ITTC Quality System Manual
Recommended Procedures and Guidelines

Guideline

Captive Model Test for Underwater Vehicles

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Manoeuvring Committee of the 30th ITTC	30th ITTC 2024
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Captive Model Test for Underwater Vehicles

1. PURPOSE OF GUIDELINE

Captive model tests are commonly used for predicting manoeuvring characteristics. Procedure 7.5-02-06-02 focusses on displacement ships, whereas the present guideline is specifically intended for underwater vehicles (UV), such as Autonomous UV (AUV), Remotely Operated Vehicles (ROV) or submarine models, which all share similar hydrodynamic characteristics.

The aim of this guideline is to provide an outline of captive model test for underwater vehicles to determine the values of the hydrodynamic coefficients for a manoeuvring simulation model of the underwater vehicle.

The hydrodynamic coefficients in the model must be obtained before using the hydrodynamic model for manoeuvrability prediction. The accuracy of manoeuvrability prediction of underwater vehicle is closely related to the accuracy of hydrodynamic coefficients. There are many methods to obtain hydrodynamic coefficients, and for some unconventional manoeuvring movements, the special hydrodynamic coefficients in the forecast model are often difficult to obtain through conventional constrained model tests. Therefore, based on the selected structure of the manoeuvring motion model, the identification algorithm is used to identify and obtain the relevant parameters in the model with the free selfpropelled manoeuvring test data as training samples. The advantage of system identification is that all manoeuvring hydrodynamic derivatives can be estimated from one or more maneuverability test data.

The present guideline is based on literature and especially the book of Submarine Hydrodynamics by Renilson (2018).

2. TEST FACILITIES

Captive model test for underwater vehicles can be divided into four different categories:

2.1 Low Speed Wind Tunnels

Wind tunnels are popularly used in testing of applications such as aerodynamics, automobiles, naval architects, submarine etc. The model mounted in a low-speed wind tunnel on a single, vertical support pylon, where attitude is controlled via a pitch-arm. The vertical support pylon is shrouded by a detachable aerodynamic fairing, and mounted on a rotating turntable, allowing the model to be yawed relative to the free-stream flow. During testing, the model is usually fitted with an internal six-component strain gauge balance, enabling steady-state aerodynamic forces and moments to be measured.

2.2 Rotating Arm **Facility**

A rotating arm facility measures the rotational derivatives on the model, in a special type of towing basin. The model is rotated in circular motion at a constant linear speed at various radii R, and a six-component strain gauge balance measures the forces and the moments acting on the model.

2.3 Planar Motion Mechanism

A Planar Motion Mechanism (PMM) is the most used method for the determination of hydrodynamic coefficients in manoeuvring equation. Generally, for UV this is done in the vertical plane, using a Vertical Planar Motion Mechanism (VPMM).

The model is mostly attached inverted (see 3.1.2) and pure translation gives pure heave, and pure rotation gives pure pitch. When the model is on its side, pure translation gives pure sway, and pure rotation gives pure yaw.

2.4 Marine Dynamics Test Facility

An alternative approach to the PMM is to use a single mechanism to provide motion in all six degrees of freedom. Such a device was developed by the National Research Council, Canada, known as a Marine Dynamics Test Facility (MDTF).

The control system for the MDTF enables it to perform all kinds of motions, including pure or combined manoeuvres. The model is attached to a sting, and the sting is attached to two struts.

3. DESCRIPTION OF GUIDELINE

3.1 Preparation

3.1.1 Model dimensions

The model should be manufactured according to 7.5-01-01-01, especially the tolerance of the appendages is more important for an UV. The size of the model should be according to 7.5-02-06-02.

In addition, the blockage considerations are more complex compared to the surface ships, because on one hand, in order to avoid free surface effects, the model has to be sufficiently submerged, and on the other hand sufficient distance is needed from the bottom and the walls of the tank to avoid UV-bottom interaction, respectively UV-bank interaction. A limiting factor on the submergence is the stiffness of the support system. As a rule of thumb a minimum submersion of 3 to 4 times the diameter of the axisymmetric section is recommended (Conway, 2018; Crossland, 2013), as long as the Froude number is below 0.4. The same can be stated for UV-bottom interaction. For higher Froude numbers these minimum distances have to be increased.

In practice these problems may be addressed as well by executing CFD tests with and without depth/width limitations.

3.1.2 Model equipment and set-up

In principle, tests can be conducted in either water or air in a towing tank or a water/wind tunnel. A common procedure is to test in a large towing tank, with the model supported from the carriage using struts as shown in Fig.1.

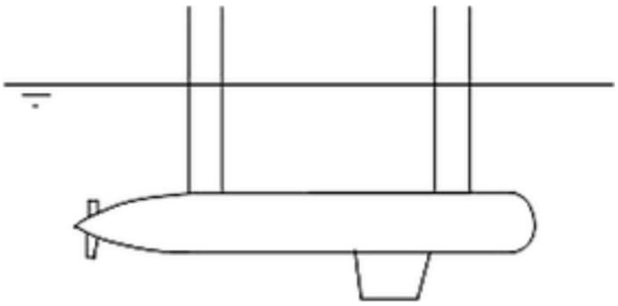

Fig.1. Typical set up for captive model tests in a towing tank (Renilson, 2018)

The effects of the support struts also have to be considered. In order to minimize those effects, load cells should be installed inside of the model. Although the forces on the struts are not included in the measurements, the presence of the struts do affect the flow around the model, and thus, the measured forces and moments.

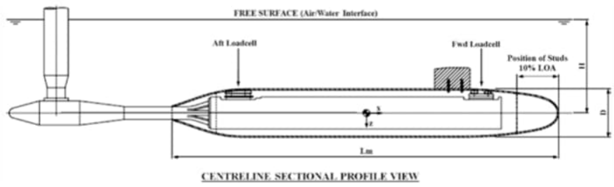

Fig. 2 Set up for captive model tests using a sting support (taken from Renilson et al. 2011)

It is possible to use a sting type mount, as shown in Fig. 2, however this generally means that the propulsor cannot be included. As the propulsor has a significant influence on the flow over the stern of the model care needs to be taken with this approach.

3.1.3 Scaling effects

The scale effect is caused by the difference between the scale of the model and the real vehicle and cannot satisfy the law of full similarity at the same time, which causes some differences in force or coefficient and even flow mode and other performance. For submarines, the size of the shell is about 1/10 of the size of the hull, and the size of the control planes is about 1/100 of the size of the hull, and the scale effect of the appendages is more obvious. There are few research on scale effect in manoeuvring motion. But how to solve or reduce the scale effect problem, there is no unified feasible method at present. The main difficulty lies in the following: scale effect is related to vehicle type, that is, it is difficult for a certain method to consider many vehicle types or new vehicle types. Due to the limited data of real vehicles and the numerous interfering factors of real ship test, the correction method of scale effect is difficult to be effectively verified.

Compared to ships, the Froude number is less important for underwater vehicles, but it is not recommended to only rely on the Reynolds number, especially if the underwater vehicles are manoeuvring close to the free surface. On the other hands, while the towing test are to be conducted near free surface, the surface effect must be considered, as for submarines, the size of the shell is about 1/10 of the size of the hull, and the scale effect of the appendages is more obvious. So, the Froude number is also important.

3.2 Execution of the tests

3.2.1 Low Speed Wind Tunnel Test

3.2.1.1 Steady straight-line tests

Steady straight-line tests means dragging the model straight in the income flow, and as a distinction, the steady straight line tests include the bare body straight towing test and the full-appendaged body straight towing test.

3.2.1.2 Horizontal plane tests

Horizontal plane tests include variable drift angle test, rudder deflection (δ_r) in the horizontal plane and combined variable drift and vertical rudder deflection tests.

A schematic of the typical results from such an experiment, where the non-dimensional side force (Y') is plotted as a function of the non-dimensional sway velocity (v') is given in Fig. 3.

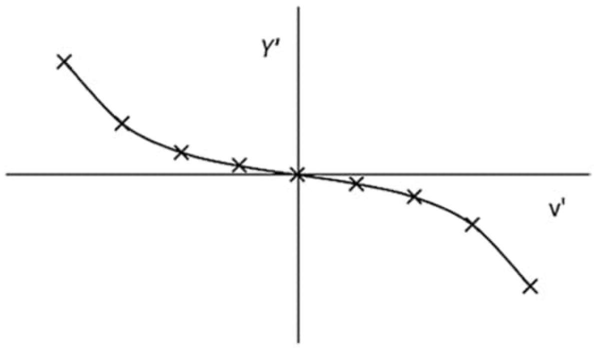

Fig. 3 Schematic of results from a translation test (Renilson, 2018)

The purpose of horizontal tests is to determine the hydrodynamic derivatives concerning side velocity and rudder angle, see Table 1. Those derivatives are commonly obtained by means of polynomial regression, as similar as the procedure for surface ships.

Table 1. Horizontal plane tests coefficients

Linear coefficients	Nonlinear coefficients
$Y'_v, K'_v, N'_v,$ $Y'_{\delta_r}, K'_{\delta_r}, N'_{\delta_r}$	$X'_{vv}, Y'_{v\|v\|}, Z'_{vv}, K'_{v\|v\|}, M'_{vv}, N'_{v\|v\|}$ $X'_{\delta_r\delta_r}, Y'_{v\delta_r}, K'_{v\delta_r}, N'_{v\delta_r}$

3.2.1.3 Vertical plane tests

Vertical plane tests include variable attack angle, rudder deflection (δ_s) in the vertical plane, and combined variable attack angle and rudder deflection.

Vertical plane tests are usually used to determine the derivatives concerning heave and pitch velocities, see in Table 2.

Table 2. Vertical plane tests coefficients

Linear coefficients	Nonlinear coefficients
Z'_w, M'_w $Z'_{\delta_s}, M'_{\delta_s}$	$X'_{ww}, Z'_{w\|w\|}, Z'_{\|w\|}, Z'_{ww},$ $M'_{w\|w\|}, M'_{\|w\|}, M'_{ww}$ $X'_{\delta_s\delta_s}, Z'_{w\delta_s}, M'_{w\delta_s}$

3.2.1.4 Spatial tests

Spatial tests include combined variable drift and attack angle to determine coupled derivatives such as $Y'_{vw}, K'_{vw}, N'_{vw}$ etc.

3.2.2 Circular motion test

3.2.2.1 Horizontal plane tests

Similar to the testing of surface ship models, to obtain the values of the coefficients which represent the forces and moments as functions of yaw velocity, it is necessary to test the models in rotation, using a rotating arm. This is done in the horizontal plane, and the model is tested inverted, as shown in Fig.4.

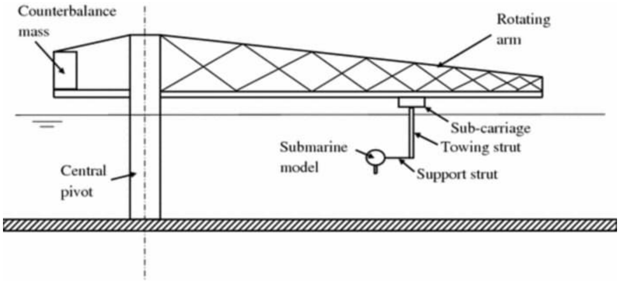

Fig.4. Typical set up for captive model tests using a rotating arm (Renilson, 2018)

A sketch of the results from a rotating arm is given in Fig. 5.

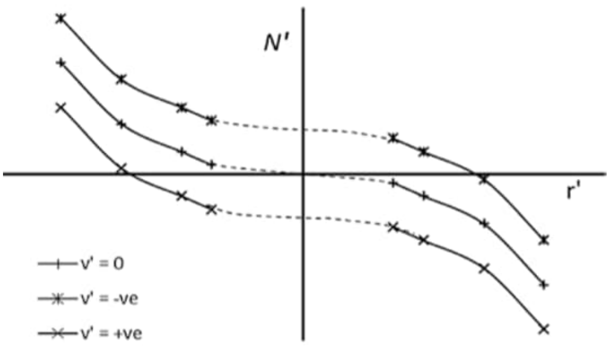

Fig.5 Schematic of results from rotating arm (Renilson, 2018)

Horizontal plane tests can determine the coefficients see Table 3.

Table 3. Horizontal plane tests coefficients

Linear coefficients	Nonlinear coefficients
Y'_r, K'_r, N'_r	$X'_{rr}, X'_{vr}, Y'_{r\|r\|}, Y'_{v\|r\|}, Z'_{rr}, Z'_{vr}$ $K'_{r\|r\|}, M'_{rr}, M'_{vr}, N'_{r\|r\|}, N'_{\|v\|r}$ $Y'_{\|r\|\delta_r}, N'_{\|r\|\delta_r}$

3.2.2.2 Vertical plane tests

The rotating arm can also be used to obtain the values of the coefficients which represent the forces and moments as functions of pitch velocity q, and this is done in the horizontal plane, with the model tested on its side.

Vertical plane tests can determine the coefficients see Table 4.

Table 4. Vertical plane tests coefficients

Linear coefficients	Nonlinear coefficients
Z'_q, M'_q	$X'_{qq}, X'_{wq}, Z'_{w\|q\|}, Z'_{q\|q\|}, M'_{q\|q\|}, M'_{\|w\|q}$ $Z'_{\|q\|\delta_s}, M'_{\|q\|\delta_s}$

3.2.3 Planar Motion Mechanism

With a PMM it is possible to execute the horizontal and vertical plane tests mentioned for wind tunnels and rotating arm basins.

3.2.3.1 Horizontal plane tests

Horizontal plane tests include:

- pure sway
- pure yaw

The main purpose of pure sway tests is to determine the hydrodynamic derivatives concerning sway acceleration, such as $Y_{\dot{v}}, K_{\dot{v}}, N_{\dot{v}}$ etc. During the tests in the horizontal plane the model keeps a constant forward speed, but the sway velocity oscillates harmonically. The recorded longitudinal force, side force and yaw moment will oscillate versus time and can be studied by a Fourier analysis.

Pure yaw tests are usually used to determine the derivatives concerning yaw acceleration, such as $Y_{\dot{r}}, K_{\dot{r}}, N_{\dot{r}}$. Contrary to pure sway tests the yaw rate changes over time (harmonic motion). The recorded longitudinal force, side force and yaw moment versus time can be analysed by Fourier series as well.

3.2.3.2 Vertical plane tests

Vertical plane tests include:

- pure heave
- pure pitch

The pure heave tests are also dynamic tests to determine the derivatives concerning heave acceleration, such as $Z_{\dot{w}}$ and $M_{\dot{w}}$. Rather than pure sway tests, the motion is confined in vertical plane but not in horizontal plane anymore. The forward speed is fixed and the heave velocity change over time in a harmonic law too. The measured results in stable oscillation can also be analysed by Fourier series to determine the derivatives. The static motion tests are preferred to obtain Z_w and M_w, to avoid frequency effects.

The pure pitch tests are used to determine the derivatives concerning heave acceleration, such as $Z_{\dot{q}}$ and $M_{\dot{q}}$. The model motion is confined in vertical plane rather than in horizontal plane. The forward speed is fixed and the pitch velocity varies harmonically over time. The measured results in stable oscillation are analysed by Fourier series to determine the derivatives. The static motion tests are preferred to obtain Z_q and M_q as well, which is explained previously.

4. VALIDATION

4.1 Benchmark Tests

At present, the model most commonly used in experimental facility and numerical benchmarking is DARPA SUBOFF and Joubert BB2.

The SUBOFF project provides a forum for the CFD community to compare the numerical predictions of the flow field over an axisymmetric hull model with and without various typical appendage components with experimental data.

The BB2 experiment was carried out by The Australian Defense Science and Technology Group (DSTG) and the Dutch Defense Materiel Organization (DMO) in 2014 to work together on background research (R&D) in the hydrodynamic behaviour of submarines (Over-pelt, 2015). The free sailing manoeuvring tests were conducted in the Seakeeping and Manoeuvrings Basin (SMB) in June 2014. The tests include roll decay and kinds of manoeuvres in the horizontal plane or the vertical plane, but the downloadable data set does not contain all the manoeuvres conducted, and only the roll de-cay at 0 kn, the horizontal zigzag and turning circle, and vertical zigzag are available.

4.2 Uncertainty analysis

Uncertainty analysis should follow 'Guide to the Expression of Uncertainty in Experimental Hydrodynamics'7.5-02-01-01 and related procedures.

5. LIST OF SYMBOLS

5.1 English

Lpp	Ship's length between perpendiculars	[m]
t_a	Initial turning time	[s]
t_S t_B	Time to check heading angle	[s]
t	Time of a complete cycle	[s]
V	Speed of ship	[m/s]
B	Breadth	[m]
T	Draft	[m]
D	Depth	[m]
C_B	Block coefficient	[-]
GM	Transverse metacentric height	[-]

5.2 Greek

δ	Rudder angle	[rad]
ψ	UV's heading angle	[rad]rad
$\dot{\psi}$	Yaw rate	[rad/s]
Ψ	Gyro compass course	[rad]
$\dot{\Psi}$	Rate of turn	[rad/s]
θ	UV's pitch angle	[rad]
$\dot{\theta}$	Pitch rate	[rad/s]

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