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Parametric roll resonance monitoring using signal-based detection

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ABSTRACT

Extreme roll motion of ships can be caused by several phenomena, one of which is parametric roll resonance. Several incidents occurred unexpectedly around the millennium and caused vast fiscal losses on large container vessels. The phenomenon is now well understood and some consider parametric roll a curiosity, others have concerns. This study employs novel signal-based detection algorithms to analyse logged motion data from a container vessel (2800 TEU) and a large car and truck carrier during one year at sea. The scope of the study is to assess the performance and robustness of the detection algorithms in real conditions, and to evaluate the frequency of parametric roll events on the selected vessels. Detection performance is scrutinized through the validation of the detected events using owners' standard methods, and supported by available wave radar data. Further, a bivariate statistical analysis of the outcome of the signal-based detectors is performed to assess the real life false alarm probability. It is shown that detection robustness and very low false warning rates are obtained. The study concludes that small parametric roll events are occurring, and that the proposed signal-based monitoring system is a simple and effective mean to provide timely warning of resonance conditions.

1. Introduction

Parametric roll resonance in head seas is one of the phenomena that can create extreme roll motion of ships. This type of roll motion can grow exponentially to extreme values that cause considerable damage to cargo and also include the risk of capsizing. The phenomenon created international awareness when roll resonance events occurred on large container vessels and caused huge fiscal losses before and after the Millennium. Training of navigators has helped to improve ship's ability to escape from most of the severe consequences if getting subjected to parametric roll resonance, but events on both container vessels and car carriers indicate that the phenomenon persists. Following stringent methods to characterize parametric resonance, this paper exploits a signal based approach to analyse and detect parametric roll.

Significant research followed the APL China event in 1998 (France et al., 2001) and that on Maersk Carolina in 2003 (Carmel, 2006). The hydrodynamic effects that cause parametric roll resonance are now well understood to be phenomena described by the behaviour of nonlinear differential equations with time-varying parameters (Hashimoto and Umeda, 2004; Bulian et al., 2008), and complex mathematical models have been published to simulate roll resonance behaviour (Neves and Rodriguez, 2005; Neves and Rodriguez, 2006; Holden et al., 2007a). The likelihood of getting into a parametric roll resonance condition was investigated using first order reliability analysis methods by Jensen (2007, 2012) showing a low but non-negligible likelihood of large resonance events. An overview of the phenomenon and its characteristics was presented in Dohlie (2006). Despite the awareness, events do occur and three cases were recently reported from car carriers (Rosén et al., 2012). The analysis of roll resonance events has so far been mainly a manual effort but novel results on signal based automated detection (Galeazzi et al., 2013) suggested a methodology to detect resonance events from low-cost motion sensor information. However, this method was not evaluated on long-term voyage data and not on full-scale resonance events, due to lack of real life data.

This paper fills this gap of knowledge by analysing long-term data for two different vessels: selected parts of data from a 2800 TEU container vessel for which data were available over a 2 year

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period, and motion data from all voyages of a large car carrier (LCTC) over a one year period. Furthermore, motion data from two of the parametric resonance events reported in the literature have been made available for this study. The paper employs the signal-based, statistical change detection method (Galeazzi et al., 2012b;[1] Galeazzi et al., 2013) that will alert when motion signals indicate that a vessel is close to or already in roll resonance. The monitoring system employs two detectors: one evaluates whether pitch and roll are close to a 2:1 ratio in frequency and the other tests the phase alignment between pitch and roll. A resonance event is diagnosed when both indicators are positive. Wave radar data are used as an independent source of information to characterize sea conditions.

The paper presents long-term results for the ships mentioned and demonstrates how timely detection is achieved using only motion signals from inexpensive inertial measurement units onboard. Detection performance is scrutinized and statistics of maximum roll amplitudes, time from detection to maximum roll, etc., are presented. The events detected by the monitoring system are validated by DNV-GL and Wallenius Marine according to the manual evaluation criteria they use. A scrutiny is then made of the bivariate distribution of data from the combined detectors to assess the false alarm probability, and analysis of the joint distributions shows that a very low false alarm probability can be achieved. The paper documents that parametric roll resonance is still a risk, despite increased awareness of the phenomenon, and that signal-based detection is a simple and effective method to provide early warning.

The paper is organized as follows: Section 2 explains parametric resonance as one of the phenomena that cause large and rapidly growing roll motion and explains the seamanship required to escape from a parametric roll condition if the resonance has been triggered; Section 3 presents a mathematical treatment of parametric roll resonance and gives the empirical conditions for its onset; Section 4 introduces the full-scale motion data and analyses the presence of resonance phenomena on two vessels based on time and frequency domain analysis; Section 5 introduces signal-based detection methods, it discusses the selection of thresholds and shows how robustness can be achieved through combined hypothesis testing; Section 6 discusses the findings from applying the condition monitoring on two years of fast sampled motion data from the two vessels; Section 7 explains how ship operators are managing the risk associated with parametric roll; Section 8 offers conclusions and addresses topics of further research.

2. Large roll motion in context

A ship's life consist of a design phase, the operation, and the end-of-life scrapping. The design and scrapping phases are relatively short while operation is in the order of 25 years. It is therefore not only important to design the vessel for its intended operation, but also to safeguard the vessel, crew and cargo during its operation. During design, there are functional requirements that should be satisfied. A design need to be made according to classification society rules, which include regulations by IMO (International Maritime Organization) and others. These rules may not cover all aspects and they are based on assumptions to the design. The assumptions may be related to the amount of cargo allowed on board and also the roll angles and accelerations, which are used in the design calculations to simultaneously secure the cargo and to ensure that the hull is not damaged by the cargo. It is implicit that these assumptions are not being exceeded during the operation.

Excessive roll angles can clearly cause damage, and the physical reasons for large roll motion in waves can have several causes (France et al., 2001; Boonstra et al., 2006; Bulian et al., 2008; Rosén et al., 2012; Krüger et al., 2013): parametric roll, of which the 2:1 resonance is most common; forced roll in stern quartering or beam seas; resonance roll motions in stern or beam seas; broaching caused by loss of directional stability when relative water particle velocity at the rudder is low; loss of stability due to loss of water line area in front and aft when stuck on a wave crest; loss of stability due to maneuvering and water on deck and lost remaining stability.

Some of these phenomena are well understood and known by the officers on board, others are less well known and further development of decision support systems and training are needed. Based on reports of vessels exceeding 30° roll, in the references above, IMO's Maritime Safety Committee issued a circular describing events of extreme roll and emphasized parametric resonance as one of the phenomena giving rise to unexpected and rapidly growing roll motion.

During operation the seamanship is important. The Master should ensure that the vessel is not overloaded and that the roll angles and accelerations do not exceed acceptable levels. This may be difficult to ensure, but the navigators have various tools at hand to provide decision support. Examples are systems that provide weather information, calculate the loading conditions and monitor hull stress. Nevertheless, a large number of containers fall over board or are getting damaged each year. The international joint industry project *Lashing@Sea* (Koning, 2010) estimates this number to be 10 000 per year and states that it is not an insignificant number of vessels that are involved annually. Decision support systems were developed following the APL China incident. A framework of an Active Operator Guidance system was made by DNV, and industrial vendors have made commercially available decision support systems for this purpose. It could be questioned why large roll incidents still happen and whether the decision support systems at hand are sufficient. One answer is that excessive roll can have several causes and another is that parametric resonance has apparently not been detected with sufficient accuracy in present systems.

This paper presents extensive testing and refinement of the parametric roll detection method (PAROLL) the theory of which was described in Galeazzi et al. (2012a, 2013). Some of the data include several events that were reported as parametric resonance while the majority of records show only forced roll. The presence of both conditions gives a unique opportunity to investigate both detection performance and false alarm probabilities. Three features have been added to the condition monitoring system to enhance its operational usability. A colour coded risk coefficient informs about how close the vessel is to experience a parametric roll event. An audible alarm is only issued after further real-time checks on (a) exponential growth of the roll and (b) a check on the magnitude of roll angle. With these additional indicators to filter an already very low false alarm rate, exceptional performance is shown to be obtained in false alert properties of the algorithms, yet leaving detection agile and timely to make navigators able to react with remedial actions if in risk.

2.1. Escaping from resonance conditions

Courses are given worldwide to create awareness on parametric roll, and on how to escape a resonance condition. The parametric roll detection system presented in this paper may contribute to build awareness on board. While the existing decision support systems suggest what is the critical sea state, the

[1] The detection methods are patented under EP2419804 by the Technical University of Denmark and are available on royalty terms.