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Peregrine breathers as design waves for wave-structure interaction

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ABSTRACT

This paper introduces the Peregrine breather solution of the nonlinear Schrödinger-type equation as an innovative design wave. The major benefits are the potential to generate abnormal waves of certain frequency up to physically possible wave heights, the symmetrical abnormal wave shape and the availability of an analytical solution. The characteristics of Peregrine breathers as well as their impact on marine structures were investigated. To evaluate the applicability of the Peregrine breather solution as design wave, wave-structure investigations with a LNG carrier were performed in a set of Peregrine breathers at certain frequencies. The investigations comprised model tests as well as numerical simulations. For the purpose of comparison, a real-world abnormal wave reproduction was additionally investigated allowing the evaluation of breather-type abnormal waves regarding the applicability as design wave. Therefore, the famous 'New Year Wave', an abnormal wave recorded in the North Sea at the Draupner jacket platform on January 1st, 1995, was selected.

1. Introduction

The existence of abnormal, freak or rogue waves is an incontrovertible fact due to many reports on observations and accidents (Faulkner and Buckley, 1997). There are reports from cruise vessels encountering freak waves, some escaped with no more than a fright whereas others suffered disastrous consequences (e.g. Schulz (2001), Lemire (2005), Bertotti and Cavaleri (2008)). In contrast to cruise ships, where the impact of steep waves at the bow will cause (dangerous) local damage at the superstructure with potentially serious consequences, cargo vessels are more affected by wave-induced global loads which may cause structural failure. Ship losses such as the sinking of the single-hull tankers Erika (1999) and Prestige (2002) as well as the double-hull tanker Ievoli Sun (2000) confirm the need for systematic investigations. A general overview on real sea abnormal wave records and reported accidents can be found in Kharif et al. (2009).

A precise knowledge of loads and motions in extreme wave sequences is indispensable for the design of ships and offshore structures to reduce the risk of serious incidents and disaster. The formation process and the frequency of occurrence of abnormal waves as well as the consequences of their impact on ships and offshore structures are still under intensive investigations. The research comprises investigation on different types of offshore structures with tubular members by Gorf et al. (2000), Suyuthi and Haver (2009), Clauss et al. (2010a, 2010b) and others in terms of local impact and by Karunakaran et al. (1997) in terms of global response. Floating structures of FPSO type have also been studied for example by Guedes Soares et al. (2006) and Fonseca et al. (2007, 2010), focusing on aspects of local impact on the bow area. Investigations by Stansberg and Karlsen (2001) revealed that the encountering wave profile in terms of wave steepness as well as the ship motions are important parameters for local loads: "relative short and steep waves are more critical than longer waves, due to the phase lag of the pitch motion", in particular in combination with large pitch amplitudes. Guedes Soares et al. (2007) has observed experimentally that the occurrence of large wave slamming loads depend on the local steepness of the waves. Besides the local impact of abnormal waves, the effect on global loads of different ship types have been intensively studied (e.g. Pastoor et al., 2003; Clauss et al., 2004; Guedes Soares et al., 2008). Watanabe et al. (1989), Rajendran et al. (2011) and Clauss et al. (2010a, 2010b, 2011a, 2011b) showed that the geometry of the bow flare in combination with the wave steepness as well as encountering wave length influences the global loads significantly, in particular the sagging loads.

Tailored wave sequences are indispensable for the evaluation of a design, be it wave events identified by numerical investigation such as design wave concepts or wave events of a more general nature such as abnormal waves embedded in irregular sea states or real-world reproductions. Abnormal wave events are of particular interest as they are outstanding situations relevant for all ships and offshore structures. The numerical and experimental modelling of such wave conditions to

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be investigated in the design process is a challenging problem. Different alternatives are available to evaluate offshore structures in high, steep waves - transient wave packages (Clauss and Kühnlein, 1996), regular waves as well as irregular sea states with random phases. More sophisticated methods focus on tailored critical wave sequences such as from design wave concepts (e.g. Torhaug et al., 1998; Tromans et al., 1991; Friis-Hansen and Nielsen, 1995; Adegeest et al., 2000; Dietz, 2004), extensive numerical simulations or real-world abnormal wave reproductions (e.g. Schmittner, 2005; Fonseca et al., 2006, 2008; Clauss et al., 2006; Klein, 2015). In particular, wave/structure interaction investigations with real-world abnormal wave reproductions are indispensable for a complete understanding as they represent abnormal wave events happened on sea at which floating structures have to survive. They exclude any doubt regarding discussions on possible unrealistic, artificial wave sequences. However, such complex structures of wave sequences require sophisticated reproduction procedures as presented by Schmittner (2005), Clauss et al. (2006, 2013) as well as Schmittner and Hennig (2012) and do not represent the day-to-day business of test facilities.

Thus, a straightforward method for fast generation of realistic abnormal waves with varying characteristics is required enabling systematic investigations of abnormal wave-structure interaction. Breather solutions, which are exact solutions of the nonlinear Schrödinger-type (NLS) equation, are predestined as they are considered as prototypes for abnormal waves (Dysthe and Trulsen, 1999; Osborne et al., 2000). Henderson et al. (1999) showed that these waves feature many similarities to real-world abnormal waves and Zhang et al. (2014, 2015) showed that predictions of the NLS equation reproduce well also the mechanically generated waves on laboratory conditions. They serve as suitable analytic models simulating steep wave events (Dysthe et al., 1999) and are promising candidates for extreme wave modelling (Huijsmans et al., 2005; Andonowati et al., 2006). Altogether, three (first order) solutions are known, namely Kusnetzov-Ma breather (Kuznetsov, 1977; Ma, 1979), Akhmediev breather (Akhmediev et al., 1985, 1987; Akhmediev and Korneev, 1986) and Peregrine breather (Peregrine, 1983), which have been successfully utilized in wave tanks experiments by Chabchoub et al. (2010, 2011) and Clauss et al. (2011a, 2011b). The general applicability of breather solutions to abnormal wave-structure investigations has also already been shown by Clauss et al. (2012), Onorato et al. (2013) and Klein (2015).

The Peregrine breather is particularly in focus as this solution is localized in time and space resulting in a wave that "appears from nowhere and disappears without trace" (Akhmediev et al., 2009a, 2009b). Chabchoub et al. (2010) showed the "Experimental Evidence for Breather Type Dynamics in Freak Waves" by adjusting the Peregrine breather characteristics to real-world abnormal waves such as the New Year Wave (NYW) as well as the Yura wave (Mori et al., 2000). A detailed study on Peregrine breather characteristics in terms of breaking threshold, lifetimes and travel distance of the abnormal wave has been presented by Chabchoub et al. (2012). It has been shown that the initial wave steepness is one of the decisive parameters for wave tank experiments to adjust the maximum wave height/steepness up to breaking waves and that the abnormal wave would travel few minutes and kilometres at the ocean. In addition, this study revealed that breather solutions serve as analytical model for defining the boundary condition at the wave board but the physical waves show an increasing difference to the predicted theoretical model (exact solution as well as numerical simulations based on NLS equation) with increasing finite initial wave steepness (see also Shemer and Alperovich (2013)). In this context, Perić et al. (2015) investigated the dynamics of breaking breather waves comparing experiments with numerical simulations. They have shown that numerical simulations based on Navier-Stokes equations show an excellent agreement compared to the measured surface elevation. The dynamics during evolution as well as breaking of the abnormal wave can be investigated detailed by numerical field methods. Recently, so-called super-rogue waves have also come into focus as prototype for freak wave evolution. Super-rogue waves represent a hierarchy of higher-order rational breather solutions (Akhmediev et al., 1987, 2009a, 2009b; Dubard et al., 2010; Gaillard, 2012). Higher-order rational breather solutions are characterized by superposition of a group of rogue waves. The first order solution is the Peregrine solution. The amplitude amplification factor (AAF), which is 3 for the first order solution, depends on the order N and can reach impressive values. For order $N = 5$ with $AAF = 2{\cdot}N + 1$ results in an eleven times higher abnormal wave compared to the background amplitude. Chabchoub et al. (2012) investigated higher-order breather solutions experimentally, presenting the evolution of a second-order rational breather solution. Again, the agreement between theory and experiments is excellent for small steepness and decreases with increasing initial steepness of the solution. Based on this study, Slunyaev et al. (2013) investigated the evolution of super-rogue waves more systematically by means of numerical simulations. The focus of the study lies on variation of the order of the higher-order rational breather solution $1 \leq N \geq 5$ investigating the influence of the focussing distance on the evolution, in particular regarding the AAF. The analytical solution based on NLS equation serves as initial approximation for subsequent numerical simulations using modified NLS equation (MNLS, Dysthe, 1979) and fully nonlinear Euler equations. They showed that in contrast to the first order solution the higher-order solutions show a more distinctive deviation between the analytical solution based on NLS equation and MNLS as well as fully nonlinear simulations. Altogether, the research results on breather solutions "supports the hypothesis that the Benjamin-Feir instability correlated to breathing is a possible explanation for a sudden formation of rogue waves" (Chabchoub et al., 2010) in the real ocean. However, the evolution of breather solutions on an irregular background such as under oceanic conditions is not answered up to now. Consequentially, breather-type abnormal waves are promising candidates as design abnormal waves. The existence of an analytical solution offers a fast and simple generation of the wave maker control signal. In addition, the small frequency bandwidth offers the tailored investigation of critical wave lengths in terms of structure response as well as the wave group steepness is variable up to very steep waves. Moreover, breaking breather waves represents the maximum possible wave height at a certain wave length to be suffered by a marine structure. The potential of breather solutions as design abnormal waves for abnormal wave-structure investigations is presented in this paper by means of experimental and numerical investigations. Therefore, the Peregrine breather is chosen as an example representing the limiting case of the time-periodic Kusnetzov-Ma breather solution and the space-periodic Akhmediev breather solution. However, the results presented are directly transferable to the other two solutions (Klein, 2015). This study comprises:

- Investigation of abnormal wave characteristics in terms of wave kinematics and dynamics.
- Investigation of the potential of breather solutions for the generation of tailored extreme wave sequences. The Peregrine breather is applied for the generation of a tailored irregular sea state with embedded abnormal wave.
- Abnormal wave-structure investigations with a LNG carrier (LNGC) addressing the vertical wave bending moment amidships as well as the vertical ship motion.

For the evaluation of the applicability of breather solutions as design abnormal waves, a real-world abnormal wave reproduction, namely the New Year Wave, is additionally investigated for the purpose of comparison. The objective is to draw conclusions on the differences or similarities between the real-world NYW and the somehow artificial breather-type abnormal waves allowing conclusions regarding the applicability as well as relevance of breather solutions as design