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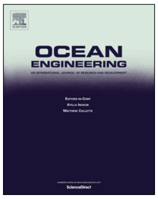

Review

A review of vertical motion heave compensation systems

J.K. Woodacre [a,*], R.J. Bauer [a], R.A. Irani [b,a]

[a] Department of Mechanical Engineering, Dalhousie University, Halifax, Nova Scotia, Canada B3H 4R2
[b] Rolls-Royce Canada Limited - Naval Marine, 461 Windmill Road, Halifax, Nova Scotia, Canada B3A 1J9

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ABSTRACT

This paper provides a comprehensive review of vertical heave motion compensation systems used on ocean vessels from the early 1970s up to, and including, modern systems. Specifically, this review provides details on passive heave compensation, active heave compensation, hybrid active–passive heave compensation systems, and wave synchronization systems along with detailed explanations of the most common motion actuation methods, control schemes, and heave motion decoupling potential found with each. Based on the results of this review, it is recommended that more experimental work be carried out on real-world systems to experimentally validate the active heave compensation controllers being designed and simulated in literature. It is also suggested that future work involving model-predictive control may be used to further improve upon the performance of the current active heave compensation systems.

Contents

1. Introduction

Equipment handling on the ocean can be a difficult task, especially during rough seas. When lifting, lowering, or holding a load at sea, heave compensation is used to remove vessel heave motion from the load, resulting in the decoupling of load motion from ship motion and, therefore, reduced variation in cable tension. The past 40 years have seen heave compensation systems to become commonplace in many maritime operations. Fig. 1 provides a timeline of the major developments within the field of heave compensation.

Southerland (1970) presented a paper outlining the difficulties in payload handling at sea. Focusing on sub-sea salvage, recovery, and rescue operations, Southerland states that the most significant hurdle to these operations comes from surface ship motion in rough seas. He goes on to present examples of both passive and active heave compensation systems to alleviate the issue. The

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[*] Corresponding author.
E-mail addresses: jwoodacr@dal.ca (J.K. Woodacre), robert.bauer@dal.ca (R.J. Bauer), rishad.irani@rolls-royce.com, rirani@dal.ca (R.A. Irani).

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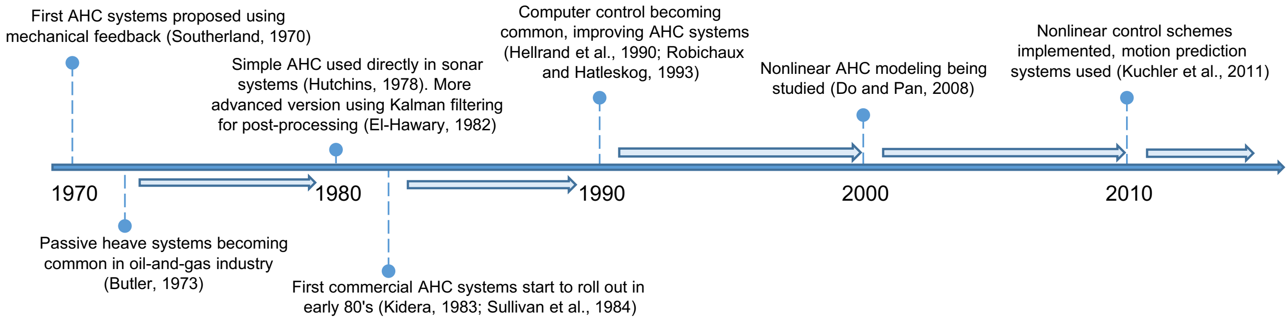

Fig. 1. An approximate timeline of heave compensation development (Hellrand et al., 1990; Sullivan et al., 1984).

passive system is designed to maintain a constant line tension, while the active system uses a simple mechanical feedback system to adjust for the ship heave amplitude.

Not long after Southerland (1970) was suggesting that heave compensation be used in handling operations, a study by Butler (1973) demonstrated a heave compensated drill string prototype being tested for offshore drilling. These tests showed successful isolation of the drill string from ship heave motion, resulting in longer operational windows and increased profits. The success of these and other similar tests allowed heave compensation to become widely accepted in the drilling industry, leading to further research and development.

Since the 1970s heave compensators have been benefited from computational advances allowing advanced sensor integration and better system modeling, hydraulic advances allowing faster and more accurate control, and control system advances allowing the application of more evolved control algorithms. These developments have largely been applied to heave compensation systems related to the oil and gas industry; however, both active and passive heave compensation are also prevalent in remotely operated vehicle (ROV) operations such as is seen in the work by Nicoll et al. (2008), as well as payload transfer between vessels as shown in an early patent by Blanchet and Reynolds (1977).

The current authors have found a great deal of literature on the subject of heave compensation systems; however, the works are spread through multiple sources such as journals, conference proceedings, theses, and patents with no extensive review of this increasingly important field being published. It is therefore the major contribution of this paper to provide a review of vertical heave compensation systems within a single, comprehensive study. First, in Section 2, a detailed explanation and comparison of active and passive compensation techniques will be provided including a brief history of each technique, current applications, as well as a discussion of their advantages. Following heave compensation, a discussion of wave synchronization methods is provided in Section 3, as wave synchronization is a closely related field. Next, Section 4 examines methods of actuation as they apply to heave compensation. Section 5 of this review paper looks at control theory as it is applied to heave compensation and what issues exist in current systems. Finally, the present authors conclude by summarizing the current state of the art and by proposing a new control method for use in heave compensated systems.

2. Heave compensation

Heave compensation can be divided into two main categories: passive heave compensation (PHC) and active heave compensation (AHC). Additionally, hybrid active–passive systems exist which combine features of both passive and active systems. Regardless of the compensator type, the goal of heave compensation is to decouple load motion from ship heave motion. In Sections 2.1–2.3 a basic functional description of different heave compensator implementations will be given.

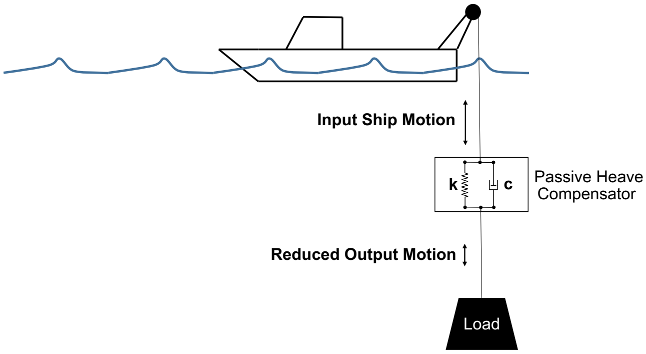

Fig. 2. This schematic shows an example of a small vessel hauling a load using a passive heave compensator in line between the load and the vessel.

2.1. *Passive heave compensation (PHC)*

At their simplest, PHCs are vibration isolators; open-loop systems, where the input is ship motion and the output is a reduced amplitude motion of the attached object, partially decoupling the load from the vessel. PHCs require no input energy to function. In Fig. 2 a simplified PHC is represented as a parallel spring–damper system placed at the center between crane and load — although the compensator can be placed anywhere on the load-carrying line, including on the deck of the ship.

The theory of vibration isolation is well established in many textbooks and the reader may refer to the literature by Inman (2001), Rao (2010), and Wow (1991) for a few such examples. In most vibration isolation systems, a parallel spring–damper is placed in series before the load which the designer wishes to isolate. The parallel spring–damper acts as a mechanical low-pass filter in which different values of spring-constant k, and damping c, produce a different low-pass filter corner frequency. Consider the system in Fig. 2 which shows a small surface vessel using a PHC, consisting of a parallel spring–damper, to help isolate the load motion from the vessel motion. The following differential equation can be written to describe the load motion:

$$m_L\ddot{x}_L = -k(x_L - x_H) - c(\dot{x}_L - \dot{x}_H), \tag{1}$$

where x_H is the ship heave, x_L is the load displacement and m_L is the load mass. Taking the Laplace transform of Eq. (1) results in

$$\begin{aligned} m_L s^2 X_L(s) = & -k(X_L(s) - X_H(s)) \\ & -c(sX_L(s) - sX_H(s)), \end{aligned} \tag{2}$$