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Steering and Rising Testing of an Innovative Tourist Submarine

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Abstract: An innovative tourist submarine was studied by scale-model tests in a towing tank to determine its steering capabilities and detect motion instabilities during usual manoeuvres and emergency rising. Motion instabilities are caused by the combination of the submarine motions and the fluid flow, leading to excessive roll and pitch that can cause severe endangerment to passenger safety. The submarine model was built on a scale of 1:9. The model had six thrusters to conduct the tested manoeuvres, i.e., two main thrusters at the stern, two side thrusters, and two vertical thrusters. The thrusters were computer-controlled, so each thruster had a speed controller and could run forwards and backwards. Six different steering tests and four rising tests were conducted, with at least two runs per test. During the tests, the roll and pitch were measured. Lifting the submarine by a crane was also a part of the experimental campaign. In general, the steering capabilities of the submarine were satisfactory and rolling instabilities were absent. Just a few deficiencies in the steering capabilities were detected. The rising tests were performed without any major motion instabilities, but in one case, the final position of the model at the surface was unstable.

Keywords: tourist submarine; steering test; manoeuvring; emergency rising test; surfacing; roll instabilities

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1. Introduction

A tourist submarine must be designed to provide safety in intact and possibly damaged conditions. Besides structural integrity, safety needs to be considered from the standpoint of steering and emergency rising (in a damaged condition). In these manoeuvres, the combination of the motions of the submarine and the fluid flow can lead to instabilities in the roll and pitch that can cause severe endangerment to passenger safety.

When submarines blow ballast to reach the surface in an emergency, they can experience roll instability [1]. Submarines are subject to underwater roll instability caused by the destabilising hydrodynamic rolling moment on the sail, overcoming the static righting moment as buoyancy accelerates a submarine upwards. In a typical rising scenario, ballast is blown at some depth, the nose of a submarine is pitched up, and speed is increased to minimise large negative angles of attack. Combining high speed and pitch changes increases the chances of instability, so once the desired pitch angle is achieved, it is recommended to keep this fixed until the boat has surfaced [2]. Despite these precautions, full-scale trials show that underwater roll instability still can occur and can result in excessive roll when the submarine surfaces [3].

A Reynolds Average Navier–Stokes (RANS) code was applied to study the flow around a tourist submarine of 18 m in length. Pronounced non-uniform flow directions and regions of separated flows were detected at external tanks, supporting frames, and the sail tower [4]. An unsteady version of RANS with the dynamic mesh method was utilised to simulate the manoeuvring motions of pure heaving, swaying, pitching, and yawing [5]. This implicit predictor–corrector method provides faster convergence in simulations of an emergency rising and a horizontal zig-zag manoeuvre [6].

An in-house computational fluid dynamics (CFD) solver was used for a submarine's free-running turning-circle manoeuvre in open-water conditions [7]. The comparison in terms of the turning-circle diameter was very satisfactory since the error was of the order of 10% in deep water and close to the free surface. The study also showed that the X-rudder provides better steering capabilities than the cross-rudder [8]. A newly developed, full ocean-depth, human-occupied vehicle was numerically studied during the descent and ascent manoeuvre [9]. The aim was to speed up the manoeuvres by setting the proper values of the attacking angles. Planar-motion mechanism (PMM) experiments with an axisymmetric submarine hull were used to validate CFD simulations [10]. Part of the research examined the influence of the support struts on the results of the PMM experiments.

A dynamic overset technique was applied within the CFD simulations involving moving planes and rotating propellers to study a 10/10 vertical zig-zag manoeuvre of a generic submarine [11]. A large-eddy simulation (LES) was used for a fully appended Joubert BB2 submarine model to complement the experimental investigations of the wake of the hydroplanes and sail [12]. The open-source OpenFOAM library was used for pure drift tests, rudder tests, and pure rotation in both the vertical and horizontal planes of the Defence Advanced Research Projects Agency (DARPA) SUB-OFF model [13]. It was shown that the expected errors between the measured data and the predictions for the fully appended configuration are within 5% for the linear part and 15% for the higher drift angles.

An unsteady RANS with six DOF was developed to evaluate emergency-rising manoeuvres [3]. The RANS simulation aims to reproduce the instability and investigate mitigation strategies. This work has shown that the initial heel and low-pitch angles significantly increase the roll angles while rising. When the initial heel angle is much less than a degree, the resultant emergence roll angle is too small to be of concern [14]. However, if the initial heel angle is approximately 2°, the emergence roll angle is large enough to initiate excessive roll at surfacing.

The influence of regular waves on the emergency-rising manoeuvres was studied by the level-set method used to model the free surface within RANS simulations [15]. It was found that the maximum roll angle increases with the increase in wave height and wavelength. The results of the simulation showed that a particular wave height and length causes the surfacing speed to fluctuate significantly. The wave heading also has a noticeable impact on the emergency rising [16].

A detailed experimental examination of the flow around a fully appended generic submarine model was performed for straight-ahead and 10°-yaw conditions [17]. The experiments were carried out in a low-speed wind tunnel, where data was collected using pressure probes, particle image velocimetry (PIV), and flow visualisation using wool-tuft streamers.

A set of submarine model tests at near-surface depth in a towing tank was carried out to determine the induced resistance between the struts and the hull [18]. This induced resistance could be considered 70% of the resistance of lone struts with tip vortex effects. Hydrodynamic coefficients for simulations of submarine manoeuvres were determined by conducting towing-tank and wind-tunnel tests [19]. A turbulence stimulator was applied for a more realistic boundary-layer development and pressure distribution. The hydrodynamic coefficients were also determined in a series of captive-model tests of a generic submarine [20]. Overall, thirteen types of captive-model tests were conducted using a vertical planar-motion mechanism.

A set of towing-tank tests of submarine models with a cross-rudder and an X-rudder were conducted to study the X-rudders' performance in non-uniform flow fields [21]. The tests examined the resistance, lateral steering force, yaw moment, stern velocity field, and flow-field inhomogeneity coefficient under low- and high-speed conditions. It was detected that the superiority of the X-rudder becomes more evident with increasing rudder angle.

Model tests and numerical simulation results revealed the strong coupling between roll and yaw motions when ascending [22]. An optimised controller of the rudders was proposed, which reduced the maximum roll angle by up to 96% in some simulated cases. Yet another experimental result revealed that the roll and yaw are strongly coupled and interact [23]. The excessive roll occurs inevitably when the drift angle is greater than 5° during the underwater rising process for submarines with relatively large sails. A decrease in the roll angle before surfacing was related to increased pitch [24]. However, the increased pitch reduces the metacentric height when emerging through the water surface.

This paper brings results of extensive experimental measurements of an innovative tourist submarine's roll and pitch angles when steering in usual manoeuvres, in an emergency, and during regular rising. Lifting the submarine by a crane was also a part of the experimental campaign. Since the primary purpose of the submarine is to carry civilian passengers, the utmost concern is their safety in all the possible cases that can be expected to arise during the submarine use, which needs to be addressed during the design stage. The motion instability in some situations can lead to uncontrollable situations and endanger passengers, reducing safety. Although motion instabilities are studied numerically and experimentally in the current literature, the focus of these studies has never been a submarine type that resembles the type examined in this paper. In contrast to numerical calculations, experimental research was conducted as a more reliable way of detecting motion instabilities. Hence, this paper presents novel, valuable material for designing such a submarine type.

The research presented here continues the work on the tourist submarine. Resistance of the bare hull with spherical heads, moving in forward and transverse directions, was analysed with OpenFOAM [25]. An artificial neural network was trained to predict the resistance coefficients [26]. A detailed study of the resistance, again with OpenFOAM, was conducted, where the focus was on the influence of the exostructure elements on the total resistance of the submarine [27]. Finally, [28] brings experimental measurements of the resistance, towing, seakeeping, and open-water propeller tests.

2. Model and Experimental Set-Ups

2.1. Submarine Steering

The main particulars of the tourist submarine are given in Table 1. Data from the towing tank, where the experiments are conducted, are shown in Table 2. The model was manufactured on a geometrical scale of 1:9, comprising various parts attached to the pressure hull, as presented in Figure 1. The hull was constructed from glass-reinforced plastic (GRP), cover parts were made from plywood and obeche wood, and the exostructure was made of steel. The battery pods were produced from tin, while the variable ballast tanks were made from plastic.

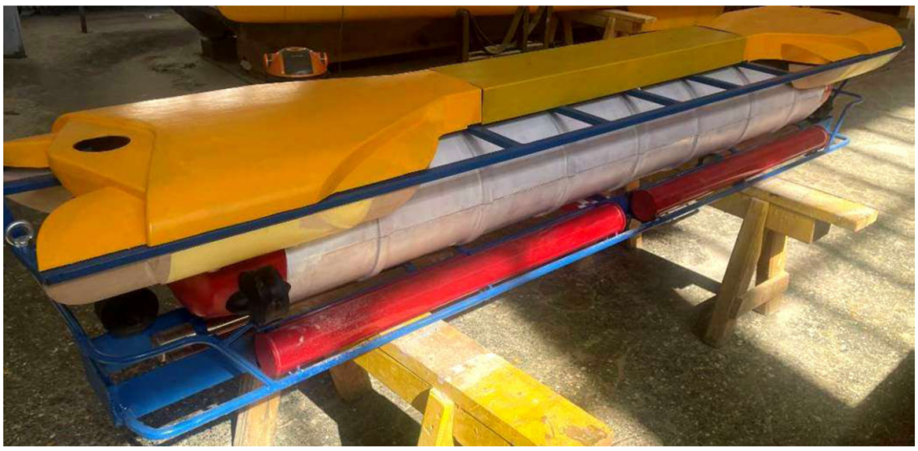

Figure 1. The 1:9 scale model of the tourist submarine.

Table 1. The particulars of the tourist submarine.

Feature	Value
Length (overall)	25.09 m
Beam	4.750 m
Draft	3.420 m
Dry weight	155 tons
Hull acrylic outer diameter	2.64 m
Forward speed (max.)	2.5 knots
Passengers	48
Test depth	65 m

Table 2. The particulars of the towing tank.

Feature	Value
Dimensions:	
Length	276 m
Breadth	12.5 m
Water depth	6 m
Max. model length	10 m
Carriage data:	
Speed range	0.014 m/s
Max. acceleration	1 m/s^2
Wave generator (double-flap):	
Wave lengths	1–40 m
Wave heights	0.08–0.7 m
Wave periods	0.1–3 s

The mass of the main parts, like the mass and volume of the battery pods, were also reproduced at model scale. Therefore, the distribution of mass was the same for full and scale models, ensuring correct values of mass moments of inertia and centre of gravity. The model was balanced to appropriate displacements and could move in all 6 degrees of freedom (DOF) during all the tests.

Throughout the tests, the Froude scaling law was applied. The tests are conducted in model-scale self-propulsion points, so the model thrust values are larger than the ones corresponding to the self-propulsion points at full scale. The resistance and wake are larger at model scale due to the larger frictional resistance.

Reynold's similarity was not satisfied since, in this case, it requires very high velocities from the model. Such velocities would not be attainable with the power of the installed thrusters, which are dimensioned to fulfil geometrical and dynamical similarities. Viscous scale effects have a certain influence on manoeuvres. Those effects mainly refer to physical occurrences in the boundary-layer region, like transition, turbulence, separation, and the impact upon the wake region. An appropriate way to investigate these effects would be by using a larger submarine model for comparison and by conducting numerical simulations with different approaches to turbulence. The stability of the movements of the submarine was investigated within this research, so it is estimated that it is not necessary to conduct additional investigations of these phenomena since the length of the model was 2.8 m, which ensures that, even for the lowest tested speeds conducted for deep or shallow water situations, the Reynolds number is above 2×10^5, i.e., the critical transitional limit. The viscous effect would play an important role when manoeuvres are accomplished with the control surfaces as rudders or when hydroplanes are exerting the forces necessary for manoeuvres. In this study, only the thrusters were used.

The tests were conducted in deep-water conditions but also in shallow and restricted water conditions to be expected in reality. Any restriction (depth or breadth) represents a more conservative approach, i.e., somewhat better behaviour (manoeuvrability) could be expected in deep and unrestricted water conditions. The tests were focused on the stability of the movements during the manoeuvres. Therefore, the inclination angles, i.e., the roll and pitch, were constantly measured during the tests.

The submarine model was equipped with six thrusters to conduct the manoeuvrability tests, i.e., two main thrusters at the stern, two side thrusters, and two vertical thrusters, as seen in Figure 2. In this way, the model can manage any operative condition. In the tests, the vertical positions of the vertical thrusters were altered to determine the relation between the positions and the diving ability of the submarine.

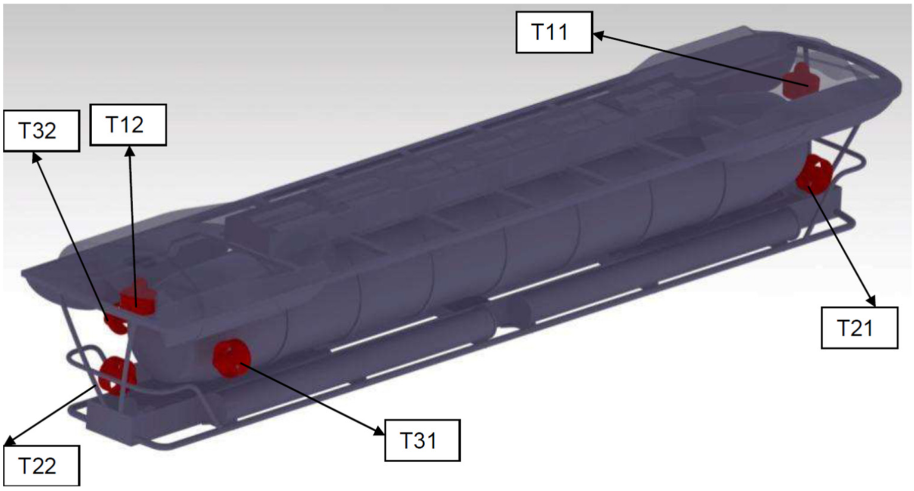

Figure 2. The positions of the thrusters on the submarine model: the main thrusters at the stern—T31 and T32; the side thrusters—T12 and T21; the vertical thrusters—T11 and T12.

The properties of the full-scale thrusters are given in Table 3. In choosing the appropriate thrusters for the model, the main criterion was the dimensions of the thruster, which should be on the same scale as the rest of the model. Further, the model's thrusters must have sufficient power and thrust to attain the speeds suitable for testing the manoeuvres. The type of the selected thruster is shown in Figure 3, while its properties are given in Table 4. All thrusters installed on the model were of the push type.

Figure 3. The type of thruster used for the submarine model.

Table 3. The properties of full-scale thrusters.

Thruster Group	Feature	Value
Main stern thrusters for propelling the vessel (T31 and T32)	Power	35 kW
	Diameter	0.75 m
	Pitch/Diameter ratio	0.75
	Area ratio	0.65
	Open-water efficiency (at advance coefficient of app. 0.2)	approx. 0.35
	Achievable thrust (at velocity of 3 kn)	approx. 7.6 kN
Side thruster for manoeuvring (T21 and T22)	Power	6 kW
	Diameter	0.5 m
	Pitch/Diameter ratio	0.80
	Area ratio	0.65
	Open-water efficiency (at advance coefficient of approx. 0.05)	approx. 0.1
	Achievable thrust (at velocity of 0.5 kn)	approx. 2.2 kN
Vertical thrusters for diving/emergence (T11 and T12)	Power	15 kW
	Diameter	0.75 m
	Pitch/Diameter ratio	0.80
	Area ratio	0.65
	Open-water efficiency (at advance coefficient of approx. 0.2)	approx. 0.33
	Achievable thrust (at velocity of 2 kn)	approx. 4.3 kN

Table 4. Main particulars/performances of the thrusters installed on the submarine model.

Feature	Value
Propeller diameter	76 mm
Length	113 mm
Duct outer diameter	97 mm
Thrust forward/reverse:	36.39 N/28.64 N at 12 Volts 58.99 N/45.02 N at 18 Volts
Minimum thrust	0.196 N

The system of thrusters was computer-controlled, and each thruster had a speed controller that could run in a forward or reverse regime. The operative regimes of thrusters were recorded during the tests. The direction of the positive (i.e., forward) thrust for each thruster is presented in Figure 4. Each group of thrusters (vertical, side, main) could work in pairs or individually to carry out different manoeuvres. The system was powered with voltages of 12 and 18 V. A wired connection enabled the communication between the controller and the thrusters.

The following tests, i.e., manoeuvres, were performed to determine the submarine's steering capabilities:

- Diving of the submarine from the surface with vertical thrusters.
- Forward/backward sailing in the submerged condition.
- Turning manoeuvre in the horizontal plane of the submerged submarine.
- Sideways movement (crabbing) of the submerged submarine.
- Steering in the horizontal plane of the submerged submarine.
- Steering in the vertical plane of the submerged submarine.

Figure 5 describes the reference coordinate system with the denotation of the positive orientation of angular motions, which is used during the test to monitor the submarine's behaviour and inclination angles.

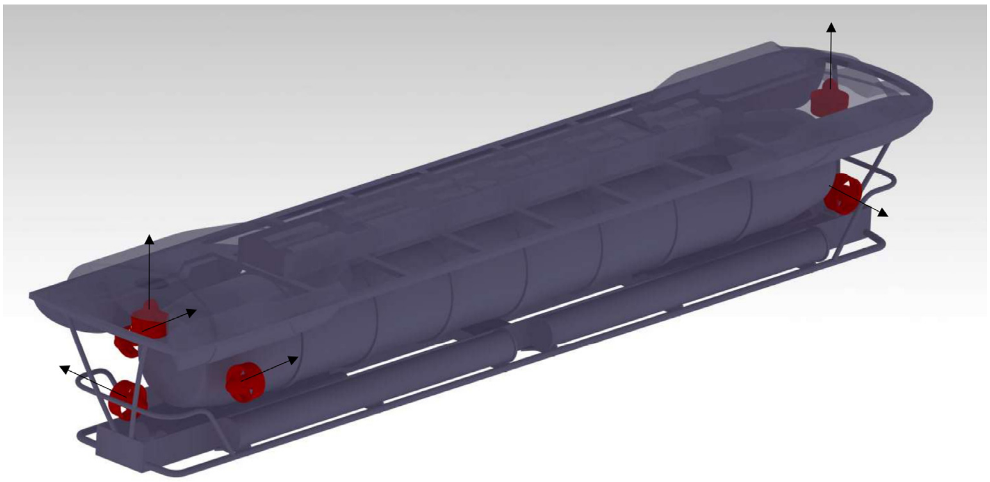

Figure 4. The directions of the positive (i.e., forward) thrust of the thrusters.

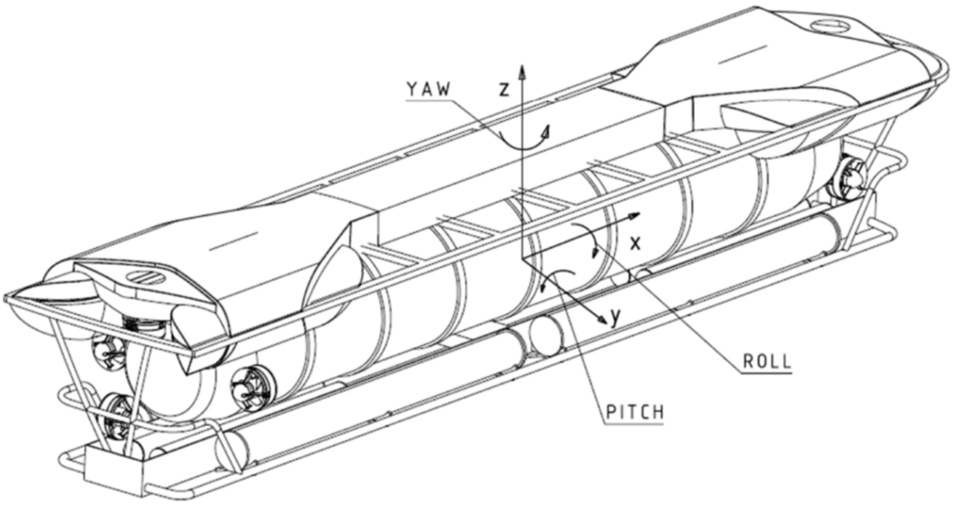

Figure 5. Reference coordinate system for the submarine model movements.

2.1.1. Diving of the Submarine from the Surface with Vertical Thrusters

The submarine model had a buoyancy reserve, so in the initial position, the hatches were above the water surface. Only the vertical thrusters, T11 and T12, were used in a forced diving manoeuvre throughout these tests. Three different vertical positions of the thrusters were tested to evaluate the influence of the positions on the diving manoeuvre. For each vertical position, the diving was conducted with four different numbers of propeller revolutions.

In these tests, the model was submerged to a depth corresponding to 14.4 m at full scale. The time intervals needed for the diving manoeuvres were recorded along with the model motions. In addition to the regular scope of these tests, the surfacing achieved by the vertical thrusters and the buoyancy were qualitatively checked.

2.1.2. Forward Sailing of the Submerged Submarine

The tests comprised forward manoeuvres with the submerged model propelled by main stern propulsive thrusters, T31 and T32, working as a pair. The model was sailed along the wall of the towing tank, simulating real conditions, where moving along some underwater object would be required. The diving depth of the model was maintained by the vertical thrusters (T11 and T12). The required time intervals and the distance travelled were measured, which enabled the determination of the model's velocity. Besides forward movement, qualitatively backward movement was observed as well.

2.1.3. Turning Manoeuvres in the Horizontal Plane of the Submerged Submarine

These manoeuvres were conducted using only one side thruster: the bow thruster (T21) or the stern thruster (T22) to identify the ability of the side thrusters to turn the submarine in confined underwater locations. The vertical thrusters (T11 and T12) maintained the model's diving depth. The main stern propulsive thrusters, T31 and T32, were inactive, so the submarine turned in place without approaching the tank walls.

All manoeuvres were conducted counterclockwise, rotating around the z-axis; see Figure 5. Different angular velocities were tested through the appropriate setting of thruster revolutions.

2.1.4. Sideways Movement (Crabbing) of the Submerged Submarine

Within these manoeuvres, the submarine model was set in the initial condition near the wall of the towing tank for a given depth. Both side thrusters, T21 and T22, were operative during the manoeuvres. Since the side thrusters are oriented in opposite directions, the forward and reverse regimes were combined to achieve sideways movements; see Figure 4. The "crabbing" test was conducted for different drift velocities.

2.1.5. Steering in the Horizontal Plane of the Submerged Submarine

The main propulsive thrusters (T31 and T32) were operative for the movement in the horizontal plane, working as a pair. The vertical thrusters (T11 and T12) maintained the model's diving depth, while the bow side thruster (T12) was used to alternate the model's direction of rotation.

2.1.6. Steering in the Vertical Plane of the Submerged Submarine

For the complex movement in the vertical plane, the main propulsive thrusters (T31 and T32) were operative in combination with the vertical thrusters (T11 and T12), which produced thrusts in opposite directions.

2.2. Emergency and Regular Rising Tests

The rising/surfacing tests were conducted for the submarine in emergency (damaged) and regular (intact) conditions. The same model was used for the manoeuvrability test. The model was additionally equipped with the blowing system in the main ballast tanks. In this test, the false thrusters, i.e., the non-functional models, were installed with the mass and buoyancy distribution kept in mind. The parts of the submarine model are visible in Figure 6.

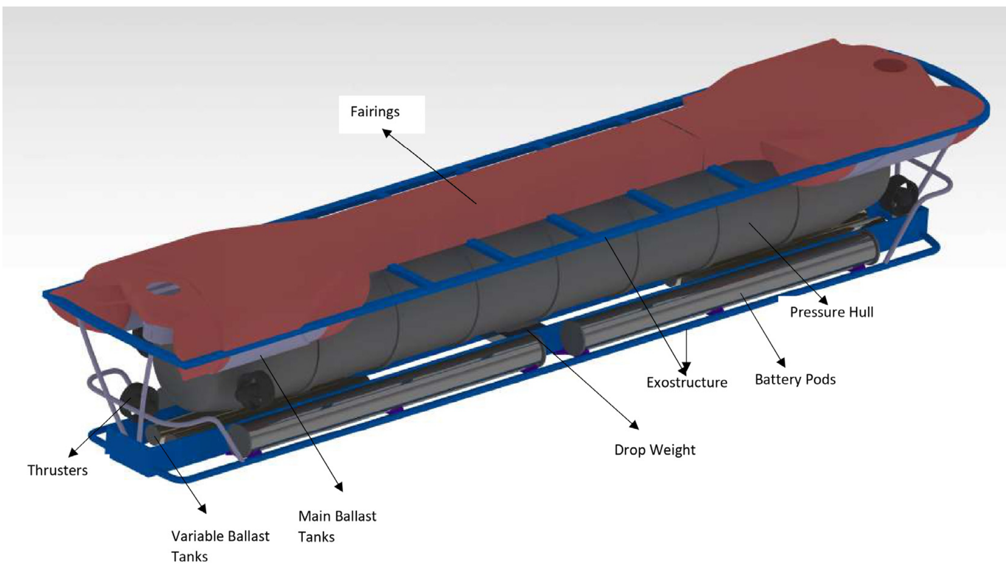

Figure 6. Main parts of the model for the submarine rising tests.

Rising tests were conducted for the following cases:

- Rising in regular conditions.
- Rising with a damaged main ballast tank (MBT).
- Rising with a damaged variable ballast tank (VBT).
- Rising with a damaged battery pod.

As part of these tests, lifting the submarine by two ropes was conducted from a depth corresponding to 50 m in full scale. The loading condition at the beginning of the rising manoeuvre for each condition and the surfacing procedure are given in Table 5. Each test was repeated several times, presenting at least two runs per test.

Table 5. Description of submarine rising tests.

Case No.	Loading Condition at the Beginning of the Rising Manoeuvre	Surfacing Procedure
1	MBTs flooded, all passengers on board, VBTs empty; the total mass is 162.1 t at full scale	Blowing of all MBTs.
2	MBTs flooded, all passengers on board, VBTs empty, damaged rear aft MBT; the displacement loss is 1.311 m^3 at full scale.	Releasing the drop weight *, blowing all MBTs except the damaged rear aft MBT.
3	MBTs flooded, all passengers on board, both fore and aft port VBTs empty, damaged aft starboard VBT; the additional mass is 1 t at full scale.	Releasing the drop weight, blowing all MBTs.
4	MBTs flooded, all passengers on board, VBTs empty, damaged aft starboard battery pod; the additional mass is 3.346 t at full scale.	Releasing the drop weight, blowing all MBTs.

* The drop weight mass is 3.2 t at full scale.

Emergency rising involves highly non-linear and complex coupled motions, especially as the vessel approaches the surface. It belongs among the most critical measures for submarines. So, the aims of these tests were the following:

- To observe movements during the rising process (monitored visually and through measurement of the inclination angles).
- To record the time/velocity needed to reach the surface.
- To monitor the hull's final position upon surfacing to determine the availability of the hatches for the evacuation process.

Emptying the MBTs was performed by blowing pressurised nitrogen into the tanks through a system of reinforced plastic tubes. The system was checked separately before being attached to the model hull. A human operator conducted the emptying procedure and applied a certain degree of manual regulation. The nitrogen pressure used was 0.46 bar at model scale, except for the two last surfacing tests with a damaged battery pod, where the applied pressure was increased to 0.6 bar (the model-scale value).

The model was submerged to a depth of 2.8 m at model scale and held by a crane. At this depth, the zero readings of the measuring devices were taken. Additionally, three tests for surfacing with the damaged battery pod were performed at greater depths, i.e., 3.5 m and 3.7 m (the model-scale values).

After submerging the model in intact conditions and taking the zero readings, the emptying procedure of the MBT started as a recording was made of the roll and pitch angles, along with the time needed for the model to reach the surface.

Similarly, when testing the emergency conditions, a diver released a drop-weight from the model structure at the beginning of the test. The emptying procedure of the MBTs started immediately after dropping the weight and recording the inclination angles and time intervals.

The model behaviour was observed during the rising/surfacing experiments while the model was underwater and at the water surface. These records made it possible to establish if the evacuation hatches were below the water's surface.

Finally, the lifting test was conducted with the equipped submarine model. The model was lifted from the depth corresponding to 50 m in full scale by two ropes, as shown in Figure 7.

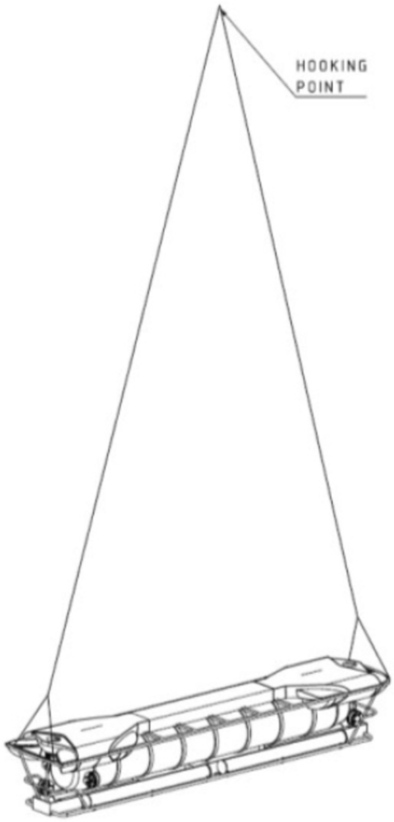

Figure 7. Lifting test of the submarine model.

3. Results on the Submarine Steering

3.1. Results on the Diving of the Submarine from the Surface with Vertical Thrusters

In the scope of this set of manoeuvres, 12 different combinations of the thrusters' positions (T11 and T12) and revolutions were tested in total, as presented in Table 6.

Table 6. Testing scheme for diving with vertical thrusters.

Vertical Position of Vertical Thrusters	Regime/Revolutions, r/s *			
	A/22.4	B/37.4	C/49.1	D/60.7
1st: initial design position; 1040 mm from WL	A1	B1	C1	D1
2nd: 680 mm from WL	A2	B2	C2	D2
3rd: 1400 mm from WL	A3	B2	C3	D3

* Revolutions per second.

For each position, the thrusters were operating at four constant revolutions. For the lowest revolutions, it was not feasible to conduct a diving manoeuvre, i.e., the force exerted by the thrusters was not sufficient. For the three other settings, the average velocity of diving was determined based on the travelled distance and measured time. During the manoeuvres, the behaviour of the submarine was observed, and for the third position of the vertical thrusters, the inclination angles were measured as well. The results are presented in Table 7 and in Figure 8, where the time axes are at model scale.

Table 7. Average diving velocities (at full scale).

Vertical Position of Vertical Thrusters	Regime/Average Diving Velocities, kn			
	A	B	C	D
1st: initial design position; 1040 mm from WL	N/A	0.27	0.45	0.55
2nd: 680 mm from WL	N/A	0.28	0.46	0.55
3rd: 1400 mm from WL	N/A	0.27	0.47	0.55

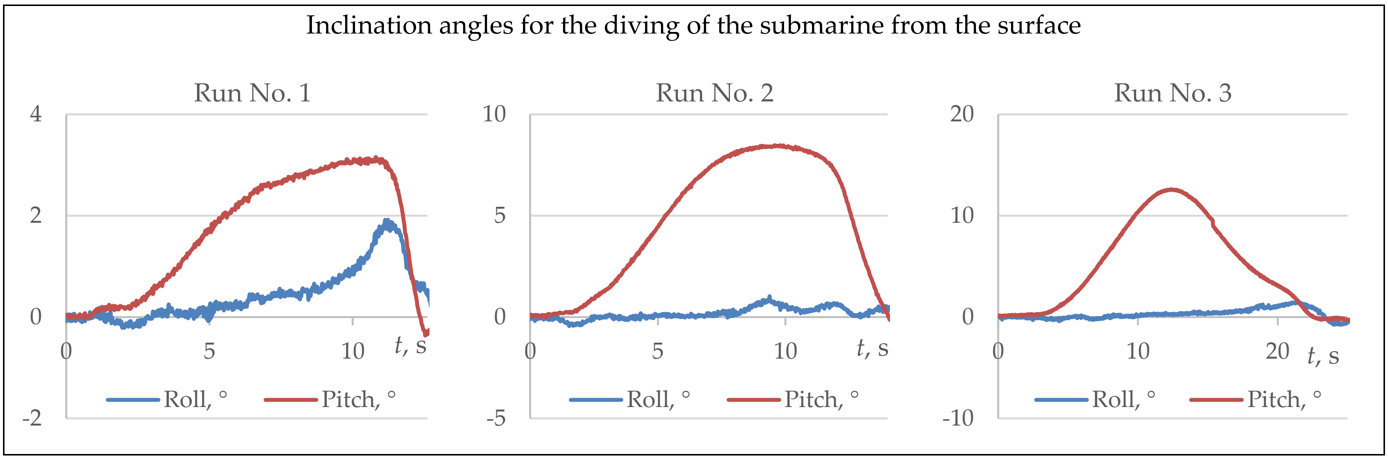

Figure 8. The inclination angles for the diving of the submarine from the surface with vertical thrusters (time axes at model scale).

Based on the observations and measurements, two phases within the diving manoeuvre are evident for B conditions. The first is transient, when the thrusters are rotating and the vertical position of the submarine is not changing. In the second one, the submarine model is in the process of diving. This transient period is the same for B2 and B3, while it is somewhat longer for B1, indicating that all three vertical positions of the thrusters yield similar initial conditions for the dive. Overall, for all B conditions, the thrusters are rotating, and the model is not moving vertically for more than one-third of the total time needed to dive. For C and D conditions, the diving starts almost immediately, after 2 s of engaging the thrusters (in the scale model).

The average diving velocities, given in Table 6, were calculated based on the total time required for the model to dive. The velocities and diving ability for the tested conditions were not sensitive to the changes in the vertical position of the thrusters. For B conditions, if the time when the model is moving vertically is considered, the diving velocities would be approximately 0.43 kn, similar to the values for C conditions.

3.2. Results on the Forward/Backward Sailing in a Submerged Condition

The model was propelled with the main propulsive thrusters (T31 and T32) at approximately 5 m (at full scale) from the towing-tank wall along a 50 m path. The tested velocities at full scale were 0.75 kn, 1.7 kn, and 3.0 kn, as presented in Table 8, where the testing scheme is given. The vertical thrusters (T11 and T12) maintained the submersion of the model. The angles of roll and pitch measured with the model sailing forward at constant velocities are presented in Figure 9.

Table 8. Testing scheme for the forward/backward sailing (velocities at full scale).

Run No.	Revolutions of Main Thrusters, r/s	Velocity, kn
1	49.5	3.0
2	30.7	1.7
3	20.7	0.75

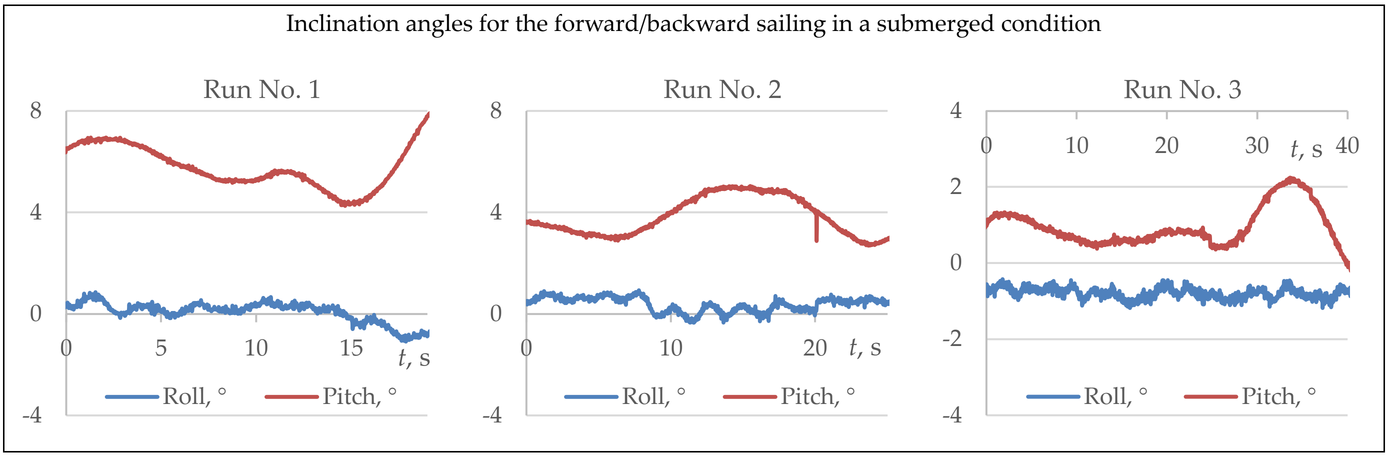

Figure 9. The inclination angles for the forward/backward sailing in a submerged condition (time axes at model scale).

3.3. Results on the Turning Manoeuvre in the Horizontal Plane of the Submerged Submarine

The turning manoeuvre in the horizontal plane was conducted by only one side thruster (T21 and T22), attaining different angular velocities of the model. The combinations of the thrusters' operation are presented in Table 9, alongside the averaged angular velocities at full scale. As in the previous tests, the vertical thrusters (T11 and T12) kept the model submerged. For all tested cases, the rotations of the model were counterclockwise. The measured values of the roll and pitch are presented in Figure 10.

Table 9. Testing scheme of the turning manoeuvre in the horizontal plane (angular velocities at full scale).

Run No.	Operative Side Thruster	Side Thruster Revolutions, r/s	Rotation Angle, °	Angular Velocity, rad/s
1	T21	19.2	180	0.014
2	T21	9.8	180	0.008
3	T21	6.6	90	0.006
4	T21	30.0	270	0.042
5	T22	30.0	270	0.046

3.4. Results on the Sideways Movement (Crabbing) of the Submerged Submarine

The crabbing test was performed over three runs at velocities of 0.78 kn, 0.61 kn, and 0.48 kn, corresponding to the full scale. Both side thrusters provided thrust in the same direction, one of them working forwards and the other one in the reverse direction. In the initial position, the submarine was positioned against the wall of the towing tank. After that, the distance travelled and the time needed were measured. Figure 11 shows the measured values of the inclination angles.

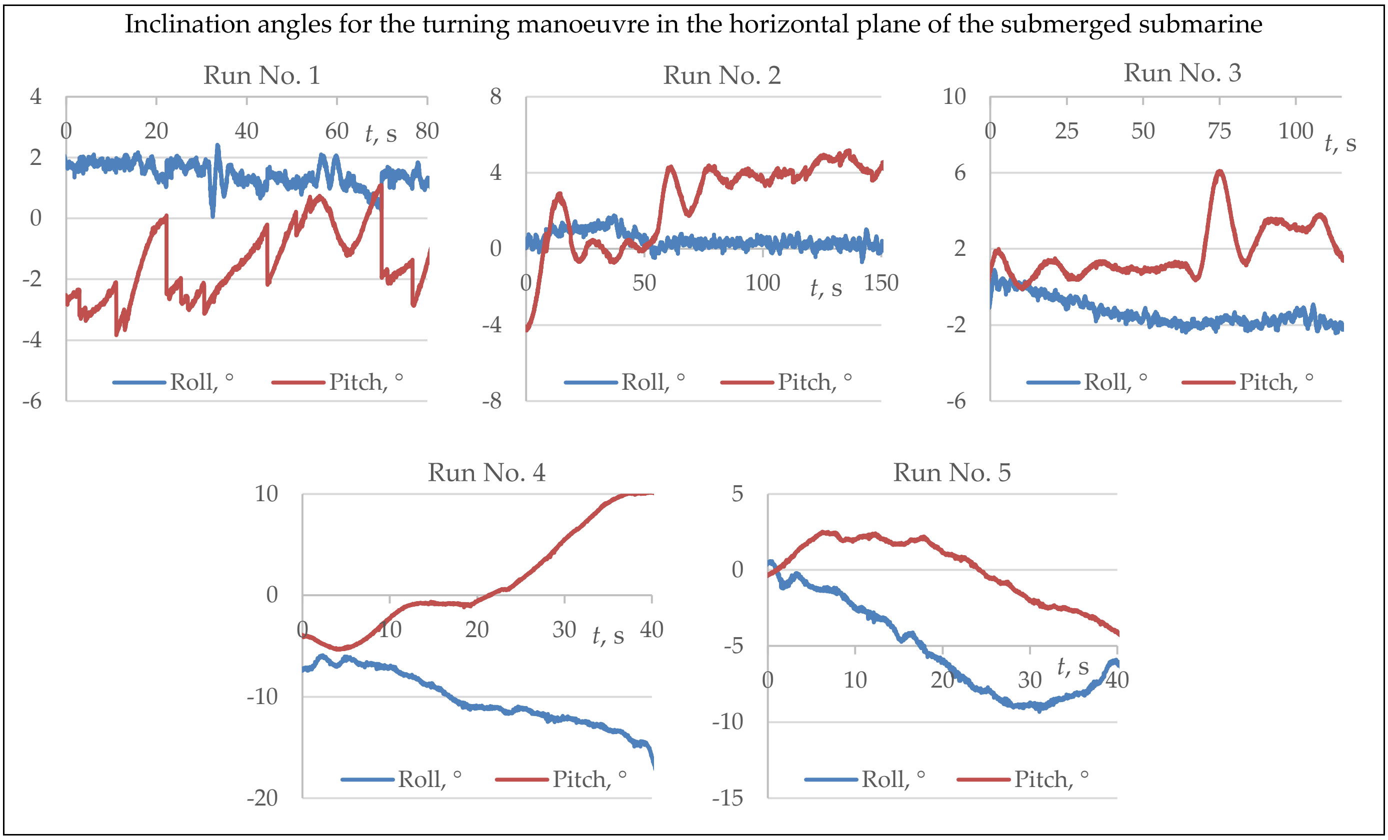

Figure 10. The inclination angles for the turning manoeuvre in the horizontal plane of the submerged submarine (time axes at model scale).

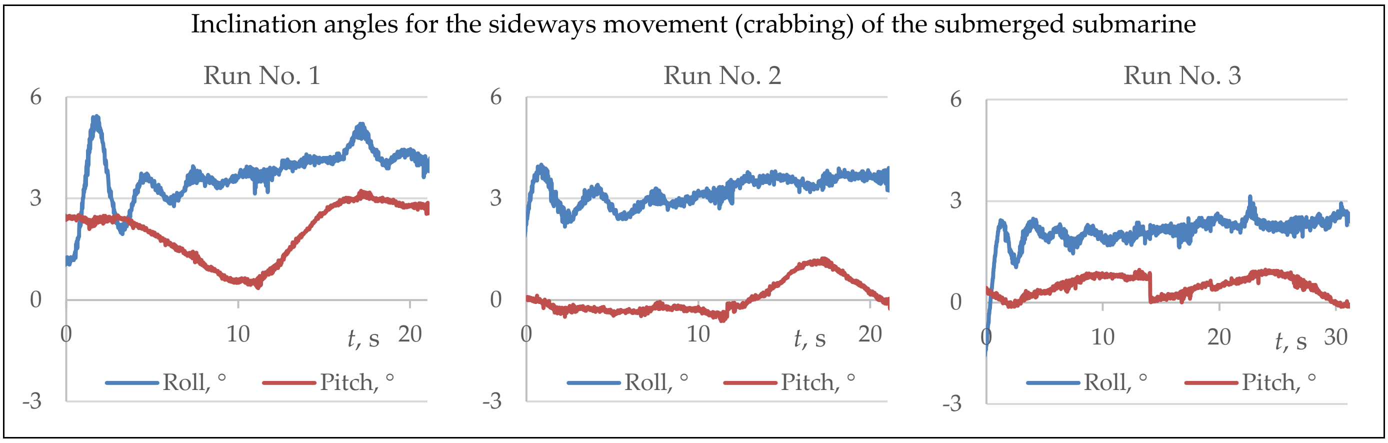

Figure 11. The inclination angles for the sideways movement (crabbing) of the submerged submarine (time axes at model scale).

3.5. Results on the Steering in the Horizontal Plane of the Submerged Submarine

3.5.1. Run No.1

The submarine model started the manoeuvre with propulsive thrusters (T31 and T32), with revolutions corresponding to the velocity of 1.35 kn (at full scale). The bow side thruster (T21), turning the model starboard, was in the operation regime corresponding to 0.33 kn. The vertical thrusters (T11 and T12) maintained the submersion of the model. The duration of the manoeuvre was 75 s (at full scale). The models changed the heading to approximately 30°.

3.5.2. Run No.2

The model entered into the manoeuvre with the propulsive thrusters in an operational regime of 1.3 kn, with the bow side thruster turning starboard at a regime corresponding to 0.57 kn. The duration of the manoeuvre was 48 s. During this time, a complete turn to the right side, i.e., a 90° change in heading, was conducted.

3.5.3. Run No.3

The turning was conducted similarly to Run No. 1 with the setting of the propulsive thrusters corresponding to the higher speed of 2.3 kn. The regime of the bow-side thruster was the same. The whole manoeuvre lasted 51 s.

3.5.4. Run No.4

Throughout this manoeuvre, propulsive thrusters operated at a regime of 0.48 kn. The rotation of the bow side thruster was altered in the following order:

- 30 s to the right;
- 40 s to the left;
- 20 s to the right.

The regime of the side thruster corresponded to a velocity of 0.5 kn. It was noticed that the model was not able to change the heading to the left after the model was directed to the right, possibly due to inertial forces and moments.

3.5.5. Run No.5

Throughout this manoeuvre, the propulsive thrusters were operating at a regime corresponding to a velocity of 0.32 kn. The rotation of the bow side thruster was altered, similarly to in the previous run, but in a different order:

- 20 s to the right;
- 40 s to the left;
- 40 s to the right;
- 35 s to the left;
- 40 s to the right.

The regime of the bow thruster again was 0.5 kn. The total time needed for the manoeuvre was 175 s. The change in heading to the right was fully efficient, while a heading change to the left was efficient in a second attempt. The model turned from heading to the right to the straight course for the first change to the left.

3.5.6. Run No.6

The propulsive thrusters were at a regime corresponding to a velocity of 0.32 kn. The bow side thruster operated at a velocity of 0.5 kn, alternating the thrust direction as follows:

- 20 s to the right;
- 40 s to the left;
- 40 s to the right;
- 30 s to the left;
- 40 s to the right;
- 30 s to the left.

The total time of this manoeuvre was 200 s.

The measured inclination angles for all the runs are presented in Figure 12, where the time axes are at model scale.

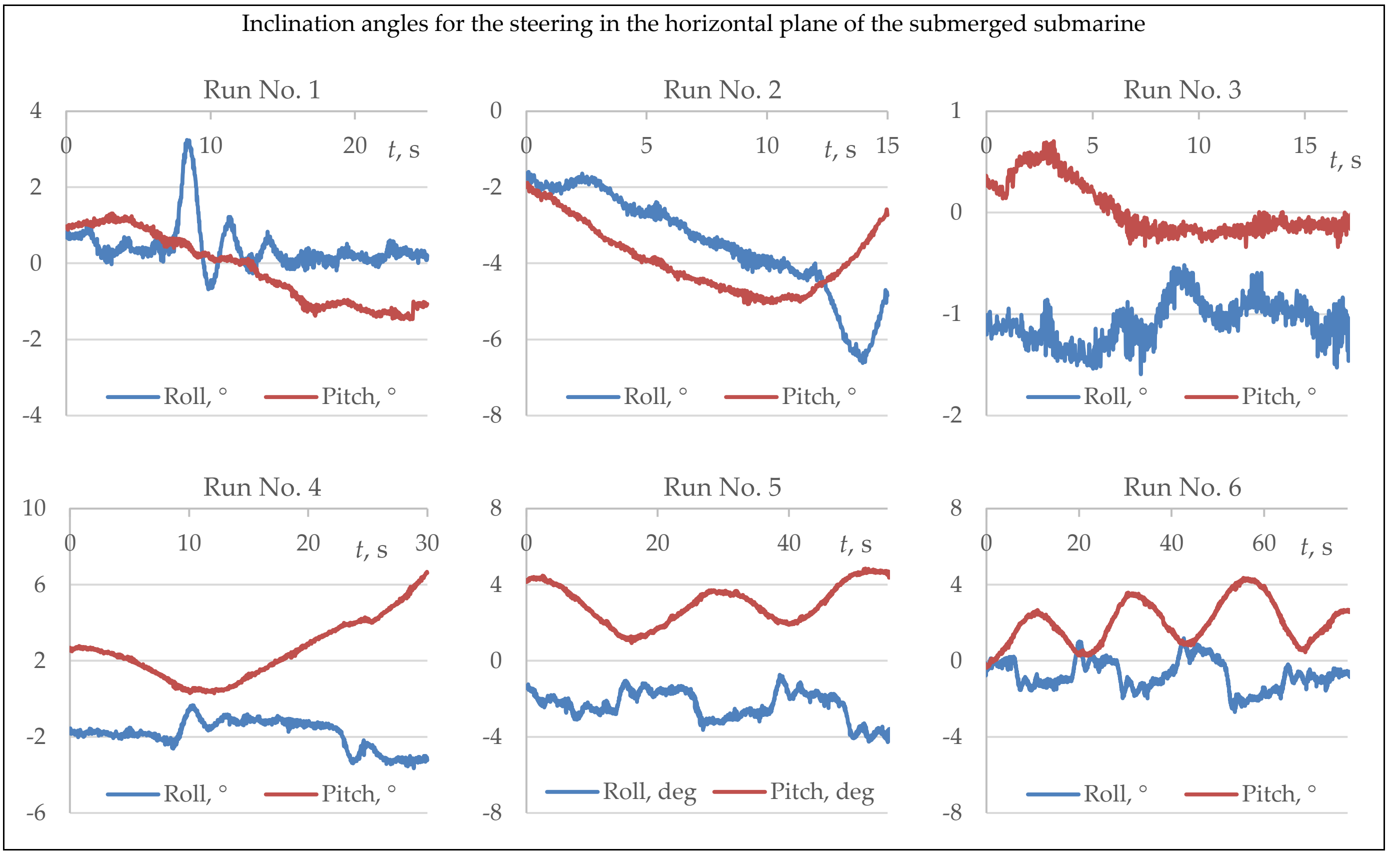

Figure 12. The inclination angles for the steering in the horizontal plane of the submerged submarine (time axes at model scale).

3.6. Results on the Steering in the Vertical Plane of the Submerged Submarine

3.6.1. Run No.1

This manoeuvre was conducted with operative vertical (T11 and T12) and propulsive (T31 and T32) thrusters. The propulsive thrusters provided forward thrust at the regime corresponding to the full-scale forward velocity of 2.15 kn. The vertical thrusters simultaneously provided thrust up and down, i.e., the front thruster down, the aft thruster up and vice versa. The total duration of this manoeuvre was 60 s (at full scale).

3.6.2. Run No.2

This run was performed in the same way as the previous one, except that the forward velocity corresponded to 2.2 kn. The total manoeuvre time was 50 s.

3.6.3. Run No.3

In this run, the combination of the velocity of 1.95 kn and the total manoeuvre time of 90 s was applied.

3.6.4. Run No.4

In this run, the velocity of the model was the same as in Run No. 1, corresponding to the value of 2.15 kn, but the total manoeuvre time was 105 s.

The measured inclination angles for all the runs are presented in Figure 13. The time axes in this figure are at model scale.

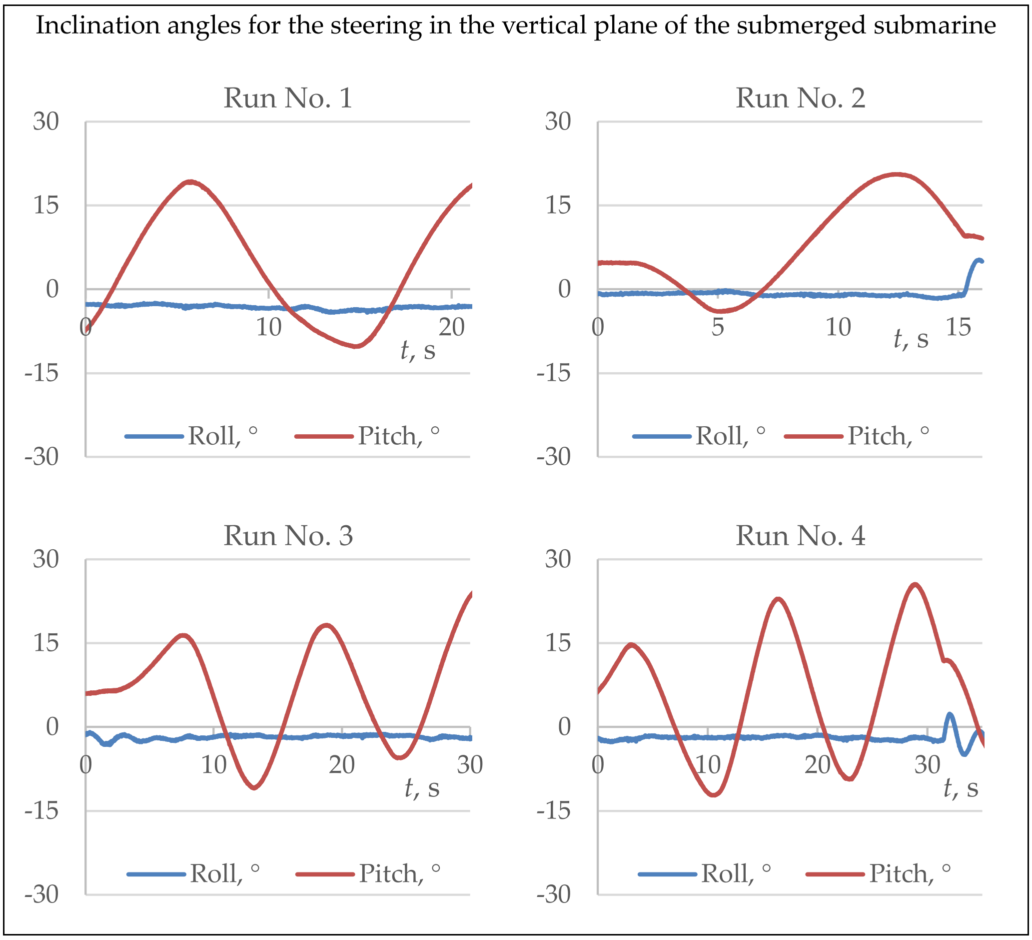

Figure 13. The inclination angles for the steering in the vertical plane of the submerged submarine (time axes at model scale).

4. Results on the Emergency and Regular Rising Tests

4.1. Results on the Rising in Regular Conditions

The testing depth was 2.8 m, corresponding to 25 m at full scale. The pressure applied for blowing MBTs was 0.46 bar (4.2 bar at full scale). In total, four runs were conducted. The graphs of the measured roll and pitch angles are in Figure 14, where the time axes are at model scale.

For all four measurements (runs), the roll values were small, below 2°; i.e., the model did not experience any roll instabilities during the ascending process (see Table 10).

Pitch angles were significant during all the conducted manoeuvres, whether to the stern or to the bow side. The pitch rate had similar values in all runs, as seen in Table 10. It was noticed that after emptying the MBT, the pitch angle decreased significantly (to the stern of the bow). As the rising process continued, the pitch angle decreased, and eventually, a stable position was obtained at the surface.

4.2. Results on the Rising with a Damaged Main Ballast Tank

The tests with damaged MBTs were conducted with the same blowing pressure of the tanks (4.2 bar at full scale) and at the same starting depth (25 m at full scale) as in the previous case. The measured inclination angles are given in Figure 15.

The roll instabilities were not detected; i.e., the roll values were small and below 3.7°, as presented in Table 11. Some of the roll oscillations were present immediately after releasing the drop weight. The pitch angles were significant during all the runs, as seen in Table 11. The release of the drop weight did not influence the pitch in terms of causing oscillations like in the roll.

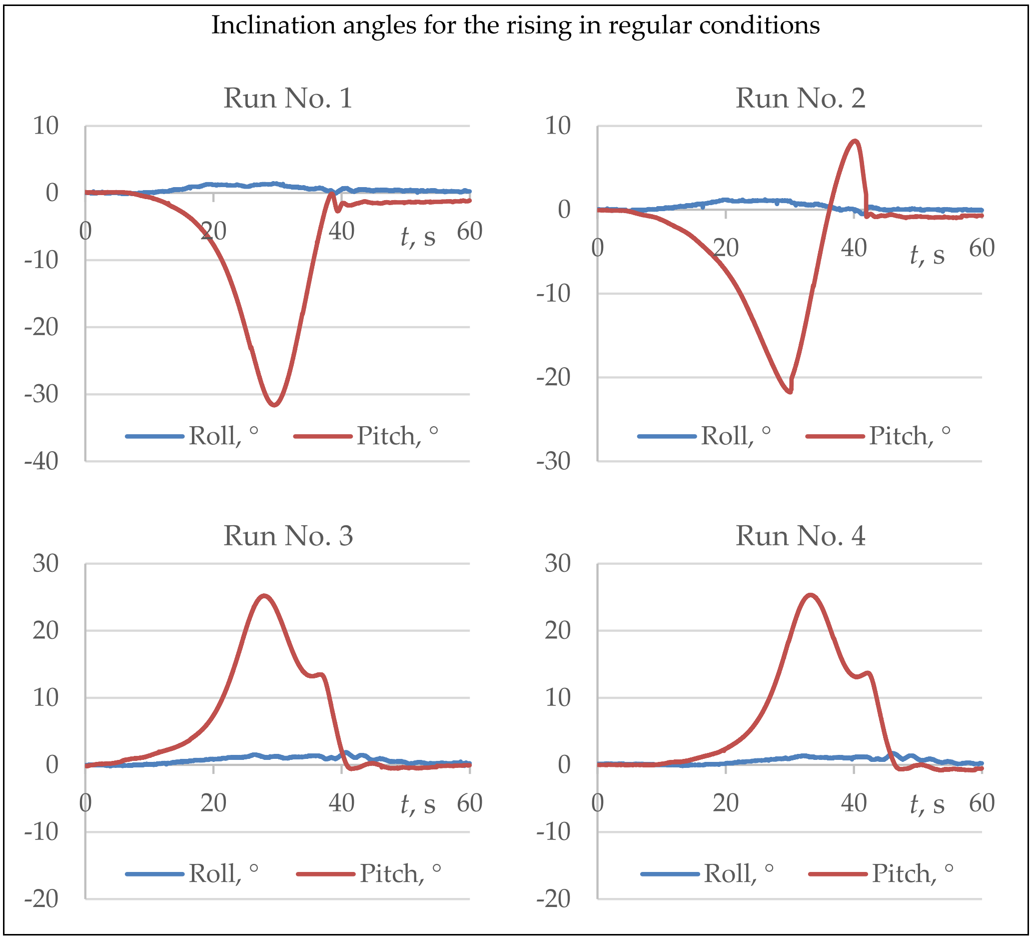

Figure 14. The inclination angles for the rising in regular conditions (time axes at model scale).

Table 10. Summarised results on the rising in regular conditions (pitch rate, duration, and velocity at full scale).

Run No.	Max. Roll, °	Max. Pitch, °	Pitch Rate, °/s	Duration, s	Velocity, kn
1	1.4	−31.7	0.5	105	0.47
2	1.2	−21.7	0.3	120	0.41
3	1.9	25.2	0.3	126	0.39
4	1.7	25.3	0.4	120	0.41

Table 11. Summarised results on the rising with a damaged main ballast tank (pitch rate, duration, and velocity at full scale).

Run No.	Max. Roll, °	Max. Pitch, °	Pitch Rate, °/s	Duration, s	Velocity, kn
1	3.3	−20.5	0.7	75	0.64
2	3.7	−27.4	0.8	81	0.58
3 *	3.0	−9.3	0.4	78	0.58
4	1.1	28.1	0.5	78	0.64

* Asymmetrical loading condition.

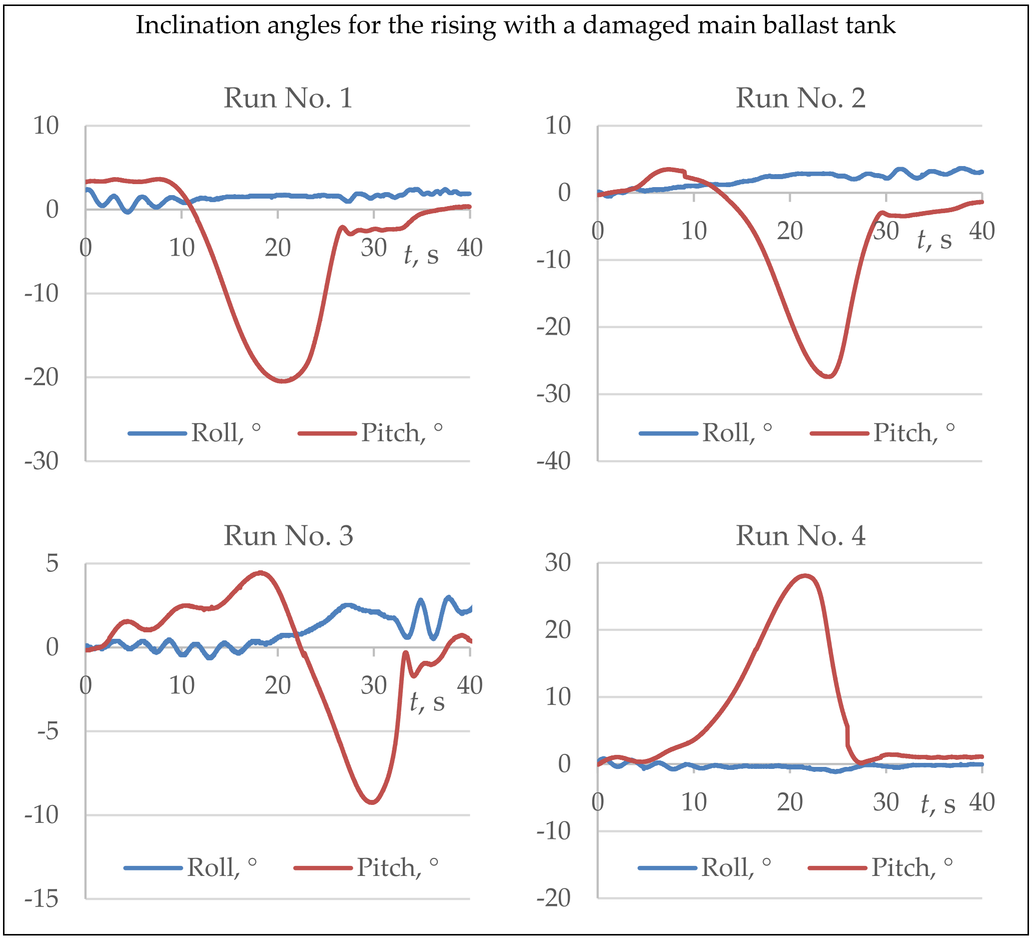

Figure 15. The inclination angles for the damaged main ballast tank (time axes at model scale).

Overall, the ascending process is faster than in the intact case, which can be attributed to the fact that the drop weight is released first, creating extra buoyancy in the hull. Once the ascending process was finalised, the final position of the submarine on the water was stable.

In Run No. 3, the asymmetric condition was tested in which the MBT's starboard side was damaged and not functioning. In this run, the pitch was lower than in other runs. The roll had higher values due to inequalities in the fulfilment of the tanks on the port and starboard sides.

4.3. *Results on the Rising with a Damaged Variable Ballast Tank*

Two runs were performed with a damaged variable ballast tank. After releasing the drop weight, minor oscillations in the roll are present for all conducted runs without affecting the pitch and the ascending process. Once the ascending process was finalised, the model's position on the water was stable. The measured inclination angles are in Figure 16 and summarised in Table 12.

Table 12. Summarised results on the rising with a damaged variable ballast tank (pitch rate, duration, and velocity at full scale).

Run No.	Max. Roll, °	Max. Pitch, °	Pitch Rate, °/s	Duration, s	Velocity, kn
1	1.7	−28.0	0.8	99	0.60
2	2.0	−20.1	0.8	96	0.51

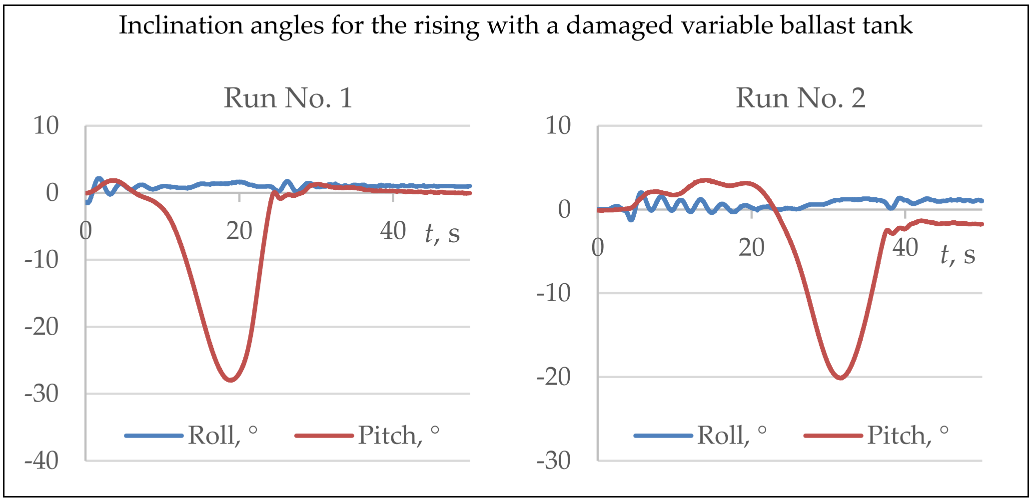

Figure 16. The inclination angles for the rising with a damaged variable ballast tank (time axes at model scale).

4.4. Results on the Rising with a Damaged Battery Pod

Tests with the damaged battery pod were conducted in the following way:

- Run No. 1—25 m depth at full scale and with a blowing pressure of 4.2 bar, also at full scale.
- Run No. 2—31.5 m depth and a pressure of 4.2 bar.
- Run No. 3—33 m depth and a pressure of 5.4 bar.
- Run No. 4—31.5 m depth and a pressure of 5.4 bar.

The roll was below 6.2° for all the conducted tests, without significant oscillations; see Figure 17 and Table 13. However, the oscillations were more pronounced than in the previous ascending tests, probably due to excess weight on the starboard side. The maximum value of the pitch was considerably high, and the corresponding rate was also significant, except for Run No. 4, which was conducted under higher pressure. As a result, the surfacing time was shorter and the pitch angle was also smaller.

Table 13. Summarised results on the rising with a damaged battery pod (pitch rate, duration, and velocity at full scale).

Run No.	Max. Roll, °	Max. Pitch, °	Pitch Rate, °/s	Duration, s	Velocity, kn
1	3.9	13.5	0.32	174	0.28
2	5.9	10.0	0.17	354	0.17
3	6.2	21.9	0.37	231	0.28
4	4.5	8.8	0.35	201	0.30

In general, the pitch angle decreases as the rising process evolves. Eventually, at the surface, the value settles approximately at 5° due to the aft trim caused by the flooded starboard battery. Since the excess mass of water that flooded the battery pod was larger than the mass of the drop weight, after surfacing and after the blowing was stopped, the submarine started to sink again with a significant aft trim.

4.5. Results on the Lifting of the Submarine

The lifting test was carried out with two values of the lifting velocity. The velocities were 0.07 and 0.42 m/s at full scale for Runs No. 1 and 2, respectively. The corresponding lifting times were 10.7 and 1.8 min (at full scale). The second run was significantly faster; consequently, one jump in the lifting force was observed, as seen in Figure 18. In the figure, the presented values are at full scale. In general, during the lifting, there were no significant sudden changes or oscillations in the lifting force for either of the lifting velocities.

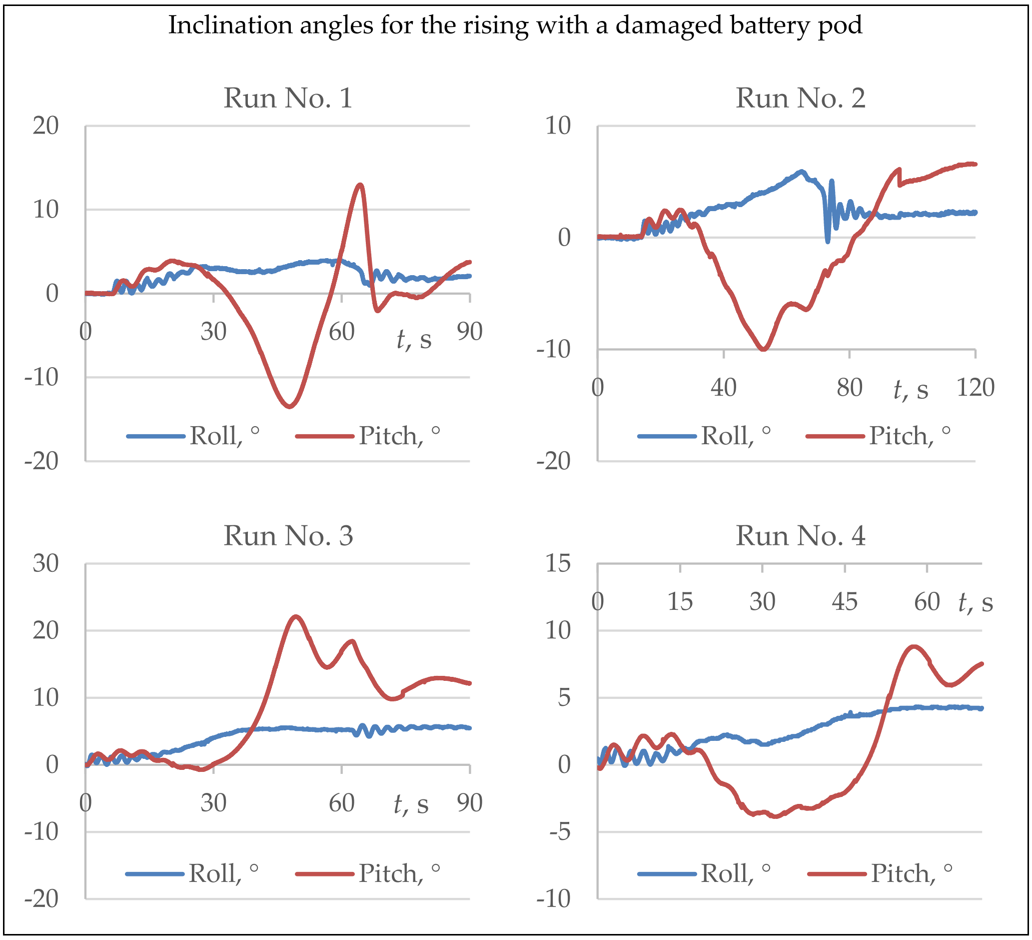

Figure 17. The inclination angles for the rising with a damaged battery pod (time axes at model scale).

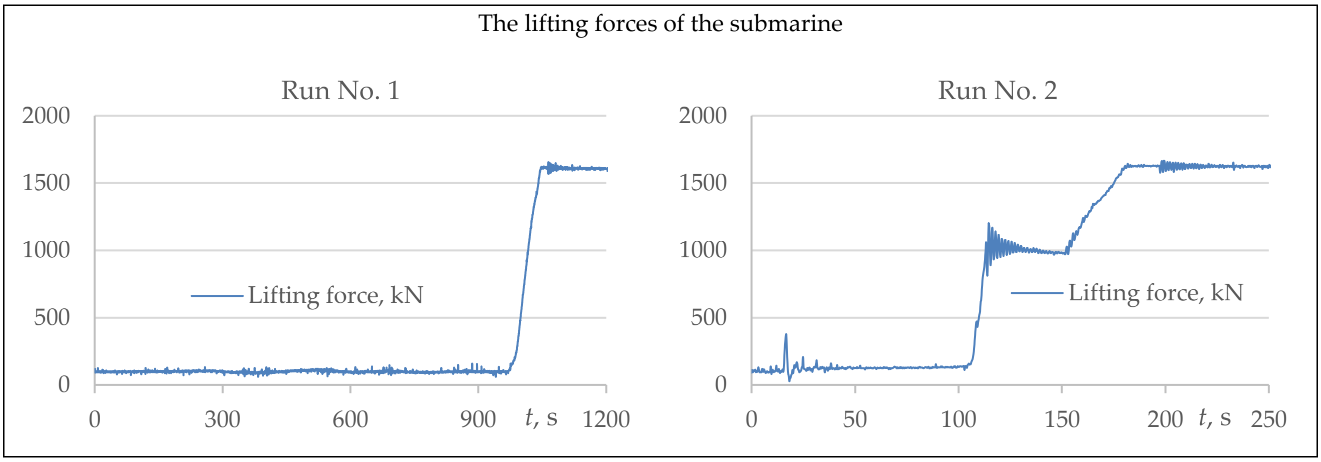

Figure 18. The lifting forces of the submarine (values at full scale).

5. Conclusions

Scale-model tests were conducted in the towing tank to study the innovative tourist submarine to determine its steering capabilities and to detect motion instabilities during usual manoeuvres and emergency rising. The submarine model was built on a scale of 1:9. Six different steering tests and four rising tests were conducted. During the tests, the roll and pitch were measured. Lifting the submarine by a crane was also part of the experimental study. Overall, the steering capabilities of the submarine were satisfactory, with just a few deficiencies. Major motion instabilities were not detected, even for the rising tests. In one rising test, the final position of the model at the surface was unstable. The conclusions for each test set are given in Sections 5.1 and 5.2. The obtained experimental measurements and conclusions can be used in the design of this type of submarine, indicating the safety issues concerning motion instabilities that need to be resolved. So, the paper brings valuable material for designing such a submarine type.

5.1. Conclusions on the Submarine Steering

Experiments of the submarine steering were conducted in a towing tank with a model of the innovative tourist submarine. The model had all six DOFs and was equipped with six functional thrusters operating in different combinations (working in pairs or separately). The stability and safety of the manoeuvres were evaluated based on visual observations and measurements of the inclination angles.

5.1.1. Conclusions on the Diving of the Submarine from the Surface with Vertical Thrusters

The vertical diving test was conducted with vertical thrusters working in pairs (T11 and T12). Three different vertical positions of the thrusters were checked, i.e., the initial position and positions 0.36 m up and down from the initial position (the full-scale values). For all three positions, four different operative thruster revolutions were applied. With the revolutions of the model thrusters set at 22.4 r/s, the model could not dive.

For the three other tested thruster revolutions, the diving was feasible, and the average diving velocity was similar for all three vertical positions of the thrusters, meaning that the change in the vertical position within the limits of ± 0.36 m does not affect the thrusters' efficiency. The average velocity increased when higher revolutions were applied.

The diving manoeuvre consisted of two phases for the applied revolution of 37.4 r/s. The first phase was transient, where the thrusters rotated but without significant vertical motion of the model. In the second phase, the diving started and was maintained by the thrusters. The duration of the transient phase was considerable, i.e., over one-third of the total manoeuvre time. Such a transient phase is absent for revolutions of 49.1 and 60.7 r/s. Therefore, the thrusters need to provide a certain amount of thrust to enable instant diving of the submarine. At full scale, the amount of thrust per thruster should be 11.5 kN, which is much more considerable than the estimated maximum thrust for vertical thrusters. Although such a calculation is a rough estimate, it is an indication that should be considered when dimensioning the vertical thrusters.

Overall, once the diving manoeuvre started, the differences in diving velocity with regard to the thrusters' positions were insignificant. The roll angle was not pronounced for any tested conditions; i.e., the maximum measured value was below 2°. The values of the pitch angles were similar for the tested cases. At first, the pitch angle increases, and when the diving progresses, it returns to the initial value (zero value). For lover average diving velocities, the maximum pitch values were approximately 12°. The maximum pitch was reduced as the diving velocities increased, so for the maximum velocity, the pitch was up to 3°.

5.1.2. Conclusions on the Forward/Backward Sailing in a Submerged Condition

Forward sailing along a wall at an approximately 5 m distance at full scale was tested for three different forward velocities. At the highest tested velocity of 3.0 kn (the full-scale value), the model inclined with the bow part towards the wall of the towing tank. The behaviour was more stable for lower velocities, and no approach to the wall was detected.

The roll values were low for all tested cases, while the pitch values changed more pronouncedly during the manoeuvres. The maximum pitch for the lowest tested speed of 0.75 kn was insignificant, but for the highest velocities like 3.0 kn, the maximum pitch value was 7.8°. For all tested cases, the pitch values were positive, i.e., the bow went up.

5.1.3. Conclusions on the Turning Manoeuvre in the Horizontal Plane of the Submerged Submarine

In turning manoeuvres conducted in the horizontal plane with the submerged model, different rotational velocities were tested; i.e., the angular velocity was changed in a range from 0.006 rad/s to 0.046 rad/s (at full scale). The manoeuvres were conducted with only one side thruster active (T21).

For lower angular velocities, the roll values are insignificant, while the pitch angles are somewhat higher, up to 6°, and there is no pattern of inclination angles during the manoeuvres. For higher angular velocities, the roll and pitch values tend to increase over time, so the maximum absolute value of the roll angle was 16°. The pitch values are somewhat less pronounced.

The test showed that rotation in the horizontal plane is a feasible manoeuvre with an arbitrarily chosen angular velocity. The velocity influences the time needed for the manoeuvre without affecting the path much. Such a manoeuvre can be conducted in real conditions with two side thrusters working in opposite directions. The applied approach in the tests with only one active thruster can be considered conservative.

Obtained values of the inclination angles can be considered small for lower angular velocities and moderate for higher tested angular velocities (over 0.04 rad/s), but there was no tendency towards stability loss during the manoeuvres.

5.1.4. Conclusions on the Sideways Movement (Crabbing) of the Submerged Submarine

Sideways movement manoeuvres ("crabbing") were conducted at three different velocities. Although the side thrusters are contra-oriented, finding corresponding revolutions to achieve the same level of thrust was easily manageable. The difference in revolutions for two side thrusters was approximately 10%.

The pitch angles were small for all three tested velocities, and no trend was established. The roll angles were also small, somewhat oscillating around the average value. Therefore, this manoeuvre can be considered stable even with an arbitrarily chosen velocity.

5.1.5. Conclusions on the Steering in the Horizontal Plane of the Submerged Submarine

These manoeuvres were conducted with the main propulsive thrusters (T31 and T32) operating as a pair, and with the bow side thruster (T21) used to provide thrust to the starboard or port side. The first set of manoeuvres included only turning to starboard, while the second set comprised turning alternatively in both directions (starboard and port).

Turning to starboard with a moderate thrust by the side bow thruster (T12) in combination with different revolutions of the main propulsive thrusters (T31 and T32) yielded similar resultant motions of the model. The roll and pitch angles were up to 3.2°. Turning to starboard with the larger thrust of the side thruster was more efficient in changing the heading, but the inclination angles (both roll and pitch) were somewhat more prominent, approximately 5 to 7°. Even such values can be considered acceptable for such manoeuvres.

The manoeuvre with alternating movements to starboard and portside was not conducted successfully when the main thrusters propelled the model at a velocity of approximately 0.48 kn (at full scale), despite the bow side-thruster revolution corresponding to a sideways velocity of 0.5 kn. When the thrust of the main thrusters was reduced to the forward speed of 0.33 kn, this manoeuvre was successful, so an alternate change in heading was observed. Throughout these manoeuvres, roll angles were small without a particular pattern. The pitch angles were also small, with the maximum values below 5°, but a slight oscillating pattern was established. Related to the limitation of inclination angles, frequent changes of heading in the horizontal plane were manageable and safe.

5.1.6. Conclusions on the Steering in the Vertical Plane of the Submerged Submarine

These manoeuvres were conducted by the main propulsive thrusters (T31 and T32) as well as the vertical thrusters (T11 and T12). The model maintained a straight course while manoeuvring in the vertical plane while the roll angles were below 5°. The pitch angles changed in a range from −15 to + 20°. The inclination angles were not too large, even at higher tested velocities, so the manoeuvres were performed stably.

5.2. Conclusions on the Emergency and Regular Rising Tests

Based on the conducted tests and the corresponding measurements and observations, the following can be concluded:

- All manoeuvres were accomplished successfully; i.e., for all tested conditions, the rising manoeuvres were completed.
- Even in the case of a damaged VBT or a damaged MBT, the final position of the submarine at the surface was such that both hatches were accessible (i.e., dry), and the final position of the submarine was stable. The stern hatch was in the water and inaccessible in damaged battery-pod conditions. Also, the final position of the model at the surface was unstable. Finally, the temporary hydrostatic instability due to sudden changes in the centre of buoyancy and gravity was not present in the tested cases.
- The fastest ascent was observed with a damaged MBT, but in all tested conditions, the measured velocity revealed that the required time to ascend from 50 m (at full scale) would be significantly less than 30 min.
- During all the conducted manoeuvres, the roll angels were small, and roll instability was not observed at any moment.
- During most of the conducted manoeuvres, the pitch angles were significant (above 20°) but did not endanger the rising manoeuvre or lead to any instability. The pitch was highly sensitive to the applied blowing pressure, but when arriving close to the surface, the pitch was always significantly reduced, and a final stable position of the model was obtained, except for the case with the damaged battery pod. The rising velocity was also highly sensitive to the applied blowing pressure.
- Overall, the rising stability was present in all the tested conditions, and overturning of the submarine model did not occur.
- Yaw behaviour was observed but without any significant occurrences. Also, excessive oscillation of the model or coupled motions was not observed.
- Based on the conducted tests, the recommendation is to examine the condition of the damaged battery pod since the rise time was significantly longer compared with other manoeuvres, and the final position at the surface was rather unstable.
- Lifting of the submarine model from the depth corresponding to 50 m at full scale was performed using a crane and rope while the lifting forces were measured. Two lifting velocities were tested without any issues or unexpected occurrences. However, for the full-scale submarine, it is necessary to check the structural integrity of the steel structure and the connection points that must withstand the lifting process.

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