

Several full-scale measurements of propeller loads have been conducted in the past. Measurements can be divided into shaft line and blade measurements. In shaft line measurements strain gauges are installed on the shaft line at some point between the propeller and the propulsion engine to determine the torque and the thrust of the propulsion. Approximately 20 shaft line measurements were available in 1996 (Koskinen et al., 1996). However, according to Kannari (1994) determination of ice loads on the propeller is difficult or impossible based on shaft line measurement due to the dynamic response of the propulsion system, consisting of the propeller, the shaft and the propulsion engine. The problem can be overcome by installing strain gauges directly on a propeller blade. Blade measurements have been performed onboard IB POLAR STAR (Antonides et al., 1981), MV ROBERT LEMEUR (Laskow et al., 1986), MS GUDINGEN (Jussila and Koskinen, 1989), MV RAUMA I (Jussila, 1983), IB KARHU (Kannari, 1994) and IB SAMPO (Kannari, 1994). Propeller loads are obtained more directly from blade measurements than from shaft measurements. However, blade measurements have two drawbacks limiting their extensive use in various types of vessels. First, installation costs are high due to the cable ducting through the propeller blade and the shaft. Second, strain gauges on the blade surface are vulnerable to ice loads, which can break the sensor prematurely.

The purpose of this paper is to apply regularization methods from the field of *inverse problems* to determine the ice-induced load on the propeller based on the measured shaft line torque. In an *inverse problem* indirect observations are made of the quantity of interest (Kaipio and Somersalo, 2005). The opposite for an *inverse problem* is a *forward problem*. In a common *inverse problem* related to structural mechanics, the load acting on the structure (i.e. input) is determined based on a response quantity of the structure (i.e. output), such as strain, displacement or acceleration. Mathematically *inverse problems* are ill-posed. Therefore, the solution of an input quantity requires regularization. Regularization methods to be applied in this paper are truncation of singular value decomposition (TSVD), truncation of generalized singular value decomposition (TGSVD) and Tikhonov regularization. To our knowledge, this type of approach has not been presented earlier for

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shaft line measurements. A successful use of inverse methods would enable shaft line measurements to be used extensively in the development of propulsion regulations.

The content of the paper is the following. First, the response of the structure under a unit step function load will be determined by a dynamic model that combines an increment form of the governing equation of torsional vibration and Newmark-β method as presented by He and Du (2010). The unit response function will be used to form a matrix describing the dynamic response of the structure. Second, regularization methods mentioned in the previous paragraph will be verified using torque data that is produced by the dynamic model with a known load. Relevant errors are added to the dynamic model and to the strain data to simulate their uncertainties. Third, the regularization methods will be applied to shaft line torque data recorded onboard PRSV S.A. AGULHAS II during ice trials in 2012. The examination of the propeller load will be limited only to the moment component acting parallel to the shaft. In the end, regularization methods will be compared and results discussed.

2. Measurement data

2.1. Voyage

The vessel, PRSV S.A. Agulhas II, was manufactured by STX Finland in Rauma shipyard in 2012. She operates under the South African flag transporting scientists and freight to Antarctica. She measures 121.25 m between perpendiculars and is 21.7 m wide. The vessel is equipped with four 3 MW diesel generators that power two electrical motors, which are both connected to variable pitch propellers with two individual shaft lines (Bekker et al., 2014).

Full-scale measurements were conducted onboard the vessel during the ice trials in the Baltic Sea during 21st to 23rd March 2012. Winter conditions during the ice trials were relatively mild. The ice thickness varied between 0 and 0.7 m, which is lower than the designed ice thickness, 2.0 m, of the propulsion according to ice class PC-5 (IACS, 2011). Compressive and flexural strengths of ice were described to be typical for one-year brackish water ice (Suominen et al., 2013). Despite the mild ice conditions, many clear ice-induced loading events were recorded during the ice trials.

2.2. Instrumentation

The torque of the port side shaft line was measured using strain gauges that were located in the engine room as shown in Fig. 1. Four strain gauges were installed on the shaft line in a full Wheatstone bridge. Strain gauges were located in pairs on both sides of the shaft line to eliminate normal and bending loads. Inside a pair, the two strain gauges were inclined at an angle of ±45° respective to the centerline of the shaft that enables the determination of the shear stress τ_{cir} at the circumference of the shaft line. The relation between the circumferential shear stress τ_{cir} and the internal torque M_T is (Hoffmann, 1989)

$$M_T = \tau_{cir} S_p, \tag{1}$$

where S_p is the polar modulus of the section. A hollow section has a polar modulus of

$$S_p = \frac{\pi\left(d_2^4 - d_1^4\right)}{16 d_2}, \tag{2}$$

where d_1 and d_2 are the inner and outer diameters of the section, respectively. The shear strain was acquired from the shaft line at a sampling rate of 500 Hz using a telemetry system. The system consists of stator and rotor antennas that transfer the measurement data to a stationary unit by a non-contact induction procedure.

In addition to the torque measurement, the shaft line was instrumented with strain gauges measuring the thrust of the propeller. These strain gauges were installed parallel to the centerline of the shaft on the aft side of the thrust bearing, which transfers the thrust to the hull of the vessel. In theory, the thrust data could also be translated into axial load on the propeller during an ice contact using inverse methods. However, this paper presents only methods to translate the ice-induced propeller moment around the longitudinal axis using torque data. Thrust data are not further discussed.

2.3. Data

An example of a loading event is presented in Fig. 2, where the internal torque of the shaft line is plotted as a function of time during an ice-propeller interaction. The internal torque has been determined from the strain gauge measurement using Eq. (1).

During the time frame of $t = 0 \ldots 0.15$ s the internal torque is nearly constant at 300 kNm indicating normal operation of the propulsion system. The constant torque is caused by the water resistance of the rotating propeller. At $t = 0.15$ s the internal torque increases rapidly to 330 kNm and starts to oscillate around the previously mentioned constant value. The rapid increase followed by the oscillation around the static torque indicates an ice-induced loading on the propeller. Multiple ice contacts might be present in the time frame of $t = 0.15 \ldots 0.38$ s, but after the time $t = 0.38$ s the amplitude of the oscillation decays smoothly to zero indicating no ice contacts to be present. The smooth decay is caused by the damping effect of water around the propeller.

In some cases the static torque changes during the loading event. The torque is either reduced temporarily or changed permanently during the event. A temporary reduction indicates that the propulsion control system is reducing temporarily the pitch of the propeller blades, whereas permanent change is indicating a change in the pitch or RPM setting of the propulsion system.

3. Methods

Methods of this study can be divided into two phases. First, the propulsion system is modeled as a set of inertia and spring elements. The model is used to solve the dynamic response of the propulsion system under a unit step function that is a *forward problem*. Second, three different regularization methods are applied to the measurement data to solve the *inverse problem*. The solution is the external moment on the

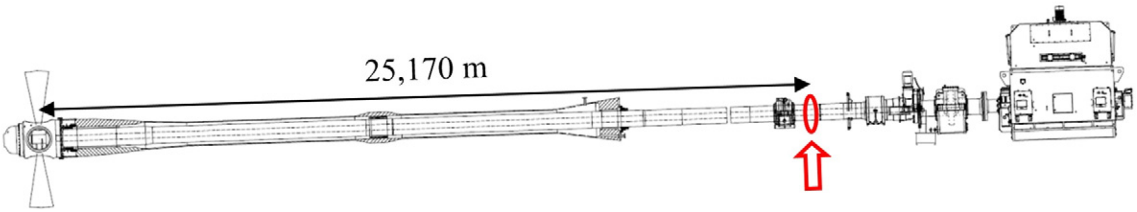

Fig. 1. Strain gauges for the shaft line torque measurement are installed directly after the thrust bearing (graph by STX Finland). The installation location is 25.170 m from the center of gravity of the propeller.