ITTC Quality System Manual
Recommended Procedures and Guidelines

Guideline

UV Full Scale Manoeuvring Trials

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UV Full Scale Manoeuvring Trials

1. PURPOSE OF GUIDELINE

This guideline provides assistance when performing full scale trials to determine the manoeuvring characteristics of an UV (Underwater Vehicle), but the present version focuses on the trials of unmanned UVs as a reaction to rudder, elevator, and other control device actions. For manned UVs, such as submarines, some trials in this guideline may not be applied by considering the safety of personals and equipment on board.

2. RECOMMENDED PROCEDURES FOR MANOEUVRING TRIALS

2.1 Overview

For operation purpose, tests should cover the following manoeuvrability:

1. horizontal inherent dynamic stability,
2. vertical inherent dynamic stability,
3. course-keeping ability,
4. depth-keeping ability,
5. course-changing ability,
6. depth-changing ability,
7. yaw checking ability,
8. pitch checking ability,
9. turning ability in horizontal plane,
10. horizontal stopping ability,
11. vertical stopping ability.

Table 1 shows a total of 8 manoeuvring tests recommended in this guideline, providing the information on above mentioned handling characteristics.

Furthermore, recommendations are formulated for operation purposes, including the operation near the water surface or near the bottom and the operation at low speed.

Test procedures should document trials in a way which is compatible with both UV design and scientific purpose (e.g. validation of predicted manoeuvres).

Table 1: Recommended Manoeuvring Tests for UV

Type of Test	Manoeuvrability to be checked
Turning Circle Test	9
Zig-zag Test	5,6,7,8
Spiral Test	1,3
Pull-out Test	1,2
Stopping Test	10,11
Stopping Inertia Test	10,11
Thruster Test	5,6,7,8,9
Crabbing Test	5,6

2.2 Trial Conditions

2.2.1 Environmental Restrictions

Manoeuvrability of an UV is affected by the ocean environment. Therefore, the trial site should be located in waters of adequate depth with low current and tidal influence as possible, and manoeuvring trials should be performed in the calmest possible weather conditions. It is recommended that:

1. the test must be executed in open water, far away from banks and UV traffic;
2. the water depth should be deep enough, so that the interactions with the bottom and free surface are minimized;

3. the maximum sea state should be chosen considering the UV's characteristics such as size, speed, , control surface, etc.
4. the maximum current speed should be chosen considering the UV's characteristics such as size, speed, control surface, etc.

2.2.2 UV Operational Conditions

It is recommended that the trials are to be carried out with the UV in a normal operational condition. It is essential that the UV must be able to execute fine adjustments to its mass/buoyancy balance, both in the vertical and longitudinal planes, in order to achieve a balanced trim condition. Depending on the test and its purpose, some tests might be conducted in a non-normal operational condition.

2.2.3 UV Initial Conditions

Before the execution of the manoeuvring tests in the horizontal plane, it may be necessary to operate the forward and aft hydroplanes to ensure that the UV remains at constant trim and depth, as the asymmetry due to the casing and the sail will result in a vertical force and pitching moment when turning.

The approach speed is suggested to be at least 90 per cent of the UV's speed corresponding to 85 per cent of the maximum engine output, but some tests should also be carried out at low speed.

The manoeuvrability of an UV is affected by the initial conditions. Therefore, before carrying out the manoeuvring test, the initial conditions of UV should be recorded, such as:

- initial speed,
- initial position,
- initial depth,
- initial heading(yaw) angle,
- initial pitch angle,
- initial rudder angle,
- initial elevator(fin) angle,
- initial propeller(thruster) rpm,
- etc.

2.3 Test procedures and parameters to be obtained

2.3.1 Turning Circle Test

A turning circle test (in a horizontal plane) of a UV is very similar to that of a surface vessel, as recommended by 7.5-04-02-01. An UV enters turning motion starting at a constant speed and constant depth (in a horizontal plane). The test is performed by deflecting the rudders to a predefined angle and holding it still resulting in the UV entering a circular path. A turning circle of at least 540 degrees is necessary to determine the main parameters of this trial. Whenever possible, turning circle tests at low or half design speed should be performed as well. Considering the UVs are usually asymmetrical in the *x*-*z* plane, a proper control should be applied to maintain the depth of the UVs during the tests.

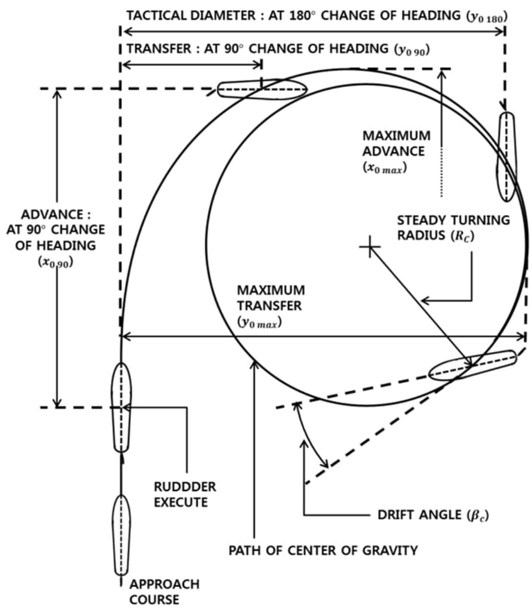

Figure 1: Turning circle: definitions

The essential information to be obtained from this manoeuvre consists of (see Figure 1):

- tactical diameter,
- advance,
- transfer,
- speed of UV,
- time to change heading by 90 degrees,
- time to change heading by 180 degrees,
- time to change heading by 270 degrees.

The first three of these may be presented in non-dimensional form by dividing their values by the UV's overall length.

2.3.2 Zigzag Test

For UVs, the zigzag manoeuvring tests must be conducted both in horizontal and vertical planes to evaluate the course-changing (or depth-changing) ability and yaw-checking (pitch-checking) ability. The execution of UV zigzag manoeuvring tests (particularly in a horizontal plane) is very similar to that of surface vessels, as recommended by the 7.5-04-02-01. However, considering the UVs are usually asymmetrical in the *x-z* plane, a proper control should be applied to maintain the depth of the UVs during the tests in a horizontal plane.

The horizontal zigzag test. This manoeuvre is conducted by reversing the rudder alternately by δ degrees to either side at a deviation ψ from the initial course. After a steady approach the rudder is put over to starboard (first execute). When the heading is ψ degrees off the initial course, the rudder is reversed to the same angle to port (second execute).

After counter rudder has been applied, the UV initially continues yawing in the original direction with decreasing yaw rate until it changes sign, so that the UV eventually yaws to port in response to the rudder. When the heading is ψ degrees off the course port, the rudder is reversed again to starboard (third execute). This process continues until a total of 3 rudder executes have been completed.

Hence, a zigzag test is determined by the combination of the heading and rudder angle and is denoted δ/ψ. Common values for these parameters are 5º/5º, 10º /10º and 20º/20º. However, other combinations could be applied.

The manoeuvres are to be executed at constant propulsion, for instant, through a constant propeller/thruster rpm.

Zigzag manoeuvres must be carried out starting with rudder to both starboard and to port, in order to identify the environmental effects (e.g. current) and asymmetric behaviour of the vehicle.

For a first simple analysis of the results, characteristic steering values defined in Figure 2 can be used; the values are plotted as a function of the rudder angle δ.

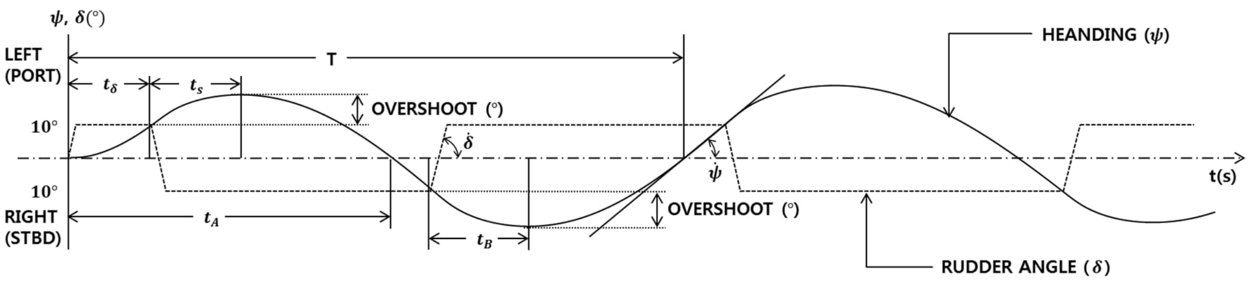

Figure 2: Time trace of horizontal zig-zag test parameters

Results of zig-zag tests are defined as follows:

- Initial turning time t_a (s): the time from the instant the rudder is put at the outset of the manoeuvre (first execute) until the heading angle is ψoff the initial course. At this instant the rudder is reversed to the opposite side (second execute).
- Execute heading angle (degrees): heading ψ at which the rudder is reversed.
- Overshoot angle (degrees): the angle through which the UV continues to turn in the original direction after the application of counter rudder. The first and second overshoot angles correspond to the maximum heading angle reached after the second and third execute, respectively.
- Time to check yaw (t_S, t_B) (s): the time between the rudder execute and the time of the maximum heading change in the original direction.
- Heading ψ (degrees): the course deviation from the straight initial course.
- Reach t_A (s): the time between the first execute and the instant when the UV's heading is zero after the second execute.
- Time of a complete cycle T (s): the time between the first execute and the instant when the UV's heading is zero after the third execute.
- Yaw rate $\dot{\psi}$(deg/s): constant yaw rate (time gradient of heading) established after the second execute. In this phase the UV executes circular motion, if a steady speed is assumed.
- Unit time (s): the time required for the vessel to travel her own length at approach speed (= L/V). The time for a complete cycle is expressed in unit times.

The vertical zigzag test. This test assesses the vehicle's manoeuvrability in the vertical plane, providing an idea of its ability to perform emergency manoeuvres to avoid collision to the seabed, as well as to submerged or floating structures, for instance. The execution of this manoeuvre is very similar to the horizontal zig-zag manoeuvre. For a zigzag in the vertical plane, the stern planes are deflected instead of the rudder, and a specified change in pitch is used instead of change in heading. The results to be measured in a vertical zig-zag manoeuvre include: initial turning time, execute pitch angle, overshoot angle, time to check pitch, pitch angle, reach, time of a complete cycle, pitch rate and unit time. The definitions of these quantities are similar to those from a horizontal zig-zag test, as defined above. It should be noted that most of the tanks are designed to have limited water depth less than 10 metres. To avoid the bottom and free-surface effects, the zig-zag tests are suggested to be performed at the mid-depth. Particularly, for vertical zig-zag tests, low speed and small stern plane angle should be applied.

2.3.3 Spiral Test

Spiral tests are applied to evaluate the inherent dynamic stability of an UV in a horizontal plane. For a dynamic stable vehicle, either the direct (Dieudonné) or reverse (Bech) spiral tests can be used to obtain response at low rudder angles. For unstable vehicle, the reverse (Bech) spiral is recommended within the limits indicated by the results of the pull-out manoeuvres. The spiral tests in the horizontal plane should be performed in a way that a UV's depth is properly controlled.

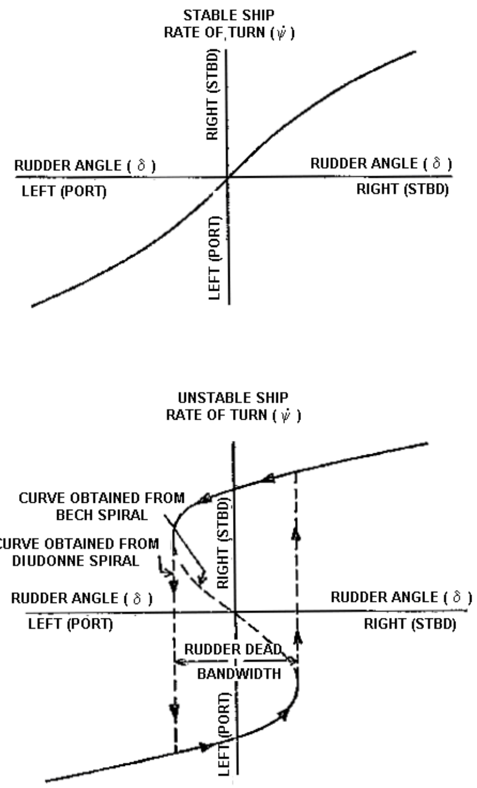

Figure 3: Presentation of spiral manoeuvre results

Direct spiral manoeuvre. With the vehicle on an initial straight course in horizontal plane at mid-water depth, the rudder is put to about 25 degrees to starboard and held until the rate of change of heading is constant. The rudder angle is then decreased by 5 degrees and again held until steady conditions of yawing have been obtained. This procedure is repeated until the rudder has covered the range from 25 degrees on one side to 25 degrees on the other side and back again. Over the range of rudder angles of 5 degrees on either side of zero or neutral rudder angle these intervals should be reduced.

The achieved steady rate of turn is registered for each rudder angle.

Reverse spiral manoeuvre. In the Bech reverse spiral test, the UV is made to approach the desired yaw rate, $\dot{\Psi}$, by applying a moderate rudder angle. As soon as the desired yaw rate is obtained, the rudder is actuated such as to maintain this rate of turn as precisely as possible. The UV is now controlled to maintain the desired yaw rate using progressively decreasing rudder motions until steady values of speed and rate of turn have been obtained. Adjustments to the rudder angle may be required until the UV achieves a steady yaw rate; therefore, it is necessary to allow some time before the values of $\dot{\Psi}$ and δ are measured.

2.3.4 Pull-out Test

The pull-out manoeuvre is a simple test to give a quick indication of a UV's inherent dynamic stability in the horizontal and vertical planes.

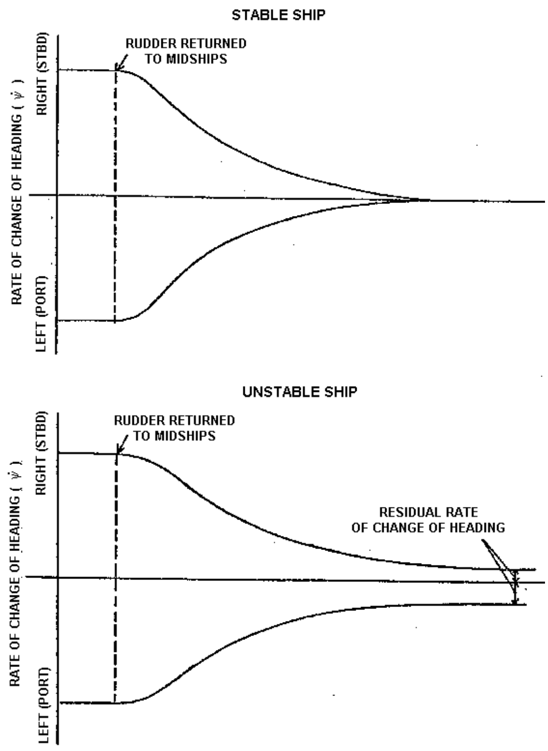

Figure 4: Presentation of pull-out manoeuvre results

Horizontal pull-out test. A rudder angle of approximately 20 degrees is applied until the UV achieves a steady rate of turn at a constant water depth; at this point, the rudder is returned to 0 degree. If the UV is stable, the yaw rate will decay to zero for turns to both port and starboard. If the UV is unstable, then the rate of turn will reduce to some residual yaw rate. The pull-out manoeuvres have to be performed to both port and starboard to show a possible asymmetry (see Figure 4). Pull-out manoeuvres can be performed at the end of a zigzag or turning circle test.

Vertical pull-out test. This test assesses the vehicle's inherent dynamic stability in the vertical plane. The execution of this manoeuvre is very similar to the horizontal pull-out manoeuvre. For a pull-out test in the vertical plane, the stern planes are deflected instead of the rudder, and a specified change in pitch is used instead of change in heading. Vertical pull-out manoeuvres can be performed at the end of a vertical zigzag, in which the speed and stern plane angle need to be small.

2.3.5 Stopping Test

The vehicle is approaching at a constant initial speed in the horizontal plane (close to mid-water depth), then its speed is reduced from the initial steady value to zero by applying full astern power.

The most common stopping trial starts from full ahead speed. When the propelling unit has reached steady full astern rpm and UV's speed becomes zero, the test is completed.

The parameters measured during crash-stop and stopping trial are (see Figure 5):

- the head reach which is defined as projected length of the track reach to the direction of the UV's initial course;
- the track reach which is the total distance travelled along the UV's path;
- the lateral deviation which is the distance to port or starboard measured normal to the UV's initial course in the horizontal plane.
- the vertical deviation which is the distance measured in the depth direction.

UVs usually are directionally uncontrollable during this manoeuvre so that the trajectory is largely determined by the ambient disturbances, initial conditions, hull form and control device actions.

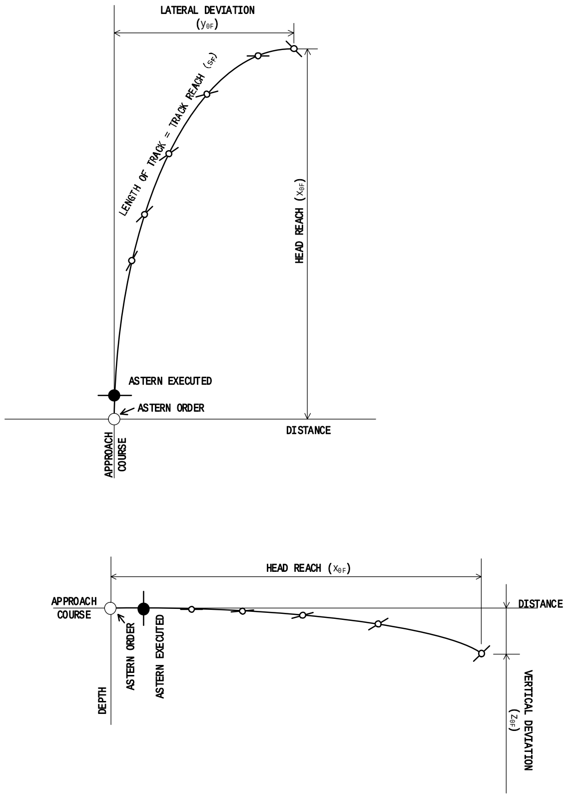

Figure 5: Definitions used in stopping trials

2.3.6 Stopping Inertia Test

Stopping inertia tests are performed to assess the behaviour of a UV during deceleration without propeller action.

Starting from full ahead speed, the engine is stopped quickly. When the UV's ahead speed has reduced to nearly zero, the test is completed.

The parameters measured during a stopping inertia test are:

- the head reach which is defined as projected length of the track reach to the direction of the UV's initial course;
- the track reach which is the total distance travelled along the UV's path;
- the lateral deviation which is the distance to port or starboard measured normal to the UV's initial course in the horizontal plane.
- the vertical deviation which is the distance measured in the depth direction.
- the duration of the manoeuvre.

2.3.7 Thruster Test

For a UV fitted with lateral thrusters (this may not be the case for submarines), the following tests are recommended.

Turning manoeuvre in a horizontal plane. With the UV initially at low speed and constant water depth, the thrusters are ordered to deliver full power while the rudder is kept at 0 degree. The manoeuvre should be continued until 90 degrees change of heading has been completed. Tests should be conducted both to port and starboard, with the bow and stern thrusters independently.

The essential information to be obtained from this manoeuvre consists of:

- time to change heading 15, 30, ..., 90 degrees.
- yaw rate must be continuously recorded. If possible, a steady state yaw rate must be provided.

Zig-zag Manoeuvre. With the UV initially at low speed, the thrusters are ordered to deliver full power while the rudder is kept at 0 degree. The test follows the same sequence as the zig-zag test (see 2.2.2) where at the instants of the executes, the thruster action is reversed instead of the rudder action. An execute heading angle of 10 degrees is suggested. The zig-zag tests should be performed at both horizontal and vertical plane.

2.3.8 Crabbing Test

An UV’s ability to move transversely and vertically at zero forward speed without altering heading and pitching is verified with a crabbing test. The purpose of the test is to document the maximum possible transverse and vertical speed.

All available propellers/rudders/thrusters/vertical planes should be used to perform the test. Obviously, an UV with only one propeller, one rudder and no bow thruster, such as most of the submarines, cannot perform crabbing according to this definition.

The essential information to be obtained from transverse crabbing tests consists of the final steady lateral speed of the UV. The forward speed and the change of heading should also be documented, although they should be kept as low as possible. The essential information to be obtained from vertical crabbing tests consists of the final steady vertical speed of the UV.

The use of propeller(s), rudder(s), vertical plane(s) and thruster(s) should be documented, including power, rpm, pitch, heading, thrust direction, rudder angle, etc.

The test should be carried out in as calm water conditions as possible. If a current is inevitable, crabbing both with the current and towards the current. Current conditions should be documented.

3. DATA ACQUISITION SYSTEM

3.1 General

During the different trials, the data has to be measured and recorded from the start of the approach run until the end of the manoeuvring trial.

Data should be acquired by a computer-based system because almost all the manoeuvring trials require time history data. The system should be able to collect, record and process real-time trial data of all measured parameters. The data acquisition system is installed in the UV hull and the communication system should be used to communicate the acquired data with the surface or other vehicles using wireless LAN, R/F modem or acoustic modem. A real time communication is not mandatory since the control logic is commonly uploaded to the UV.

The data sampling rate should be determined so that the acquired data can sufficiently indicate the characteristic of the UV. A minimal sampling rate of 5 Hz is recommended. The sampling rate should be at least twice the filter frequency according to the sampling theory.

3.2 Instrumentation

3.2.1 Overview

This section presents specific procedures and necessary equipment for the instrumentation of full-scale manoeuvring trials. A general procedure on the calibration of the instruments can be found on 7.5-01-03-01.

3.2.2 UV position

The position of the UV should be measured by adequate instrumentation. The velocity and orientation of the UV are usually measured by Doppler Velocity Log (DVL). DVL is an acoustic sensor which can measure the vehicle's velocity relative to the water or sea bottom through emitting signal to the bottom of the sea and using Doppler shift of the returned signals when the vehicle is submerged. The position should be measured using electronic tracking or DGPS while the UV is on the surface.

3.2.3 UV motions

The motions should be measured by adequate instrumentation. The AHRS (Attitude Heading Reference System) supplies information on the 3-axis angular velocities, 3-axis acceleration, 2-axis inclination, and heading angle to the control system. The yaw and pitch angles could be measured using AHRS. Inertial navigation system (INS) could be also used to measure horizontal position and velocity through integrating the linear accelerations and angular velocities.

3.2.4 UV depth

The depth should be measured by adequate instrumentation such as pressure sensor.

3.2.5 Control parameters

Rudder and vertical plane angle should be measured by adequate instrumentation (e.g. angular potentiometer) installed on the rudder or UV hull.

Propeller and thruster shaft rpm should be measured by adequate instrumentation (e.g. angular potentiometer) installed on the UV hull.

3.3 UV Parameters

Following UV related parameters should be documented:

- UV type;

- Principal dimensions and Inertial parameters (*Length, Diameter, Mass, Cruising and maximum Velocity, Diving Depth, etc*);
- Lateral/longitudinal projected area;
- Rudder/ elevator type;
- Number of rudders/elevators;
- Rudder/ elevator area;
- Rudder/ elevator angle;
- Propeller/thruster type;
- Propeller/thruster diameter and pitch;
- Number of propellers/thrusters and turning direction of each propeller/thruster;
- Battery or power supply type;
- Auto-pilot / control parameters;
- Propeller position;
- Thruster power;
- Battery volume;
- Payload information.

3.4 Initial Conditions

The following data is to be clearly recorded for each trial:

- Date / Time;
- Area of trial;
- Initial approach speed, heading, pitch, and depth of UV;
- UV's loading condition (weight, longitudinal centre of gravity and transverse metacentric height);
- Radii of gyration;
- Water depth;
- Environmental conditions, including
  - Current speed and relative direction;
  - Wind relative speed and direction;
  - Sea state.

4. DATA ANALYSIS

4.1 Correlation between Numerical Simulations and Full Scale Trials

If the full-scale trials are to be compared to numerical simulations, the sensor signals which are used in the numerical simulations must be properly defined according to the sensor signals of the UV in the full-scale trials.

It is also important to check if the control force and its characteristics are equivalent in numerical simulations and full-scale trials.

4.2 Uncertainty Analysis

4.2.1 General

Trial data uncertainty analysis should be carried out to assess the level of confidence in the trial results and to provide the statistics associated with UV trial measurements.

For the uncertainty analysis of UV position and speed, shaft rpm and torque, reference can be made to the uncertainty analysis section of the Final Report and Recommendations to the 23rd ITTC - The Specialist Committee on Speed and Powering Trials (ITTC, 2002).

The effect of errors in rudder angle or control device setting on the manoeuvre is difficult to assess through conventional uncertainty analysis. It is recommended to make use of simulation techniques for this purpose, for instance the method described in 7.5-02-06-05.

4.2.2 Correction due to Environment

The environmental conditions such as current can significantly affect the UV's manoeuvrability. For particular trials close to the sea surface, the wave elevation will also be a disturbance. IMO Resolution MSC.137(76) (2002) suggests a method to account for environmental effects. It could also be a reference to full scale trials test of UV.

4.2.3 Correction due to UV Initial Conditions

When the trials are performed, the UV's manoeuvrability can be affected by the initial condition of the UV. In general, initial speed, position, depth, and heading angle affect the determination of control input and the trial results.

It is also important to keep the initial conditions constant in the full-scale trials in order to ensure the reliability of test results.

5. LIST OF SYMBOLS

L_{PP}	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	[1]
$\overline{GM}$	Transverse metacentric height	[m]
δ	Rudder angle	[rad]
ψ	UV's heading angle	[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]

6. REFERENCES

International Maritime Organization, 2002, “Standards for Ship Manoeuvrability”, Resolution MSC.137(76).

International Towing Tank Conference, 2002, "The Specialist Committee on Speed and Powering Trials - Final Report and Recommendations to the 23rd ITTC", Proceedings of 23rd ITTC, – Volume II, Venice, Italy.