Experimental Results for Pitch Damping in Speed and Wave for a Surface Effect Ship with Split Air Cushion*

Vahid Hassani[1,3], Øyvind Auestad[2], and Marco Nataletti[3]

***Abstract*— This paper presents experimental results in damping the pitch motion on a Surface Effect Ship (SES) in high vessel speeds in presence of regular wave. The SES is a marine craft supported by pressurized air cushion. It consists of two side-hulls, a flexible rubber bow and reinforced stern seal. The air cushion is pressurized thanks to the lift fans blowing air into the cushion. Modern SES are equipped with controllable vent valves that allows adjusting the pressure of the air cushion. Air Split Cushion SES is one of the new design by Umoe Mandal AS where the main air cushion is divided to four smaller air chambers, each one equipped with a lift fan and controllable vent-valve. Using a derivative controller, this paper presents an active pitch control in waves. Controlling the pressure in each air cushion through adjusting the air leakage on the vent-valve, provides an effective pitch regulator that demonstrates, through simulations and experiments, reduction of up to 60 % of the pitch motion in waves and high speeds. The effectiveness of the proposed system is examined through experimental model testing of the vehicle in SINTEF Ocean's towing tank.**

I. INTRODUCTION

Marine transport is driven by safety, comfort and speed. Hence, the transport efficiency has become a significant factor in maritime transport imposing the new direction in concept development. In the Norwegian offshore oil and gas sector, strong policy of zero accident puts even higher importance on safety matters [1]. However, up to this day, the main mean of the personnel transport in the Norwegian offshore oil and gas industry, is helicopters, despite it being one of the transport means with highest associated risk for an offshore worker [2]. UMOE Mandal AS has developed a new concept in crew transfer vessels that holds a great promise as a viable and appealing alternative in replacing the helicopters for crew transfer in the Renewable and Oil & Gas applications [3]. These vessels are based on proven Surface Effect Ship (SES) technology and air-cushion catamaran design, which guarantees rapid transit time, superior seakeeping and passenger transport comfort, excellent fuel economy and reduced environmental footprint as compared with conventionally hulled ships.

A SES is a marine craft with catamaran hull, with reinforced flexible rubber stern bag and bow skirt systems. The air cushion is defined as the enclosed volume between the hull, seals and water plane. Centrifugal lift fans blow air into the air cushion, pressurizing the air cushion that lifts up to 85% of the vessel weight. This allows for: a) significant reduction of frictional resistance and hence, higher vessel speed; b) smaller wave induced motions; c) improved seakeeping performance; and d) reduced seasickness index.

While traditional SES has a single air cushion, a new SES concept, by UMOE Mandal AS, consists of four air chambers, each one equipped with a lift fan and an adjustable vent valve, through which air chamber pressures can be controlled by adjusting the air out-flow from each cushion. The new air cushion split allows active pitch damping in speed and waves, hence, it provides the solution for higher comfort and passenger safety. Furthermore, it expands the operational window for the surface effect vessels at harsh weather conditions.

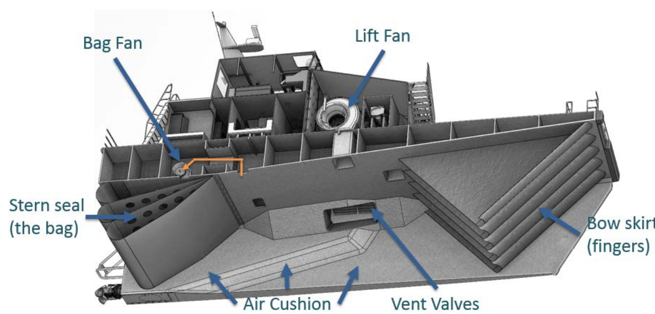

Fig. 1. Cross section of a SES. Courtesy of Umoe Mandal AS.

Figure 1 illustrates a cross-section of a typical modern SES. Centrifugal lift fans blow in-flow air into the air cushion, enclosed by port and starboard sidewalls, stern bag and bow skirt seals, sea surface, and SES deck. In order to have an isolating effect, the air inside the stern bags are further pressurized using a separate bag fan fed with air from cushion. Modern SES are also equipped with adjustable vent valves allowing out-flow air from the pressurized cushion. The use of vent valves to design motion damping in low speed application for both Ride Control System (RCS) and Boarding Control System (BCS) is studied in [4], [5], [6], [7], [8], [9], [10].

In this paper, we consider a new SES design where the main air cushion is divided into four air compartments by the use of inflatable separators. Figure 2 illustrates the UMOE Mandal's SES design with air split cushion. The implementation of the four chambers solution using inflatable bags allows for usage of a traditional one-cushion solution

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[1] Department of Mechanical, Electronics and Chemical Engineering, Oslo Metropolitan University (OsloMet), Oslo, Norway vahid.hassani@oslomet.no
[2] Umoe Mandal AS, Mandal, Vest-Agder, Norway.
[3] Department of Ships and Ocean Structures, SINTEF Ocean, Trondheim, Norway.

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when the four cushion division is not needed.

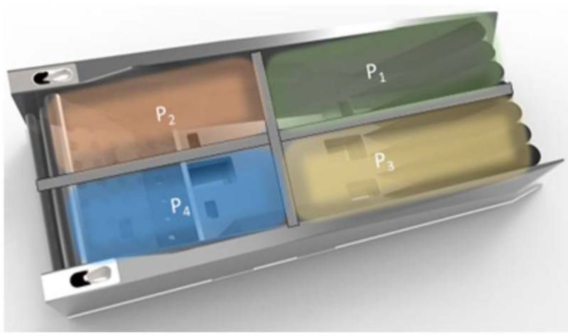

Fig. 2. The cushion separation concept, courtesy of UMOE Mandal AS.

A ship in sea wave experiences unavoidable wave induced translational and rotational modes of motion that are undesirable. In the design of high-speed crew transfer vehicles, the coupled heave-pitch motions for twin and multi-hulls are of paramount importance. Waves induced motions in the high speed marine vessels, may cause seasickness for passengers. The vertical accelerations (associated with heave, roll, and pitch motions) are found to be the main cause of motion sickness [11]. There exist many ways to regulate and smoothen such excessive motions in high speed vessels. Among those, using active T-foils and flaps and interoceptors to design ride control system (RCS) for regulating the motions in high speed vessels has shown promising results and found its way in the market [12], [13], however, they are not applicable in SES due to small submerged section.

In this paper the problem of designing an active pitch control system is studied. The VEssel RESponse (VERES) program [14], [15], [16] is exploited to develop a linear model of the high speed vessel. Then, the measurement from the two accelerometers onboard the vessel are used to build a feedback control law. The results are experimentally tested using a model scaled high speed SES in SINTEF Oceans's towing tank.
The main emphasis of the paper, after a brief review of modelling the vessel using VERES, is to present primary experimental confirmations of the efficacy of developed pitch damping system in regulating the pitch motions of the vessel in waves. While the adopted controller in this paper is of a very simple derivative form, the main contribution of the paper falls in the experimental tests that were carried out in the SINTEF Ocean's towing tank. Verifying the efficacy of the design, these tests paved the road for full scale design and development of SES with split cushion.

The structure of the paper is as follows. In section II, a very brief summary of application of the strip theory for modeling ship motions is presented. Section III presents the process of the controller design. In section IV, a short description of the scaled model, and experimental results of model tests are presented. Conclusions and suggestions for future research are summarized in Section V.

II. Dynamical Modelling of the Vessel In Speed

In what follows we exploit the linear strip theory [17] and its counterpart for high speed vessels [18] for developing a linear model of a high speed SES. The effect of cushion pressure for SES is accounted using a linear formulation for prediction of motion response and global loads on SES. Similar formulation has been reported in [19]. The main assumption in the strip theory is considering the ship to be made up of a finite number of transverse two dimensional slices called "strips", which are rigidly connected to each other. Then, each strip is treated, from hydrodynamics point of view, as if it is a segment of an infinitely long floating cylinder. Hence, the vessel needs to be slender, i.e. the length of the hull is much larger than the breadth and the draught, for better results. In the traditional strip theory [17], the three-dimensional hydrodynamic problem can be reduced to a set of two-dimensional strips, without interaction between the strips. Total forces can be obtained by integrating cross sectional two-dimensional forces over the ships length (using superposition principle to derive the loads and motions in a sea-state). This means that three dimensional effects are neglected. However, in the high speed theory [18], interaction from the strips upstream is accounted for and the total forces can be obtained by integrating cross sectional two-dimensional forces over the ships length. Then, the ship is assumed to oscillate harmonically with frequency equal to the frequency of encounter wave, not taking into account any hydroelastic effects or transient effects due to initial conditions. Then, using Newtonian mechanics, for each single frequency, the equation of motion for each degree of freedom for an oscillating ship in waves is considered as a linear mass-damper-spring system with frequency dependent coefficients:

$$\sum_{k=1}^{6}[(M_{kj}+A_{kj})\,\ddot{\eta}_k + B_{ij}\,\dot{\eta}_k + C_{kj}\,\eta_k] = F_j\,e^{i\omega t}, \qquad (1)$$
$$k = 1,\dots,6,$$

where M_{kj} denotes the elements of the generalized mass matrix; A_{kj} represents the elements of the added mass matrix; B_{kj} denotes the elements of the linear damping matrix; C_{kj} represents the elements of the stiffness matrix; and finally, F_j are the complex amplitudes of the wave exciting forces and moments, with the physical forces and moments given by the real part of $F_j\,e^{i\omega t}$. The angular frequency of encounter wave is denoted by ω. The surge, sway, heave, roll, pitch and yaw motion amplitudes are represented by $\eta_k \quad (k = 1,\dots,6)$, respectively.

For each single frequency, using the assumptions in strip theory, one can solve a boundary value problem of potential theory [20] and find all the coefficients in (1). For the high-speed formulation [18], the free-surface condition is used to step the solution in the downstream direction. The solution is started assuming that both the velocity potential and its derivative along the longitudinal axes of the vessel are zero at the first strip, counted from the bow.

A. Effect of air cushion

In order to extend the aforementioned results to SES, the effect of air cushion should be considered in the vessel dynamics. The motion of an ordinary catamaran is determined by solving the equations of motion obtained from the principles of conservation of linear and angular momentum. Determining the motions of a SES will in addition require the solution of the continuity equation for the air in the cushions. The governing equations for the cushion pressures are the continuity equation and the equation of state for the air. The rate of change of the mass of air inside each cushion must equal the net mass flux into the cushion. Air is supplied or withdrawn from the cushions by fans or vent valves. By assuming that the changes in volume and pressure occur rapidly, the adiabatic gas law is taken as the equation of state inside the cushion.

Due to compressibility effects of the air retained in the air cushion compartment, the prediction of motions is quite complex. The adopted formulation in the current work is based on a linear formulation; similar formulation is reported in [19]. We assume that the pressure in each air cushion subcompartment is uniform in space. Furthermore, in order to calculate the hydrostatic forces, we approximate the cushion compartments as rectangular boxes. Using the continuity equation for the air cushion, and assuming an adiabatic relation between density and pressure of air, one can study the effect of wave pump into the cushion when ship moves through the waves. Furthermore, one needs to calculate the effect of the bow and stern seals [21].

At this point, we need to emphasize that (1) is not truly a set of differential equations. It is only valid for a single frequency, i.e when the right hand side varies sinusoidally over an infinite interval of time at a single frequency. Furthermore, the coefficients on the left hand side are frequency dependent and they change if the encounter frequency changes. Since the experiments reported in the current paper are carried out in regular waves, we do not seek to find the true differential equations of motion in time domain.[1]

In the current work we practiced using the VEssel RESponse (VERES) program [14], [15], [16] and [28] to compute single frequency equation of motions.[2] We compute the encounter frequency of waves for each speed, and wave condition, beforehand and then, we use VERES to compute the relevant coefficients in the frequency of interest. In other words, we do not include the effect of retardation functions for all the frequencies.

The VERES is a commercial software from SINTEF Ocean AS. [29] that is extensively used by maritime industry for design and analyses of ships. The reader is referred to [14], [15], [16], [28] for an introduction to VERES.

[1]The transformation of the equations in (1) to valid time domain differential equations is studied well in the literature. For details on time domain expression of marine vessels motion reader is refereed to [22], [23], [24], [25], [26], [27].

[2]Unfortunately, due to intellectual property limitations, the numerical values for the model could not be presented in the paper.

III. PROBLEM FORMULATION & CONTROLLER DESIGN

To exactly model the dynamics of the vent valve in the SES, we ran a series computational fluid dynamics simulations and compared the results with step tests on vent-valves actuators in the laboratory [10]. Combining the results in section II and [10], the equation of motion (in single frequency) with control action (in heave z and pitch θ) can be re-expressed as

$$\dot{x}(t) = A_x x(t) + B_u u(t) + G_d d(t) \tag{2}$$

where

$$x = [\dot{z}\ \dot{\theta}\ z\ \theta]^T \tag{3a}$$

$$u = [\Delta A_{L1}\ \Delta A_{L2}]^T \tag{3b}$$

$$d = [d_{F_z}\ d_{F_\theta}]^T \tag{3c}$$

where ΔA_{L1}, ΔA_{L2} are vent velve opening in front and aft respectively (the two vent-valves in front are controlled with ΔA_{L1}, the two vent-valves in aft are controlled with ΔA_{L2}) and $d(t)$ denotes disturbance force and moments of incoming waves. In order to have a two-sided control signal, the leakage area is centered about some mean operating value A_0, while the actual control parameters $[\Delta A_{L1}\ \ \Delta A_{L2}]^T$ represent any deviation in leakage area from A_0. The true leakage area is given by:

$$A_{Li} = A_0 + \Delta A_{Li}. \tag{4}$$

The matrices A_x, B_u, and G_d in (2) are defined in straightforward manner and their values are computed through VERES calculations; see [14], [15], [16], [30].

A. Controller Design Process

The design of the pitch regulator in the current work is restricted with practical limitations. The only motion measurement on board the full scale SES is acceleration measurements provided by two accelerators located at bow and aft. Also the actuators that controls the air valve have a fast but limited response time.[3] Furthermore, the SES is operated with very few number of crew and hence, it is of paramount importance that the designed ride control system is simple, effective, robust, with minimum number of tuning parameters. Keeping these considerations in mind, and after a series of numerical simulation, we decided to use a simple derivative controllers. The choice of derivative controllers is also related to measurement limitation on the real vessel, where the accurate position measurements are not available while the velocities can be computed robustly and with high precision.

[3]The typical encounter wave period for such a vessel is 2.5 seconds. The actuator should have a response time of minimum 3-5 times faster than the encounter wave period to be effective in motion damping.

IV. EXPERIMENTAL RESULTS

The proposed pitch regulator was tested using the model vessel m3219A, designed by UMOE Mandal AS, at the SINTEF Ocean's facilities, see Fig. 3. The performance of the pitch regulator was evaluated under different sea conditions produced by a hydraulic wave maker.

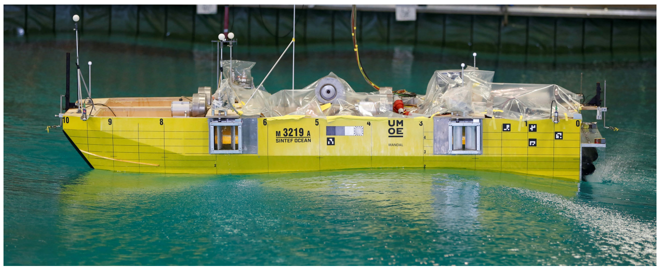

Fig. 3. Model m3219A in SINTEF Ocean's basin; photo courtesy of SINTEF ocean and UMOE Mandal AS.

A. Overview of the scaled model and testing facilities

Model m3219A is a scaled model of a surface effect ship designed by UMOE Mandal AS. It is equipped with four lifting fans, a separate bag fan, and separate fan for chamber division. The model is instrumented with four adjustable vent-valves that can be used to actively control the pressure of each air champer through adjusting of the air outflow. The actuators are controlled by an onboard industrial processor which can communicate with onshore PC through a local area network (LAN). The processor onboard the ship uses a real-time operating system. The motion capture unit (MCU), installed in the SINTEF Ocean's testing facilities, provides Earth-fixed position and orientation of the vessel. The MCU consists of multi-camera system mounted on the high speed rig and a set of markers mounted on the vessel. The cameras emit infrared light and receive the light reflected from the markers on the vessel. To simulate the different sea conditions, a hydraulic wave maker system, that can produce regular and irregular waves with different spectra, was used.

B. Experimental Results

Prior to experimental tests, a series of numerical simulations were carried out in a high fidelity time domain simulator. Through this analysis, it was found that the derivative term provides not only the greatest simplicity, but also the best performance (considering all the practical limitations). Furthermore, although during the experimental test with the scaled model in the towing tank, we had access to measurements of all the states, thanks to the motion-capture equipments, in the full scale, the ship is only equipped with two accelerometers from which one can calculate the pitch rate with good accuracy; see [4]. That being said, in this section we only present the results of the experiments that were carried out with a controller of the following form

$$u = -K_{\dot\theta}\dot\theta, \qquad (5)$$

	peak-to-peak amplitude (H_{p2p})	period (T_p)
wave No. 1	1 (m)	6 (sec)
wave No. 2	1 (m)	7 (sec)
wave No. 3	1.5 (m)	7 (sec)
wave No. 4	1.5 (m)	8 (sec)
wave No. 5	1.5 (m)	9 (sec)

TABLE I

DESCRIPTION OF THE WAVE CONDITIONS USED DURING THE LABORATORY EXPERIMENTS.

where matrix $K_{\dot\theta}$ was optimised during the numerical simulations and further tuned during the experiments for the highest performance.
A control law in form of (5) injects extra damping into the system. The physical implementation of (5) in full scale is done by using two accelerometers located at bow and aft of the vessel.

Figure 4 presents the summary of the performed tests. Effect of active control on pitch motion damping in waves and speed was very promising. In total, five regular wave conditions were tested; see Table I.

The experiment is repeated with and without the active pitch regulator. During the experiments, the ship was connected to a high speed rig (free to pitch and heave) and was pulled at speeds of $30(kn)$ and $40(kn)$. The designed controller is able to reduce the pitch motion (and its accelerations and rates of change) by 50-65 %.
Figure 5, illustrates the time evolution of the ship's pitch motion in 30 (kn) in wave No.5 (i.e. $H_{p2p} = 1.5\ (m)\,\&\,T_p = 9\ (sec)$). The effectiveness of the active pitch control is noticeable with 65% reduction in pitch motion.[4]

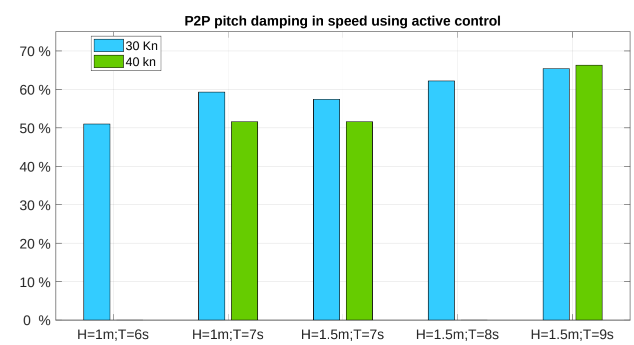

Fig. 4. Summary of experimental tests where the percentage of the pitch motion reduction is presented for different speeds and wave conditions.

V. CONCLUSIONS

This paper presented the results of an active pitch damping system through experimental tests with scaled model of Surface Effect Ship (SES) designed by UMOE Mandal AS.

[4]The results are scaled in the presentation to protect intellectual properties owned by UMOE Mandal AS.

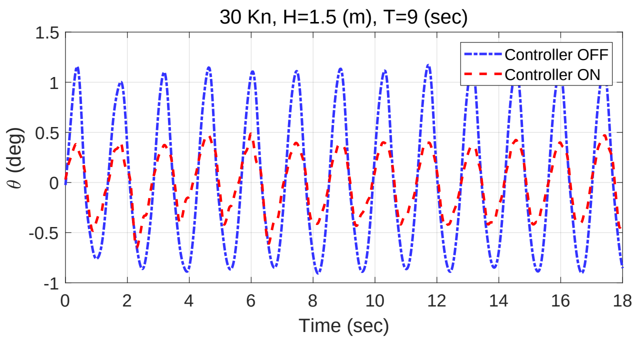

Fig. 5. Effect of active pitch control (30 (kn); $H_{p2p} = 1.5$ (m); and $T_p = 9$ (sec).

The scaled model is of the new innovative air split type which allows active control of the vessel pitch in wave and speed. The proposed methodology was experimentally verified using model m3219A, under simulated sea condition in SINTEF Ocean's towing tank. Future work will include full scale experiments.

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