ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Captive Model Test for Underwater Vehicles

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

2. PARAMETERS

Contrary to displacement ships, underwater vehicles need to be able to manoeuvre in 6 DOF. A typical mathematical model to represent the motion of underwater vehicles is given by Gertler and Hagen (1967) and revised by Feldman (1979). Captive model tests should measure the three forces and three moments to determine the manoeuvring coefficients:

- The total hydrodynamic surge force:

$$X' = \frac{X}{\frac{1}{2}\rho L^2 U^2} \tag{1}$$

- The total hydrodynamic sway force:

$$Y' = \frac{Y}{\frac{1}{2}\rho L^2 U^2} \tag{2}$$

- The total hydrodynamic heave force:

$$Z' = \frac{Z}{\frac{1}{2}\rho L^2 U^2} \tag{3}$$

- The total hydrodynamic roll moment:

$$K' = \frac{K}{\frac{1}{2}\rho L^3 U^2} \tag{4}$$

- The total hydrodynamic pitch moment:

$$M' = \frac{M}{\frac{1}{2}\rho L^3 U^2} \tag{5}$$

- The total hydrodynamic yaw moment:

$$N' = \frac{N}{\frac{1}{2}\rho L^3 U^2} \tag{6}$$

The above forces and moments are expressed in the body-fixed coordinate system similar to the one defined by Abokowitz (1964). The motion equations are described in the same coordinate system as well.

In the following the term rudder is used not only to determine the control surface in the horizontal plane, but also in the vertical plane (e.g. wing rudder, bow plane, stern plane), unless otherwise specified.

Compared to ships, the Froude number is less important, but it is not recommended to only rely on the Reynolds number, especially if free surface effects are present.

3. TEST TYPES

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

3.1 Low Speed Wind Tunnel Test

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.

3.2 Circular Motion Test

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.

3.3 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 4.1.2) 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.

3.4 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.

4. DESCRIPTION OF GUIDELINE

4.1 Preparation

4.1.1 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.

4.1.2 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.

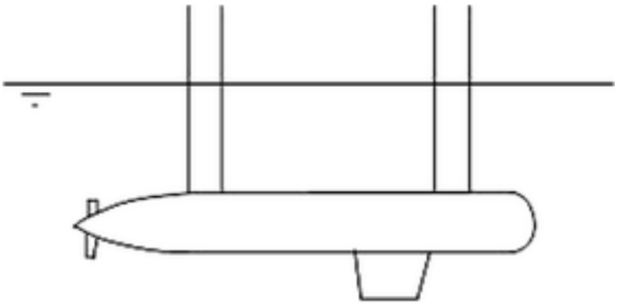

Fig.1. Typical set up for captive model tests in a towing tank (Renilson, 2018)

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.

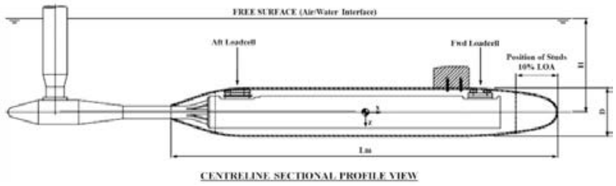

Fig. 2 Set up for captive model tests using a sting support (taken from Renilson et al. 2011)

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.

4.2 Execution of the tests

4.2.1 Low Speed Wind Tunnel Test

4.2.1.1 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.

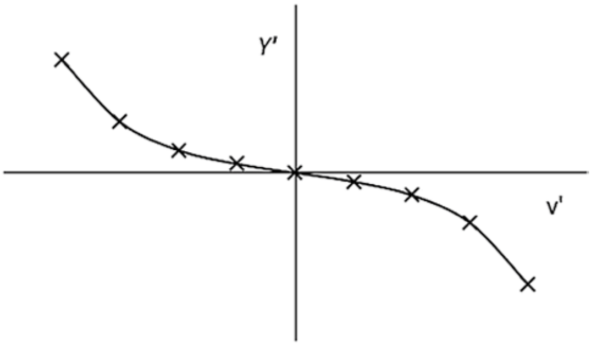

Fig. 3 Schematic of results from a translation test (Renilson, 2018)

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

4.2.1.2 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 $Z'_{\delta_s}, M'_{\delta_s}$	$X'_{ww}, Z'_{w\|w\|}, Z'_{\|w\|}, Z'_{ww},$ $M'_{w\|w\|}, M'_{\|w\|}, M'_{ww}$ $X'_{\delta_s\delta_s}, Z'_{w\delta_s}, M'_{w\delta_s}$

4.2.1.3 Spatial tests

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

4.2.2 Circular motion Test

4.2.2.1 Horizontal plane tests

As with 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.

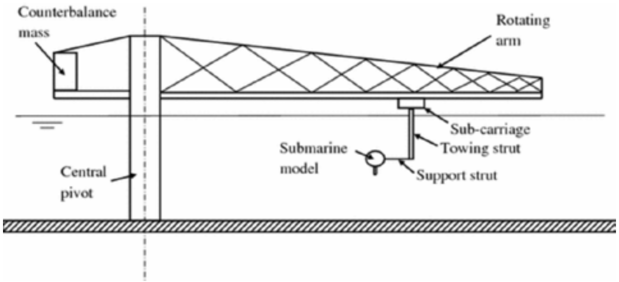

Fig.4. Typical set up for captive model tests using a rotating arm (Renilson, 2018)

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

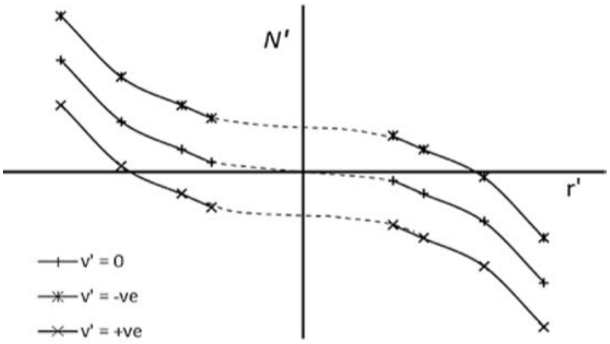

Fig.5 Schematic of results from rotating arm (Renilson, 2018)

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

4.2.2.2 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	$X'_{qq}, X'_{wq}, Z'_{w\|q\|}, Z'_{q\|q\|}, M'_{q\|q\|}, M'_{\|w\|q}$ $Z'_{\|q\|\delta_s}, M'_{\|q\|\delta_s}$

4.2.3 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.

4.2.3.1 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.

4.2.3.2 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.

5. VALIDATION

5.1 Benchmark Tests

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

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.

5.2 Uncertainty analysis

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

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