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***Abstract*—For controlling Unmanned Underwater Vehicles (UUVs) in deep water, Proportional-Integral-Derivative (PID) control has previously been proposed. Disturbances due to waves are minimal at high depths, so PID provides an acceptable level of control for performing tasks such as station-keeping. In shallow water, disturbances from waves are considerably larger and thus station-keeping performance naturally degrades. By means of simulation, this letter details the performance of PID control when station keeping in a typical shallow-wave operating environment, such as that encountered during inspection of marine renewable energy devices. Using real wave data, a maximum positional error of 0.635m in the x-direction and 0.537m in the z-direction at a depth of 15 m is seen whilst subjected to a wave train with a significant wave height of 5.404m. Furthermore, estimates of likely displacements of a Remotely Operated Vehicle (ROV) are given for a variety of significant wave heights while operating at various depths. Our analysis provides a range of operational conditions within which hydrodynamic disturbances don't preclude employment of UUVs and identify the conditions where PID-controlled station keeping becomes impractical and unsafe.**

***Index Terms*—station keeping, PID, ROV, underwater robotics, shallow water, thruster dynamics.**

I. Introduction

Offshore industries are becoming increasingly interested in operating with a higher degree of autonomy than currently available. The offshore energy and marine renewable energy sectors, in particular, need to perform systematic maintenance operations and accurate sensor deployment in order to improve structure survivability and reduce overall running costs of the plant. Unmanned Underwater Vehicles (UUVs) have previously been deployed for inspection and maintenance, but are often not equipped for undertaking more complex missions especially close to the sea surface. The task of operating in perturbed sea states remains largely unsolved due to the difficulty of enabling safe station keeping (holding a stationary position) of the vehicle when operating in proximity with submerged structures. This prevents any systematic maintenance operation of offshore structures as well as accurate surveillance of any submerged environments [1]–[3].

This letter aims to investigate the use of one of the most classical feedback control methods, Proportional Integral-Derivative (PID) control, for station keeping in these shallow water environments. The dynamic response of a vehicle subject to varying wave disturbances is tested via numerical simulations. The performance of the controller is evaluated when the vehicle is subjected to a typical, realistic wave field by monitoring the positional error in the surge, x, and heave, z, directions. Upon evaluation, results confirm that utilising PID control for station keeping yields excessive positional error outside of a narrow band of wave disturbances and operational depth. Therefore, an alternative control method is required to improve the reliability and accuracy of UUV station keeping to assist in the continued drive for fully automated operation and management of offshore structures.

This work was supported by the Engineering and Physical Sciences Research Council [grant number EP/R513209/1], the Research Council United Kingdom (RCUK) and the ORCA Hub.

II. Modelling

The simulated scenario entails a vehicle located at varying depths D within a water column of depth $D_w = 50m$ and attempting to station keep whilst subjected to an oncoming wave train of varying significant height H_s. The wave field simulated in this work was taken from [4] and is representative of a typical wave field seen at the National Northwest Marine Renewable Energy Center (NNMREC) North Energy Test Site (NETS) and correlates with data collected by a buoy deployed in the area; the composition is formed utilising the fundamentals of Airy Wave Theory [5], [6]. The particle velocities and accelerations at the vehicle location are then deduced using widely detailed wave theory [7] and input as a disturbance to the vehicle dynamics, discussed below.

The vehicle modelled in this work is the SeaBotix vLBV300 Remotely Operated Vehicle (ROV) [8], a typical type of underwater vehicle which is controlled by a pilot; in this work the vehicle is controlled autonomously. Only the surge and heave motions are considered as this letter aims to provide evidence for the requirement of more advanced control methodologies. Following the methodology outlined in [9], the vehicle is modelled as a rigid body with 2DOF whilst assuming the vehicle is neutrally buoyant and neglecting the influence of the Coriolis effect. The dynamic equation can then be simplified and expanded to give:

$$m_d \dot{v}_a + m_a \dot{v}_r - \frac{1}{2}\rho_f A_i C_D v_r |v_r| = T \qquad (1)$$

where m_d and m_a are the dry and added mass terms respectively, $v_a = (v_{ax}, v_{ay})$ and $v_r = (v_{rx}, v_{ry})$ are the absolute and relative velocity of the vehicle with respect to the water,

TABLE I

THRUSTER MODEL PARAMETERS FOR THE SIMULATIONS UNDERTAKEN IN SECTION III

Parameter	Nomenclature	Value
Thrust Co-efficient	K_T	0.464
Propeller Diameter	D	0.1 m
Time Step	Δt	0.2 s
Motor Time Constant	T_m	0.1 s
Drag Coeffcient, x	$C_{D,x}$	0.84
Drag Coeffcient, z	$C_{D,z}$	1.06
Added Mass, x	$m_{a,x}$	8.1 kg
Added Mass, z	$m_{a,z}$	36.7 kg

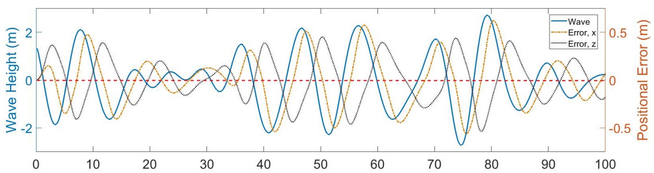

Fig. 1. A 100s segment of the wave field generated using the parameters detailed in [4] and the displacement of the vehicle caused by this wave field when the vehicle is attempting to remain stationary at a depth of 15m.

ρ_f represents the density of the fluid (in this case sea water), A_i represents the area of the incident side to the flow, C_D represents the drag coefficient and T represents the thrust produced by the propellers.

To accurately describe the behaviour of the vehicle and the controller performance, a thruster model was utilised based on [9], [10] which considers the Bilinear Thruster Model in conjunction with a reduction term, approximating the propeller angular velocity as a first order system. This reduction term accounts for the effects of the fluid flow through the propeller; this model is also utilised in [11], [12] and reads:

$$T = K_T \rho_f n|n|D^4 - \frac{1}{3} v_f \rho_f D^3 |n| \tag{2}$$

where K_t, n, v_f and D respectively represent a thrust constant, the propeller angular velocity, the fluid speed into the propeller disk and the propeller disk diameter.

III. RESULTS

Simulations were performed over a $240s$ temporal segment and the magnitude of the positional error was recorded. An example of the time history of the vehicle response while performing station-keeping at $D = 15m$ (i.e. for $D/D_w = 0.3$) and subject to a wave train with a significant wave height of $H_s = 5.404m$ (i.e. for $H_s/L = 7.72$) is presented in Fig. 1. From this simulation, the maximum positional error witnessed was $0.635m$ in the x-direction and $0.537m$ in the z-direction.

A series of test cases were performed using the same wave train but for $0.075 < D/D_w < 0.9$ and $0.25 < H_s/L < 3$, where $L = 0.7m$ represents the reference dimension of the vehicle. Maximum positional error in surge and heave are reported in Fig. 2 and 3 and it is observed that for $H_s \approx 3L$ then the positional error approaches $0.4m$ at low depth. Fig. 2-3 highlight the existence of a region of D/D_w and H_s/L values where the profile of error displacement shows a markedly non-linear trend with a steep gradient.

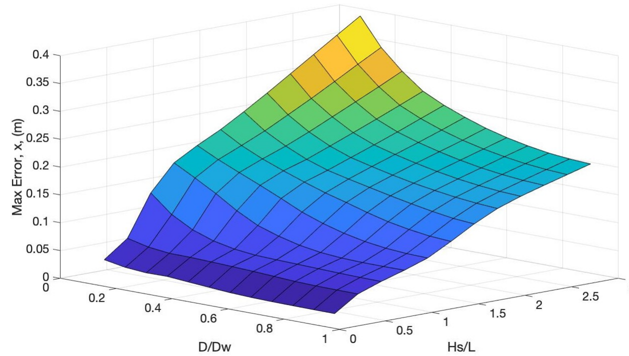

Fig. 2. Maximum error in the surge, x, direction when subject to the wave field in Fig. 1 over a range of Hs/L and D/Dw.

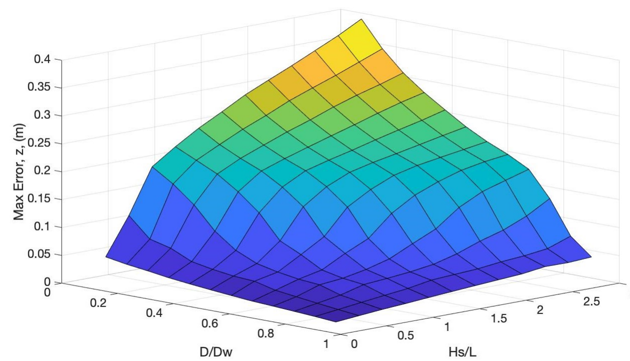

Fig. 3. Maximum error in the heave, z, direction when subject to the wave field in Fig. 1 over a range of Hs/L and D/Dw.

IV. DISCUSSIONS & CONCLUSIONS

If the positional error shown in Fig. 1-3 is considered, the results show that in a typical shallow water environment the level of control offered by PID is unacceptable. All cases operating near the free surface correlate to an increase in positional error as the effects from the waves are increased significantly. Similarly, if the depth is held constant and the wave height is increased, the positional error increases for the same reason. For missions which involve precise manipulation or inspection of fine-scale structural elements, the positional error estimated through these simulations is too large and therefore using PID control is unsuitable.

For this reason, an alternative more advanced control method is required which can offer higher performance; non-linear model-based PID has the potential to substantially improve performance without increasing the required computation power too drastically [13]. Furthermore, the use of Model Predictive Control (MPC) is envisioned; the preliminary work of [4] will be extended to include additional DOF and subsequently a controller will be developed and tested at the FloWave facility at the University of Edinburgh [14].

An alternative solution is to develop a suitable manipulator to constrain the motion of the vehicle when subjected to wave and current disturbances. Unlike the MPC approach, this would rely on the capability of hardware to simply withstand the forces exerted on the vehicle, but would require a structure to grip onto. Hence, the MPC approach is preferred.

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