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A System Identification Experiment for an Underwater Vehicle

潜水艇のシステム同定実験

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1. Introduction

In order to design the autopilot system of an underwater vehicle a recommended first step is the analysis of a mathematical model which represents its relevant dynamical characteristics.

Such a model can be derived from the maneuvering equations whose coefficients are functions of hydrodynamical derivatives. Conventional methods for estimating these derivatives include captive model tests (using planar motion mechanisms, for example), theoretical predictions together with trial and error adjustments. These methods are usually costly and time consuming, and the results obtained may lead to an incorrect model as soon as the vehicle configuration is changed by the addition of a different equipment (a camera, for example).

An alternative approach is the use of system identification techniques applied to free model tests. It is a more direct and concise method and is relatively economical in tank time.

System identification (S.I.) has been applied to the analysis of marine and oceanic systems such as wave spectrum [1], ship steering [2] [3], seakeeping of offshore structures [4] [5] and submersible dynamics [6] [7] [8]. Due to similarities to the submersible case, it is also useful to mention the application of system identification to aircraft dynamics [9] [10].

In this paper, are presented some results obtained in a tank test carried out with the submersible Pteroa-150 [11]. This is one of the first steps in a process to establish the use of S.I. methods for research on dynamics and control of submersibles in the Institute of Industrial Science of the University of Tokyo [12].

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2. Some Aspects of the Application Tested

In a system identification experiment, the vehicle is excited with prescribed movements of a control surface or propeller during a free running test. The corresponding motions of the vehicle are measured. Based on these predetermined inputs and measured outputs, a mathemathical model is built such as to respond as the vehicle considered does.

The transfer function representation was adopted for the calculations in the first experiment. If we assume a linear model for the vehicle equations of motion, it is straightforward the derivation of a transfer function for each degree of freedom considered. For example, using the set of equations based on stability derivatives [13], it follows

$$[(m'-X'_{\dot{u}})s-X'_{u}]u'-[X'_{\dot{\omega}}s+X'_{\omega}]\omega'-$$
$$[X'_{\dot{q}}s^2+X'_{q}s+X'_{\theta}]\theta=X'_{\delta e}\delta_e$$
$$[-Z'_{\dot{u}}s-Z'_{u}]u'+[(m'-Z'_{\dot{\omega}})s-Z'_{\omega}]\omega'-$$
$$[Z'_{q\cdot}s^2+(Z'_{q}+m')s+Z'_{\theta}]\theta=Z'_{\delta e}\delta e$$
$$[-M'_{\dot{u}}s-M'_{u}]u'-[M'_{\dot{\omega}}s+M'_{\omega}]\omega'+$$
$$[(I'_{y}-M'_{\dot{q}})s^2-M'_{q}s-M'_{\theta}]\theta=M'_{\delta e}\delta e \qquad (2.1)$$

where, "s" is the Laplace variable. m and I_y are the mass and inertia moment related to the y-axis (see figure 1). M_i, X_i, Z_i are the stability derivatives related surge, heave and pitch motions, i.e. i=u, ω, q, θ. The index' indicates adimensionalization of variables and coefficients.

The transfer functions u' (s)/δ_e (s) $\omega'(s)/\delta_e$ (s) and $\theta(s)/\delta_e$ (s), are obtained through the application of the Cramer's rule to the above set of equations.

For use in digital control applications, we apply the z-transform in order to obtain transfer functions in the form:

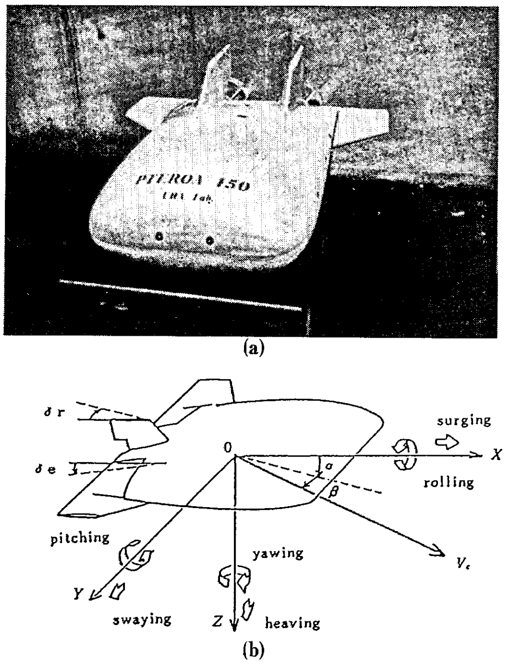


Fig. 1. (a) The "Pteroa-150" Vehicle, (b) Coordinate System

$$G(z^{-1})=z^{-k}\frac{(b_1+b_2z^{-1}+\ldots+b_{nb}z^{-nb+1})}{1+a_1z^{-1}+a_2z^{-2}+\ldots a_{na}z^{-na}} \quad (2.2)$$

Or, equivalently,

$$A(z^{-1})y(t)=z^{-k}B(z^{-1})u(t) \quad (2.3)$$

where,

$$A(z^{-1})=1+a_1z^{-1}+a_2z^{-2}+\ldots+a_{na}z^{-na} \quad (2.4)$$
$$B(z^{-1})=b_1+b_2z^{-2}+\ldots b_{nb}z^{-nb+1}$$

k is the delay from the input to the output.
u(t) is the input variable.
y(t) is the output variable.

The model assumed in this paper uses the representation above summed to an additional unmeasurable disturbance, i.e

$$y(t)=z^{-k}\frac{B(z^{-1})}{A(z^{-1})}u(t)+\frac{1}{A(z^{-1})}v(t) \quad (2.5)$$

where, v(t) is a gaussian white-noise.

Applying the least-squares method, the coefficients of $A(z^{-1})$ and $B(z^{-1})$ are estimated so that the loss function V is minimized [14], where

$$V(\theta)=\frac{1}{N}\sum^{N}\alpha_t[y(t)-\theta(t)\phi(t)]^2$$

$$\theta(t)=[a_1a_2\ldots a_{na}\ b_1b_2\ldots b_{nb}] \quad (2.6)$$
$$\phi(t)=[y(t-1)\ldots y(t-na)u(t-k)u(t-k-1)\ldots u(t-k+n_b+1)]$$

$\alpha(t)$=is a factor that weights different measures

That is, V is a loss function that incorporates the square of the estimation errors.

An important aspect of system identification experiments is the choice of the input signals. Significant simplifications in computations are obtained through the use of special types of signals, e.g., impulse functions, step functions, sinusoidal signals, white-noise, pseudo-random binary-sequences (PRBS), etc. The selection criteria are related to the estimation technique used and with practical limitations in the experiments. In the case of submersible vehicles, impulse functions, step functions, sinusoidal signals and PRBS have been applied already.

For the kind of estimation algorithm used in our experiment, a signal that excites all degrees of freedom selected and all combinations of parameters is ideal. This allied to the fact that the signals are originated from a digital computer suggest the use of the PRBS. But, the use of such a signal has showed problems due to large excursions imposed to the vehicle during the trials [6]. Another option for applying the PRBS is the insertion of it through an ordered depth to the controller instead of the direct command in open-loop to the actuators [7]. We have adopted this strategy in our experiment.

3. Experimental Procedures

The experiment was carried out in the facilities of the Ship Research Institute (S.R.I.) at Mitaka, Japan, using the vehicle "Pteroa-150" developed by the I.I.S.

Only motions in the longitudinal plane were considered, i.e. surge, heave and pitch motions. They were excited by elevator deflections.

Due to the lateral instability of the vehicle, the control of the roll motion was necessary during the experiment. It was performed by using opposite deflections for the right and left elevators. Thus, the total elevator angle in each side was the sum of angles imposed by the pitch and roll control. The input signal used for the calculations was the mean value between both deflections at each instant.

Since no measurement of the angle in each elevator was possible to be performed we have considered the command from the control algorithm as the input signal. The dynamics of the actuators was implicit to the transfer functions.

The system identification algorithms used are included in the pack "Mathlab", and the calculations were performed in a Machintosh computer.

4. Results

Figure 2 shows the input and output signals obtained in a run included in the experiment. Data were sampled at 2.5 hz by the onboard acquisition system. As can be observed, the signals from accelerometers were too noisy. This was a result of the absence of low-pass filters. Moreover, these data are also unreliable for the precision provided by the accelerometers, i.e. 0.03 g. The same problem has not occured in the case of signals from the pitch inclinometer and rate-gyro, despite the absence of low-pass filters. In a comparison of the pitch angles obtained through the integration of the pitch rate from the rategyro, and those ones provided by the inclinometer a good agreement was observed.

Figure 3 presents the results of validation tests for the pitch motion with fresh data not used for the estimations. Thus, there is a comparison between the output from the model and the real one from the experiment. All the transfer functions tested exhibit responses close to those ones from the vehicle.

The results in figure 4 are related to the depth rate which was calculated numerically from the measured depth. The estimated transfer functions are "tf1" (na=2, nb=2, k=1), "tf2" (na=5, nb=2, k=1), "tf3" (na=8, nb=4, k=3), and "tf4" (na=8, nb=5, k=2).

The data from a first run were used for the estimations, while a second run was used as a validation test.

The first transfer function exhibited a poor matching in the test, while the best results were obtained from "tf3" and "tf4". In this case, the simulated outputs are identical. Taking into account the estimated first coefficient of "tf4" and the corresponding standard deviation, we can conclude that a third order delay (k=3) is a natural choice. A more simple transfer function can be tried as shown by the validation for "tf2", with a reasonable matching with the fresh data.

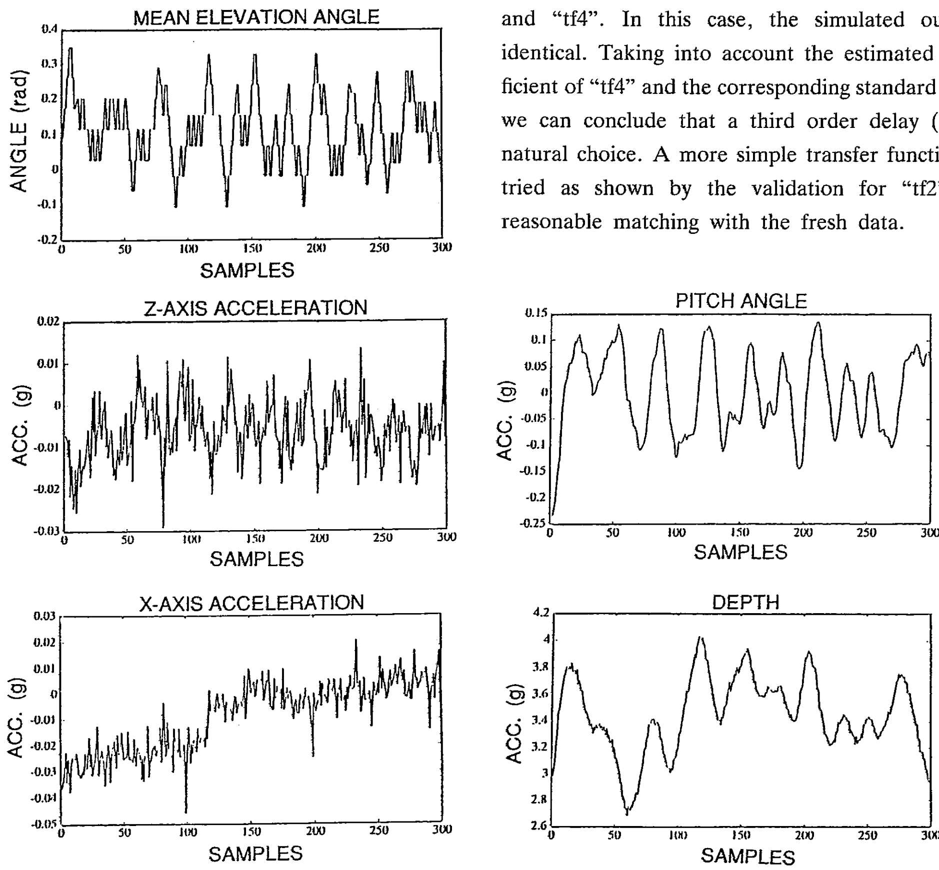
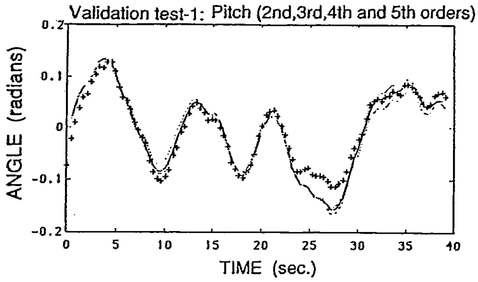
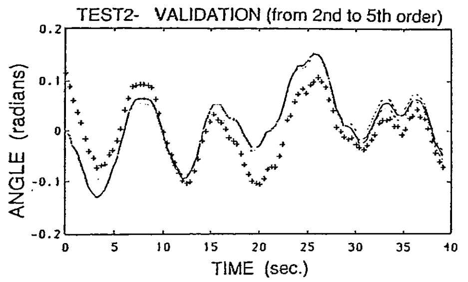


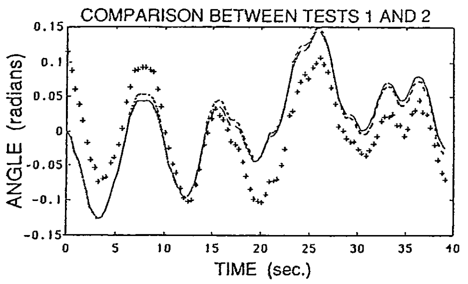
Fig. 2. Experimental Data, Test1.



(a)"+" : experiment; other curves: from estimated transfer functions

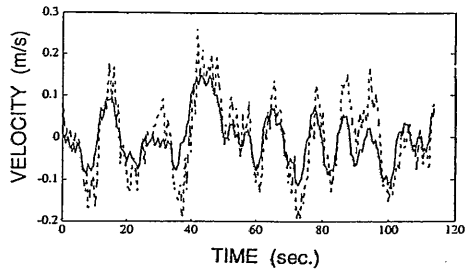


(b)

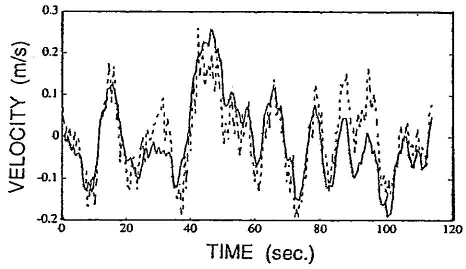


(c) 2nd. order transfer function;
solid line: from test 2;
dashed line: from test1.

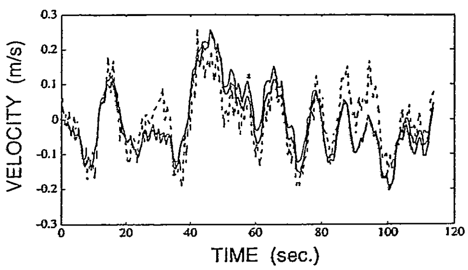
Fig. 3. Pitch Transfer Functions: Validation



(a)"- - " : experimental output
solid curve: simulated from "tf1"
(na=2,nb=2,k=1)



(b) solid curve: from "tf3" and "tf4"



(c) solid lines: "1"= from "tf3"; "2" from "tf2".

Fig. 4. Depth Transfer Functions: Validation tests

In the case of surge and heave transfer variables, the signals obtained by the accelerometers were too noisy and with low accuracy. Before the use of these signals for the calculations of surge and heave velocities, a digital filtering was still tried, but the results were unsuccessful.

5. Conclusions

System identification applied to free model tests has been revealed as a practical and useful tool for control design of underwater vehicles.

However, it must be emphasized the important role of using adequate sensors and signal treatment procedures in order to get reliable results. In this sense, an investigation of appropriate methods for measuring accelerations or/and velocities of the vehicle, for example, must be conducted. Furthermore, in order to isolate the influence of the actuator, the use of encoders for measuring elevator angles is also suggested.

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