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Dynamic stability of ships in regular and irregular seas - An overview

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ABSTRACT

Dynamic stability of ships is discussed with focus on the stability of intact ships in waves. Some of the main developments along the years are scrutinized. Regular and irregular conditions are addressed. An overview is presented, with special emphasis on the covering of the last STAB 2015 Conference.

1. Introduction

It is generally accepted that a deep understanding of ship responses in idealized regular waves is fundamental for the understanding and adequate description of responses in more realistic irregular seas. Hence, ship dynamic model responses in deterministic waves have logically preceded investigations on ship dynamics and then extended to the more realistic irregular case at a later stage.

The capsize of an intact ship is a phenomenon which by its very nature involves excessive motions. The most basic purpose of research devoted to the study of ship dynamics has to concentrate on the understanding of the role of different parameters necessary to insure safety against capsizing in waves. This, however, appears not to be a simple task. Here, it is possible to summarize indicating two main causes for not being a simple task: (a) in a random seaway we are faced with capsizing as a stochastic process. (b) capsizes are rare events in severe seaways and are dependent on a number of ship parameters as a consequence of the very low probability levels involved.

Here we consider only intact ship stability problems. Some consideration is given in the following of ship dynamic problems in regular waves, as these are elucidative of the bifurcations associated with stability problems. Also affected by clear bifurcations is the stability of ships in beam seas, to which reference will be made. Archetypical situations are: parametric rolling in following seas, surf-riding and broaching in following and quartering seas, pure loss of stability and bow diving in following seas, stability problems associated with water on deck and stability problems in beam seas.

After qualifying stability problems in regular waves, consideration will be given to stability and capsizing in irregular seas. A brief review will be given of different methodologies employed in these investigations.

From the very beginning it is important to give credit to three technical books which are exceptionally relevant sources of references on dynamic stability of ships (the complete references are given at the end of this paper):

a) Belenky and Sevastianov (2007) "Stability and Safety of Ships-Risk of Capsizing".
b) Neves, M.A.S., V.L. Belenky, J.O. de Kat, K. Spyrou, N. Umeda (eds.) (2011)“Contemporary Ideas on Ship Stability and Capsizing in Waves”.
c) Fossen T.I. and Nijmeijer, H. (eds.), (2012) “Parametric Resonance in Dynamical Systems”.

The STAB 2015 paper Backalov et al. (2015a), "Ship Stability, Dynamics and Safety: Status and Perspectives" is also worth mentioning. It is a quite complete review covering all papers that appeared in recent STAB Conferences and ISSW events, covering the period between 2009 and 2014. Along similar lines, Backalov et al (2015b), "Ship Stability & Safety in Intact Condition through Operational Measures" is another review of papers from STAB Conferences and ISSW events covering the same period with focus on operational risk control.

Due to strategic editorial reasons topics associated with stability criteria (first and second generations) are not covered in the

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present review, as these are contained in the companion paper by Francescutto (2015).

2. A first generation of studies on dynamic stability of ships

In this section a brief review is presented of the ample area of dynamic stability of ships in waves, with developments starting with Froude's time, then jumping to the period of thirty years between 1952 and 1982, when the 2nd International Conference on the Stability of Ships and Ocean Vehicles took place in Tokyo. In the mean time, reference will be made to the historical 1st International Conference on the Stability of Ships and Ocean Vehicles organized by Professor Chengi Kuo in Glasgow in 1975.

Regarding parametric rolling, it is well known that the vertical modes may in certain circumstances affect the roll motion, as Froude (1861) pointed out. He observed that ships have undesirable roll characteristics when the frequency of a small, free oscillation in heave is twice the frequency of a small, free oscillation in roll.

This is clear from the fact that for a ship in waves the righting arm will vary continuously in the process of heaving and pitching and wave passage along the hull. A parametric excitation is introduced into the ship motion problem (see for example the classical papers by Grim (1952) and Kerwin (1955)). Then the well-known differential equation of Mathieu (see for instance McLachlan (1955)) is obtained which typically characterizes the resonant rolling motion in longitudinal waves. Depending on the values of the coefficients, this equation yields a stable or unstable solution. Though it may be obtained from some couplings between roll and heave & pitch, strictly speaking the Mathieu equation is an uncoupled equation, which is used to describe the roll motion (see Wellicome (1975) for a fine analytical treatment). Reflecting the relatively limited tools available to researchers at the time, it is emblematic that in Wellicome (1975) the numerical simulations were performed using an analogical computer.

Certainly at the time there was a somewhat limited perception of the analytical resources available for advances on ship stability analysis; despite this, the technical community was well aware of the need to progress. In 1975, during the 1st International Conference on Stability of Ships and Ocean Vehicles, Kuo and Gordon (1975) carried out a survey on the opinion of the delegates on the stability problem as a whole. It became apparent that many delegates considered the IMO (then IMCO) criteria as unreliable and insufficient; therefore there was a demand for further advances and investigations on dynamic stability of ships in waves. Yet, the main perception was that beam seas was the dangerous situation from the capsize point of view. The San Francisco Bay revealing experiments were not well known to many in the community. The defining logic adopted within the community was one derived from the studies related with the consolidation of the 1977 Torremolinos Conference. Covering these first decades of studies three excellent reviews on dynamic stability of ships are worth mentioning here: Bird and Odabasi (1975), Marshfield (1976) and Kuo and Welaya (1981). These three papers offer to readers some excellent assessments of the pertinent knowledge published during that decade.

A considerable amount of work was then invested in the dynamic rolling stability of fishing vessels, e.g. Morral (1975), Wright and Marshfield (1980). In particular, accident reviews of fishing vessels capsizes offered significant contributions during the period to an increased understanding of dynamic stability of ships in waves: Dahle and Kjeerland (1980) described the investigation and recommendations for preventing similar accidents as one that resulted in the capsize of a fishing vessel converted into research vessel, the main hypothesis being that the vessel was hit by a large beam wave. Morral (1980a) conducted experiments in which a comparative analysis was performed with two very similar fishing vessels; very similar main dimensions, but having distinct stern shapes: a transom stern and a round stern. The experiments revealed marked differences in responses to waves of the two hulls and gave one of the first insights on the potentially adverse role of transom sterns from the point of view of dynamic stability. A second investigation by Morral (1980b) addressed the accident that resulted in the disappearance of the large trawler Gaul.

Before closing this section, it is worth referencing the seminal work of Blocki (1980), who applied wave group concepts in order to model parametric roll excitation of ships in irregular seas. This pioneering work opened the way to a substantial amount of papers with similar approaches, combining deterministic and probabilistic methodologies.

3. San Francisco Bay experiments and other developments

Two events contributed to significant advances during the 70's: the 1st International Conference on Stability of Ships and Ocean Vehicles and the San Francisco Bay experiments. Six years before this inaugural 1st STAB Conference, the United States Coast Guard sponsored a sophisticated program of research at the University of California which started with a comprehensive program of free sailing model testing in the open waters of San Francisco Bay, see Chou et al. (1973), Oakley et al. (1974) and Paulling et al. (1972), (1975). A real landmark in dynamic stability studies. As a result it was possible to identify from the extensive free model tests three observed modes of capsizing in quartering and following seas. These are labeled as low-cycle resonance, pure loss of stability and broaching.

The low-cycle resonant mode refers to parametric roll, which may be observed not only in following seas, as will be seen in greater detail ahead.

Pure loss of stability and broaching usually occur in following seas at high speeds. Broaching is the most dynamic mode, in appearance. Broaching is caused by directional instability of a vessel accelerated on the face of a wave. The situation can be either caused by or compounded by any loss of the effectiveness of the rudder due to wave orbital velocities and emergence. Covering the first scientific studies on surf-riding and broaching, it is necessary to mention the Du Cane and Goodrich (1962) paper. The authors conducted experiments with a free-running model in following seas which showed how a model can be ‘captured’ by the wave and accelerated to wave-velocity (surf-riding). More than one decade later Nicholson (1974) parametric experiments gave new impetus and basis for new investigations on following seas stability problems. Given the typical low encounter frequency some authors modeled surf-riding (and broaching problems) in a quasi-steady fashion, see for instance Renilson and Driscoll (1982). If directional instability takes place, the associated angular velocity will induce a dynamic heeling which may combine with the wave action to cause capsize.

Presently, other possible dangerous modes are explored in detail in the literature, beyond the three modes previously discussed: excessive accelerations, dead ship conditions, water on deck and bow diving (see Grochowalski (1989)). However, due to lack of space, these additional possible stability failure modes will not be addressed in this brief overview.

From the analytical point of view, a special position goes to the innovative work of Prof. A. Y. Odabasi. In a series of papers his investigative work examined the role of nonlinearities in the roll motion and clarified many of the theoretical tools available at the