Design and verification of a sway-yaw control system for Surface Effect Ships using vent valves ⋆

Håkon Teigland * **Vahid Hassani** **,***,[1] **Øyvind Auestad** ****

* *Department of Marine Technology, Norwegian Univ. of Science and Technology, Trondheim, Norway.*

** *Department of Mechanical, Electronics and Chemical Engineering, Oslo Metropolitan University, Oslo, Norway (e-mail: vahid.hassani@oslomet.no).*

*** *Department of Ships and Ocean Structures, SINTEF Ocean, Trondheim, Norway.*

**** *Umoe Mandal AS, Mandal, Vest-Agder, Norway.*

Abstract: For an offshore worker in the oil and gas industry, the helicopter transport is the activity associated with the highest risk. An alternative to helicopter crew transfers is to use Surface Effect Ships (SES) to transport the crew. A SES is a catamaran vessel carried in part by a pressurized air cushion. The pressure is maintained by fans and controlled using vent valves. The benefit of these vessels are the high speed to fuel consumption ratio due to decreased wave resistance. During crew transfer from the SES to the offshore installation, the position of the SES needs to be maintained within a safety region using a Dynamic Positioning (DP) system. By mounting the vent valves on the hull sides, the thrust force coming from the air exiting the vent valves can be used to act as an assistance to the DP system. This would reduce required installation power and operational cost of the DP system. Furthermore, combining the thrust from the vent valves with DP thrusters would give a DP system with a high degree of redundancy since thrust force may be generated from two different physical principles. This paper presents a sway-yaw control system for a SES to demonstrate an assisted system that is actuated purely by vent valve thrust from the pressurized cushion. The developed control system is verified using numerical simulations carried out in a high fidelity simulator.

Keywords: Surface Effect Ship, Pressure Force, Dynamic Positioning.

1. INTRODUCTION

The Norwegian offshore oil and gas industry has a high focus on safety. The main actor, Equinor, aims to be industry leading in safety (Equinor (2019)). However, personnel transport is mainly done by helicopter, despite it being one of the most high risk activities for an offshore worker (Petroleumstilsynet (2018)). An alternative to crew transfers by helicopter is to use Crew Transfer Vessles (CTVs). Among available CTVs, there is the Surface Effect Ship (SES) which has been used, among other things, for crew transfer of service personnel for offshore wind turbines.

A Surface Effect Ship (SES) is a catamaran vessel carried in part by a pressurized air cushion and in part by the two side hulls. The pressurized cushion is created by fans that blow air into the space between the hulls. The cushion is sealed off at the bow by so-called finger skirts and the aft is sealed by multiple lobes or bags, as shown in Fig. 1. The propulsion is typically provided by water jet with vector sleeves and reverser buckets. See e.g. Butler (1985); Hassani et al. (2019); Haukeland et al. (2019a,b); Teigland et al. (2019) for detailed description of SESs.

The main benefit of SESs is the high transit speed made possible due to decreased draft and consequently decreased hydrodynamic resistance. One of the drawbacks of SESs is that they are subject to an undesired effect called the cobblestone effect. The cobblestone effect is a high frequency oscillation in heave that occur at certain encounter

⋆ This work is supported by the MAROFF-2 programme for research, innovation and sustainability within marine and offshore industries (Project No. 282404).

[1] Corresponding Author.

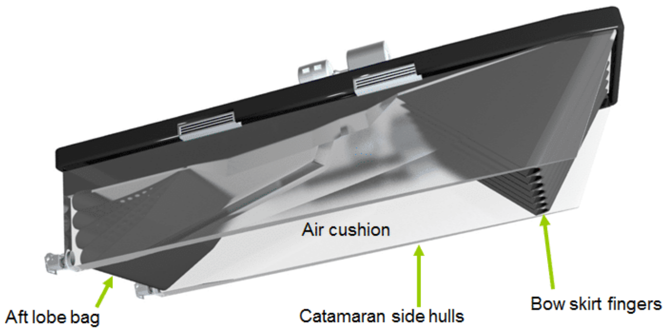

Fig. 1. Surface Effect Ship concept, by courtesy of Umoe Mandal.

frequencies. By controlling the air flow out of the cushion, the pressure in the cushion can be controlled to limit the cobblestone effect (Sørensen and Egeland (1995)). These systems are known as ride control systems (RCS) and they control the air flow by adjusting valves or louvers in vents between the cushion and outside atmosphere.

Umoe Mandal have developed a boarding control system (BCS) (Auestad et al. (2015)) for their crew transfer SESs. The BCS also work by controlling the vent valves, but the control problem is to limit the heave motion of the bow as the vessel presses against a wind mill or other installation. The purpose of limiting the heave motion of the bow is to increase operability and safety.

If these vessels are to be used as CTVs for the offshore oil and gas industry on the Norwegian Continental Shelf (NCS), it is required that the vessel is able to maintain a fixed position and heading during the transfer operation. One possible solution to this is to install a Dynamic Positioning (DP) system. Such a system typically use thrusters and propellers to maintain a desired position and heading. However, by exploiting the pressure difference between the cushion and the atmosphere, vents installed on the hull sides may be used to provide thrust in surge, sway and yaw.

Class societies divide DP systems into classes. DNV GL divide DP systems into DPS1, DPS2 and DPS3 (DNV (2011)), the main difference being the level of redundancy. For oil and gas, the industry standard is DPS2 and DPS3, which both require redundancy in technical design. The main difference between DPS2 and DPS3 is that DPS3 requires that the systems are physically separated so that e.g. flooding and fire in one system will not lead to a fault in the other system.

DP vessels typically use thrusters to control surge, sway and yaw, however, by taking advantage of the aforementioned valves, the thrust produced by these vents may be used for the DP system or as part of a DP system. DPS1 could be achieved using the vent valve thrust alone or in combination with the prime mover. Because the vent valves need to be installed for the RCS, the cost of a such system would be lower than classical DP system.

To achieve DPS2 or DPS3, additional thrusters may be installed. However, since these DP classes require redundancy, the cost of the DP system would likely be significantly less by using the vent valves as part of the DP systems. More importantly, a DP system that is able to produce thrust from two different physical principles has a higher level of redundancy than a DP system that relies only on conventional thrusters.

A final motivation for a vent valve DP system is the operational cost. To obtain desired motion characteristics at low speed, a SES is usually operated around a mean cushion pressure. In practice, this is done by running the fans at a constant speed and varying the mean valve positions (bias) such that each valve has the same opening. Thus, some of the thrust required for the DP system will come at no increase in fuel consumption.

This paper presents a sway-yaw control for a SES using vent valve thrust. The performance of the developed control system is verified with help of numerical simulation using a high fidelity simulation model.

2. SIMULATOR

The simulator used is built in Simulink and is called SESSim, with an overall configuration as shown in Fig. 2. The hydrodynamic coefficients of the vessel have been calculated using SINTEF's ShipX software and verification of the SESSim simulator has been done through experimental testing at SINTEF Ocean's towing tank. In the following section, the models used in the process plant and the environmental forces are explained.

2.1 Environmental forces

SESSim is able to simulate current, regular waves, and irregular waves that is generated from various spectra. When simulating waves both first order and second order forces are calculated and sent to the process plant. From the generated waves, SESSim calculates the first order forces and the second order drift forces by using results obtained from ShipX.

2.2 SES process plant

SES Dynamics
For RCSs, it is common to use linearized pressure models when modelling the cushion dynamics. However, RCSs typically operate close to an equilibrium pressure where linearization is an acceptable assumption. This is not the

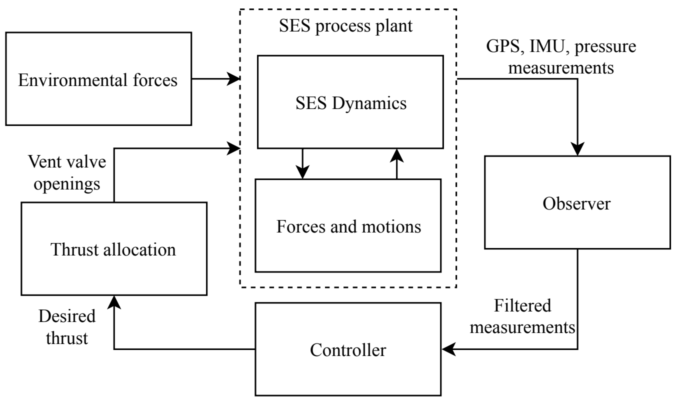

Fig. 2. Overview of SESSim.

case for the sway-yaw control since the pressure may vary a lot due to the first order wave-body interaction. In SESSim, the following nonlinear cushion dynamics are are used in the process plant.

$$\dot{p} = \frac{\gamma\left(p_a + p\right)}{V_c}\left(\left(\frac{p_a + p_0}{p_a + p}\right)^{\frac{1}{\gamma}}\left(Q_{in} - Q_{out}\right) - \dot{V}_c\right) \tag{1}$$

where

$$\begin{aligned} p &= \text{Excess cushion pressure} \\ p_a &= \text{Atmospheric pressure} \\ p_0 &= \text{Equilibrium excess cushion pressure} \\ \gamma &= \text{Ratio of specific heats for air} \\ V_c &= \text{Cushion volume} \\ Q_{in} &= \text{Air flow in} \\ Q_{out} &= \text{Air flow out} \end{aligned}$$

In (1), the air flow from the fans, Q_{in}, is nonlinear and taken from actual fan characteristics. The air flow out Q_{out} results from the passive leakage area and active leakage area. The active leakage is due to the commanded valve positions and the passive leakage is all other leakage. with A_L being the total leakage area, the air flow out is

$$Q_{out} = c_n A_L \sqrt{\frac{2p}{\rho}} \tag{2}$$

where c_n is an orifice coefficient, see e.g. Faltinsen (2012). The cushion dynamics is coupled to the heave and pitch motion of the SES through the changing cushion volume

$$\dot{V}_c = A_c\left(x_{cp}\dot{\theta} - \dot{z} - \dot{\zeta}\right) \tag{3}$$

where

$$\begin{aligned} x_{cp} &= \text{Longitudinal distance between cushion} \\ &\quad\ \text{pressure center and vessel CG} \\ \dot{\theta} &= \text{Angular pitch rate} \\ \dot{z} &= \text{Heave velocity} \\ \dot{\zeta} &= \text{Wave profile rate} \end{aligned}$$

Forces and motions

The six DOF vessel model is implemented as

$$\dot{\eta} = \begin{pmatrix} \dot{p} \\ \dot{\Theta} \end{pmatrix} = J(\Theta)\nu \tag{4a}$$

$$\left(M + A_\infty\right)\dot{\nu} + \left.\frac{\partial D}{\partial \nu}\right|_0 \nu + D\nu|\nu| + \mu + G\eta = \tau_{env} + \tau_c \tag{4b}$$

$$\dot{x} = A_r x + B_r \delta\nu \tag{4c}$$

$$\mu = C_r x + D_r \delta\nu \tag{4d}$$

where

$$\begin{aligned} p &= \text{Position in the North-East-Down (NED) frame} \\ \Theta &= \text{Orientation in the NED frame} \\ \nu &= \text{Body fixed translational and angular velocities} \\ J(\Theta) &= \text{Transformation matrix relating } \eta \text{ and } \nu \\ M &= \text{Rigid body mass matrix} \\ A_\infty &= \text{Added mass matrix at infinite frequency} \\ D &= \text{Nonlinear damping matrix} \\ G &= \text{Stiffness matrix} \\ \tau_{env} &= \text{Environmental forces} \\ \tau_c &= \text{Air cushion forces} \end{aligned}$$

μ in (4) accounts for the potential damping i.e. the fluid memory effects.

3. SWAY-YAW CONTROL SYSTEM

3.1 Control plant model

For the purpose of control, the equations of motion is reduced to a sway-yaw two DOF system. To this end, let η^p contain the sway and yaw coordinates of the vessel in a reference parallel frame (Fig. 3), such that

$$\eta^p = \begin{pmatrix} -\sin\psi_r & \cos\psi_r & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} x \\ y \\ \psi \end{pmatrix} \tag{5}$$

where (x, y, ψ) is the position and heading of the vessel in the NED frame.

The control plant model is a linearized 2 DOF DP model (Fossen (2011))

$$M\dot{\nu} = -D\nu + \tau + \tau_{env} \tag{6}$$

$$\dot{\eta}^p = \nu \tag{7}$$

where $M = M^\top > 0$ is the sway-yaw rigid body mass and added mass matrix and $D = D^\top > 0$ is the sway-yaw linearized damping matrix.

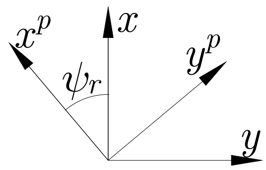

Fig. 3. Frames used for the control plant model.

3.2 Observer

The aim of the sway-yaw controller is to stop the vessel from moving in sway and yaw, when it is excited by environmental forces such as waves, wind and current. In full scale, the position and orientation of the vessel is measured by GPS and compass while the translational acceleration and the angular velocities of the vessel is measured by an IMU. During the model testing, a camera based positioning system is used to provide high accuracy measurement of the positions. Furthermore, accelerometers and gyros are used to measure models acceleration and angular rates. In DP systems,using the above-mentioned measurements, observers are used to estimate low frequency positions and velocities of the vessel.

The wave forces are typically divided into first order forces and higher order forces. In order to limit the first order motions of the vessel one typically requires large amounts of thrust force. Therefore, the focus here is to compensate for the slowly-varying forces and mean force. To this end a notch filter is used to eliminate motions around the dominating wave frequency. An ordinary notch filter may be formulated as

$$H(s) = \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \tag{8}$$

where ω_0 is the frequency to be rejected and the Q-factor determines how narrow the notch is, such that increasing the Q-factor leads to a narrower notch. To determine ω_0, a frequency estimator is used.

The frequency estimator works by measuring the time between zero up-crossings of the high-passed sway velocity v_{hp}, noting that the sway velocity is obtained by integration of the sway acceleration. The estimated frequency $\hat{\omega}_0$ that is sent to the notch filter is the mean of the n_z most recent zero up-crossing measurements.

$$\frac{2\pi}{\hat{\omega}_0} = \hat{T} = \frac{T_y(k-n_z-1)+\cdots+T_y(k-1)+T_y(k)}{n_z} \tag{9}$$

In calm sea, it is unnecessary to use the notch filter, so it is switched off if the variance of v_{hp} drops below a certain level.

The vessel is assumed to be operating in sea states within a range of wave periods $T \in [T_l, T_h]$. The Q-factor is tuned to T_l and T_h to determine a corresponding Q_l and Q_h, respectively. Note that the subscripts of Q_l and Q_h refers to the low and high limit of the wave period and therefore Q_l may be higher than Q_h. A linear relation between the Q-factor and the wave period is used such that the Q-factor for an arbitrary estimated wave period $\hat{T}$ is

$$Q = \frac{\hat{T}-T_l}{T_h-T_l}\left(Q_h - Q_l\right) + Q_l \tag{10}$$

3.3 Controller

A PID controller is used to control the sway and yaw motion of the SES and the control law is written as

$$\tau = -K_p\tilde{\eta}^p - K_d\nu - K_i z \tag{11}$$

where

$$\tilde{\eta}^p = \eta^p - \eta^p_r \quad \text{and} \quad z = \int \tilde{\eta}^p dt$$

and η^p_r is a constant desired reference for η^p.

To avoid integral windup, $\|z\|_\infty$ is non-increasing if any of the vent valves are fully open. The closed loop error dynamics of the unperturbed system become

$$\begin{aligned} M\dot{\nu} &= -\left(D+K_d\right)\nu - K_p\tilde{\eta}^p - K_i z \\ \dot{\tilde{\eta}}^p &= \nu \\ \dot{z} &= \tilde{\eta}^p \end{aligned} \tag{12}$$

Stability of (12) is shown by considering z as input to the system. The origin of the unforced system ($z=0$) is shown to be stable by considering the positive definite Lyapunov function

$$V = \frac{1}{2}\left(\nu^\top M\nu + \tilde{\eta}^{p^\top} K_p\tilde{\eta}^p\right) \tag{13}$$

Taking the rate of V along the solution

$$\dot{V} = -\nu^\top\left(D+K_d\right)\nu \leq 0 \tag{14}$$

for $K_d = K_d^\top > 0$. $\dot{V}$ is negative semi-definite and the only solution that can stay in the set $\{(\nu,\tilde{\eta}^p) \in \mathbb{R}^4 | \dot{V}=0\}$ is the trivial solution $(\nu(t),\tilde{\eta}^p(t)) = 0$. Thus, according to the Krasovskii-LaSalle theorem, the unforced system is globally asymptotically stable (GAS). For linear systems, GAS implies global exponential stability (GES) and, as proved by Khalil (2001), an unforced system that is globally Lipschitz and GES at the origin is input-to-state stable. Thus, (12) is input-to-state stable with z as input and z is bounded due to the anti-windup mechanism.

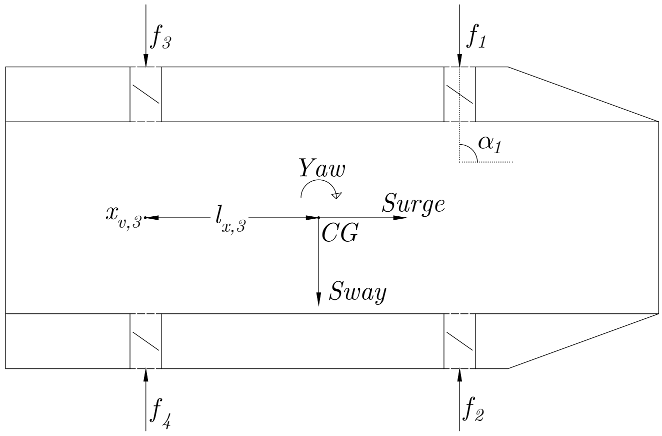

Fig. 4. Top view of SES with vent configuration as in the studied case.

3.4 Thrust allocation

Assuming steady state conditions, the thrust force from an incompressible fluid exiting a vent valve is

$$F = \frac{d}{dt}(ma) = \rho Q_{out} v_{out} \tag{15}$$

To determine v_{out}, the continuity equation is used such that

$$v_{out} = \frac{Q_{out}}{A_v} \tag{16}$$

where A_v is the vent area. Inserting into (15) gives the thrust force

$$F = \frac{2c_n^2}{A_v} pA_L^2 \tag{17}$$

Now, let f be a vector containing the thrust force from each valve. When the vents are located on the starboard and port side, as shown in Fig. 4, the force and moment in sway and yaw from vent k is

$$\begin{aligned} \tau &= -f_k \mathrm{sgn}\left(\sin\alpha_k\right)\begin{pmatrix}1 \\ x^b_{v,k}\end{pmatrix} \\ &= -\frac{2c_n^2 p}{A_v} A_{L,k}\mathrm{sgn}\left(\sin\alpha_k\right)\begin{pmatrix}1 \\ x^b_{v,k}\end{pmatrix} \end{aligned} \tag{18}$$

where α_k is the angle of the vent k in the horizontal plane, as defined in Fig. 4, and x^b_k is the longitudinal coordinate of vent k, measured from a body fixed coordinate system at the center of gravity.

For multiple vents,

$$\tau = Tf = TKu \tag{19}$$

where

$$K = \frac{2c_n^2 p}{A_v} \quad \text{and} \quad u = A_L^{\circ 2}$$

and T is the thrust configuration matrix which, for the studied case, simplifies to

$$T = \begin{pmatrix} 1 & -1 & 1 & -1 \\ l_{x,1} & -l_{x,1} & -l_{x,3} & l_{x,3} \end{pmatrix}$$

noting that $l_{x,1} = l_{x,2}$ and $l_{x,3} = l_{x,4}$.

To solve (19) for the input u one needs to find the inverse of T, but T is non-square. Fossen (2011) use Lagrange multipliers to show that one solution that satisfies 19 and minimizes the input is $f = T^{\dagger}\tau$, where $T^{\dagger}$ is the Moore-Penrose pseudo-inverse of T, i.e.

$$T^{\dagger} = T^{\top}\left(TT^{\top}\right)^{-1} \tag{20}$$

Consequently, u is found by

$$u = K^{-1}T^{\dagger}\tau \tag{21}$$

Solving the thrust allocation problem by (21) may require unbounded inputs. There are several ways of solving this issue. Since the thrust force from each vent is proportional to the excess cushion pressure and the pressure drop is proportional to the vent leakage area, it is advantageous to keep the leakage area as low as possible to ensure maximum available vent force. Also, the leakage area cannot be negative. Taking these limitations into account, it can be argued that the optimal solution is to open only two vents at any time, while the other two is kept closed. This is the solution used here.

4. NUMERICAL SIMULATION

The sway-yaw control has been tested in SESSim in a range of environmental conditions. An example with the vessel exposed to beam sea regular waves, with a period of 6s is shown in Figs. 5 and 6. From Fig. 5 it is seen that the observer is able to filter most of the wave frequency and that the controller is able to compensate for the mean wave drift force and prevent the vessel from drifting in sway and heading. Fig. 6 shows the commanded valve angles in percentage, where 0% and 100% corresponds to 0° and 90° valve angle, respectively. The thrust allocation commands two valves to be open at any time, but to prevent chattering, the commanded valve openings are passed through a lowpass filter which may cause all four valves to be open.

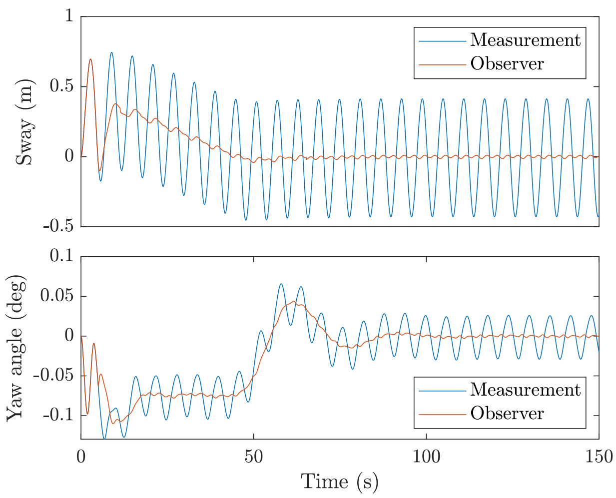

Fig. 5. Sway and yaw motion in beam sea regular waves with amplitude 0.6m

To determine the performance of the control system in a range of sea states, the capability of the system has been tested in simulation with incoming waves at every 10° from 30° to 150°. The capability is defined at the wave height where the SES starts to drift off position. Fig. 9 shows the capability in regular waves for three different wave periods

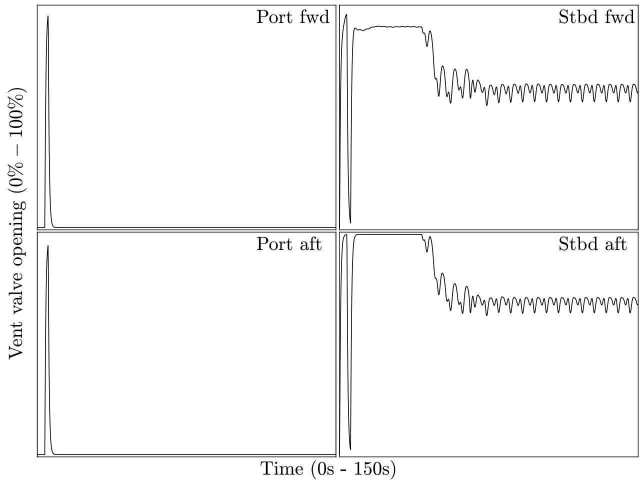

Fig. 6. Vent valve openings in beam sea regular waves with amplitude 0.6m

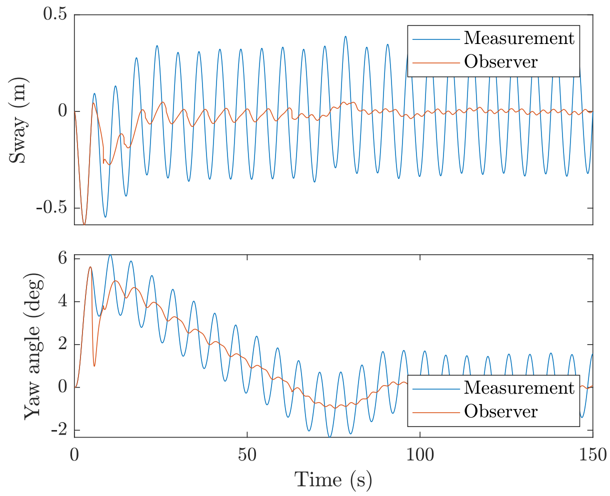

Fig. 7. Sway and yaw motion in 45° regular waves with amplitude 0.6m

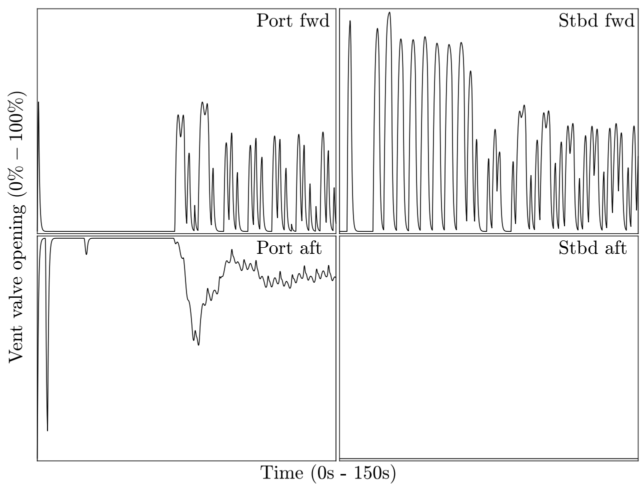

Fig. 8. Vent valve openings in 45° regular waves with amplitude 0.6m

$T_l < T_1 < T_2 < T_3 < T_h$, where T_l and T_h are the lower and upper design wave periods, respectively.

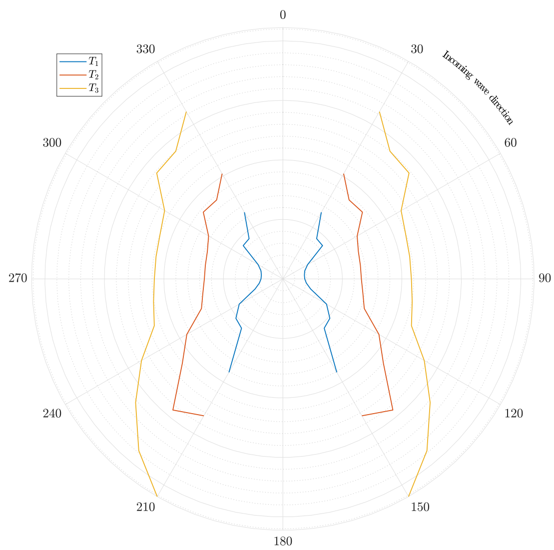

Fig. 9. Capability of vent sway yaw control system for three different wave periods.

5. CONCLUSION

This article presented a new sway-yaw controller for surface effect ships. The controller uses the thrust generated as a results of air outflow from the pressurized cushion. The numerical simulations showed that the proposed controller can exploit the generated thrust from vent valves to control the motions of a SES. Model test experiments with a scaled model of SES are planned for near future for further validation of the presented concept.

REFERENCES

Auestad, Ø.F., Gravdahl, J.T., Perez, T., Sørensen, A.J., and Espeland, T.H. (2015). Boarding control system for improved accessibility to offshore wind turbines: Full-scale testing. *Control Engineering Practice*, 45, 207–218. doi:10.1016/j.conengprac.2015.09.016.

Butler, E.A. (1985). The surface effect ship. *Naval Engineers Journal*, 97(2), 200–253. doi:10.1111/j.1559-3584.1985.tb03399.x.

DNV (2011). Dnv ship rules pt.6 ch.7 - dynamic positioning systems. Technical report, DNV.

Equinor (2019). Helse, sikkerhet og sikring. `https://www.equinor.com/no/how-and-why/health--safety-and-security.html`. Accessed: 2019-05-20.

Faltinsen, O.M. (2012). *Hydrodynamics of High-Speed Marine Vehicles*. CAMBRIDGE UNIV PR.

Fossen, T.I. (2011). *Handbook of Marine Craft Hydrodynamics and Motion Control*. Wiley-Blackwell.

Hassani, V., Fjellvang, S., and Auestad, .F. (2019). Adaptive boarding control system in surface effect ships. In *Proc. of the 17th European Control Conference (ECC 2019)*. Naples, Italy.

Haukeland, O.M., Hassani, V., and Auestad, .F. (2019a). Surface effect ship with four air cushions, part i: Dynamic modeling and simulation. In *Proc. of the 12th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles (CAMS 2019)*. Daejeon, South Korea.

Haukeland, O.M., Hassani, V., and Auestad, .F. (2019b). Surface effect ship with four air cushions, part ii: Roll and pitch damping. In *Proc. of the 12th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles (CAMS 2019)*. Daejeon, South Korea.

Khalil, H.K. (2001). *Nonlinear Systems*. PEARSON.

Petroleumstilsynet (2018). Risikonivåi petroleumsvirksomheten. Technical report, Petroleumstilsynet.

Sørensen, A. and Egeland, O. (1995). Design of ride control system for surface effect ships using dissipative control. *Automatica*, 31(2), 183–199. doi:10.1016/0005-1098(94)00090-6.

Teigland, H., Hassani, V., and Auestad, .F. (2019). Vent valve thrust force for surface effect ships. In *Proc. of the 12th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles (CAMS 2019)*. Daejeon, South Korea.

Appendix A. A NOTE ON THRUST ALLOCATION

In the case that the vent valves are combined with thrusters to obtain DPS2 or DPS3, the thrust allocation may be formulated as

$$\tau = TWf \tag{A.1}$$

where W is a weight matrix which is used to weight the various thrusters and vent valves and may be dependent on cushion pressure. As an example, consider a DP system on a SES with one vent valve on the port side and one vent valve on the starboard side, and additional thrusters. The sway is controlled in part by the vent valves and in part by the thrusters. The operator wish to stay at a bias of 50%, i.e. both valves should have a 50% opening. The thrust allocation algorithm might be designed such that the vent valves are used as long as the total airflow out corresponds to the 50% bias, while additional thrust is provided by the thrusters. This way, the fuel used to run the fans is used not only to maintain the correct cushion pressure, but also to provide thrust.