NUMERICAL AND EXPERIMENTAL ANALYSIS OF THE HELICOPTER'S FLOTATION SYSTEM

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Abstract

The paper presents the results of numerical and experimental hydrodynamic analysis of the PZL SW4 helicopter, undergoing the modifications aimed at adopting it for maritime missions. The primary goal of the analysis was to design an effective emergency flotation system, assuring sufficient buoyancy and stability in calm water as well as minimized motion response to waves. The analysis started with an optimization study, based on simplified stability model. The helicopter with designed floats was then widely analysed in respect of buoyancy, stability and motion response to waves, both by means of experimental analysis with scaled physical model, and with numerical models. Such a parallel approach allowed minimizing the uncertainty, as good agreement of the results was confirmed. As a result, satisfactory performance of the emergency flotation system was proved. The paper gives also the details of the development of physical model of the helicopter, as well as the details of experimental methods used in the analysis.

1. INTRODUCTION

1.1. Background

The research presented in the paper was conducted as part of the INNOLOT sector project (acronym HELIMARIS) entitled “Modification of an optionally piloted helicopter to maritime mission performance” coordinated by Wytwórnia Sprzętu Komunikacyjnego “PZL-Świdnik” Spółka Akcyjna. The goal of this research is to adopt the well known SW4 helicopter for maritime operations, and one of the modifications consists in equipping it with an emergency flotation system, consisting of two inflatable floats. The floats are divided into compartments so as to minimize the effect of possible damage, and the system is required to assure sufficient buoyancy and stability for each single failure mode. The paper presents the results of numerical computations and laboratory tests carried out with scale model, realized to check the performance of the emergency flotation system.

1.2. Scope of the work

The presented work can be briefly summarized as the design of the emergency flotation system and verification of its performance in respect of buoyancy, stability and motion response to waves. 9 loading conditions were analysed in total (3 values of mass and 3 locations of centre of gravity). Five of them were considered in parallel numerical and experimental analyses. Development of physical scale model of the helicopter is described in separate chapter. The analysis starts with optimization study for two types of the floats considered to be used as the emergency flotation system: the floats of constant diameter and the floats of variable diameter. In both cases, the loss of buoyancy of each single compartment is to be taken into account. The proposed optimization procedure and achieved results are presented; the application of variable diameter allowed considerable reduction of the trim and heel angle range. The design process of the floats thus includes also the preliminary buoyancy analysis, i.e. evaluation of draught, trim and heel for each loading condition. This computational analysis of buoyancy was carried out using Maxsurf Hyrdomax software.

The result of computational buoyancy analysis were then verified using the physical model of the helicopter. The verification was based on visual comparison between computed and observed position of the helicopter in calm water.

Second stage of verification of the flotation system performance is the analysis of large angle stability. The computational analysis was also carried out with Maxsurf Hydromax; the righting arm was evaluated for large range of heel and trim angle. The tailored measurement stand was

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developed to verify the computational results; it allows exerting pure heeling/trimming moment on the model.

Finally, computational and experimental analysis of the helicopter’s motion response to waves was executed. The computations were carried out with the use of ANSYS AQWA software, and the experimental verification was realized in the Offshore Laboratory of CTO S.A.

Further work, still in progress, is the experimental ditching analysis, in which the helicopter with rotating rotor will be tested in large regular waves.

1.3. Testing conditions

The analyses of buoyancy and large angle stability refer to calm water conditions; the environmental conditions specified below, selected in accordance with [1], are thus related only to the motion response analyses. The meaning of the symbols is as follows:

- Ss – denotation of sea state
- H_S – significant wave height
- T_P – wave peak period
- γ – peak enhancement factor (feature of wave energy spectral density function)
- V_W – wind speed.

Ss	H_S [m]	T_P [s]	γ [-]	V_W [kn]
2	0.5	4.5	3.3	10
5min	2.5	6.28	1.0	22

The emergency flotation system is required to prevent the contact of rotors with water at sea state "5min" for intact condition and at sea state 2 for each single failure mode. The wave energy spectral density functions ([2]) for two considered sea states are presented in Fig.1 below.

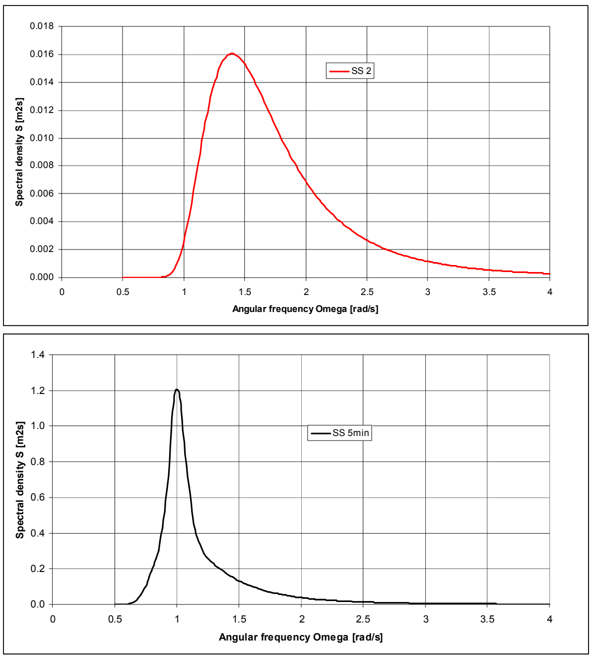

Fig.1 Wave energy spectra

For each loading condition, the helicopter was analysed for five heading angles, within the range of 0°-30°; for one case, the range 0°-90° was also analysed. The convention of heading angle is presented in Fig. 2

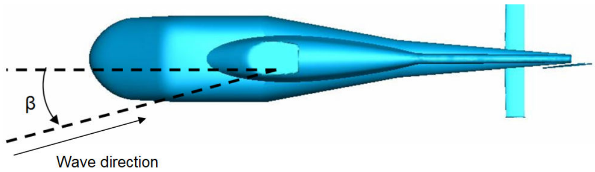

Fig.2 Wave heading angle convention

2. CONSTRUCTION OF PHYSICAL MODEL OF THE HELICOPTER

2.1. Fuselage

The hydrodynamic tests carried out by specialized model testing institutions are a commonplace in maritime industry and follow standardized procedures. The models of ships, typically 5-10m long, are usually manufactured of wood, which allows good compromise between ease of manufacturing, strength and weight for this kind of unit production of relatively large structures. However, in case of relatively small helicopter to be tested in large waves, the standard approach is not applicable. It should be noted that the mass of the model decreases with third power of the scale factor, and the scale factor for the model to be tested in waves is limited by the wavemaker capability. Moreover, dynamic balancing of the model has to cover quite large range of loading conditions, with variable mass, COG location and moments of inertia. This requires that the empty model structure is a very lightweight and sufficiently stiff and durable construction which withstands the seakeeping and ditching tests while allowing modelling its mass and moment of inertia in wide range.
The selected scale ratio, resulting from required wave height to be used in the test and the wavemaker capability, was 1:8. This means that the fuselage of the physical model is approximately 1m long, while its mass should be approximately 1kg to allow modelling all specified loading conditions. The selected construction type consists of stiffeners made of PVC foam, and the shell plating made of PET. Inside the fuselage, long threads were mounted, on which the dedicated steel weights are installed. The number and location of the weights allow changing total mass and location of centre of gravity, while symmetrical shifting of the weights allow changing the moment of inertia without changing the location of centre of gravity. Interior of the fuselage of the model is presented in Fig.3

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Fig.3 Construction of the model fuselage

2.2. Rotor

For the tests of buoyancy and stability, the rotor is only a dummy object, and the only requirement regarding its physical model is that the mass features of the helicopter with rotor are maintained. However, for the ditching tests, the situation is different, as the angular momentum of rotating rotor has crucial influence on the behaviour of the helicopter at the moment of contact with water surface; the change of direction of angular momentum vector causes gyroscopic reaction which influences considerably the fuselage motion. Thus, the angular momentum of the rotor is to be scaled accurately according to Froude's scaling laws. As the angular momentum is a product of moment of inertia and rotation rate, accurate scaling of both these quantities is sufficient to model correctly the angular momentum. However, this direct approach turned out to be problematic due to the following reasons:

- In order to avoid using external cable or heavy power cells during the ditching tests, the rotor rotates freely without propulsion; this also eliminates the risk of contact of electric engine with water;
- Froude scaling of the rotor angular speed requires the model rotor rotates faster than at full scale. Taking into account that the resistance is approximately proportional to squared angular speed, the rotation rate of the rotor without propulsion decreases very quickly. This makes the result of the test inconclusive, as the rotor speed is different in each moment of the test.

The proposed solution of this problem consists in increasing the moment of inertia of the rotor and at the same time reducing the rotation speed. This causes not only reducing the aerodynamic drag of the blades due to lower speed, but also reducing the deceleration due to larger moment of inertia. The rotor designed for ditching tests was then constructed in the following way:

- the head was constructed of aluminium;
- the blades were made of lightweight balsa wood, with stiffeners of carbon composite;
- the tips of the blades were made of bronze to maximize the moment of inertia with minimum influence on total mass.

The actual rotation speed of the rotor at full scale is 7.28 rps. The direct Froude scaling thus requires that the rotor speed at model scale is 20.6 rps, which is problematic by itself as each minimum imbalance induces strong vibration. However, the most important problem is that the rotational speed of freely rotating rotor decreases dramatically in time. The proposed solution consisting in using bronze blade tips allowed reducing the rotational speed to 5.85 rps while keeping the angular momentum constant. The figure below shows how the rotational speed changes in time for two values of moment of inertia - the one resulting directly from Froude scaling (M1) and increased value allowing correct modelling of angular momentum at reduced rotation speed (M2).

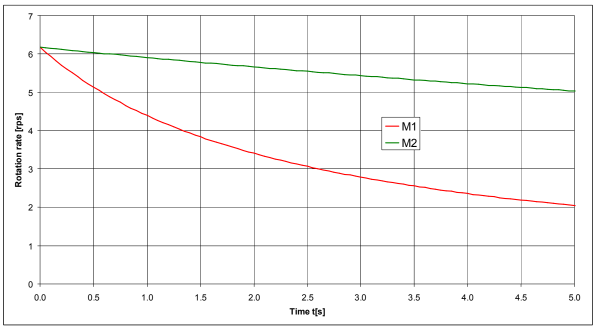

Fig.4 Model rotor rotation speed vs. time - free rotation

Note that required rotational speed for moment of inertia M1 is 20.6rps, which would result in much faster decreasing of speed, while it should remain approximately constant for at least 1 second.

2.3. Floats

The actual full scale floats are inflatable, which makes them extremely lightweight. An attempt on using the low density polystyrene foam was made for modelling the floats; an advantage of this material is that the contribution of floats to total mass and moment of inertia of the model is very small, however, its moisture absorption turned out to be unacceptable. The final models of floats were then made of heavier but more moisture-resistant styrodur foam. The failure of the floats was modelled by total elimination of damaged compartment.

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The complete model with damaged float is presented in figure below; the opening in the fuselage is provided for changing the balancing of the model, while small balls on the fuselage are the markers of the motion tracking system QUALISYS.

Fig.5 Complete model

3. FLOTATION SYSTEM OPTIMIZATION STUDY

The flotation system is required to prevent excessive trim or heel in calm water, as well as to prevent the contact of the main rotor and the tail rotor with the water surface in specified sea conditions. In presented study, two types of the float geometry were considered: the cylindrical floats, as well as the floats of variable diameter. It is assumed that the volume and length of the floats are kept constant and equal to specified upper limits. The goal is then to distribute the volume of the floats so as to minimize static heel and trim over a range of the helicopter loading conditions, as well as to minimize the motion in waves. The complexity of the task further increases due to the fact that the floats - each divided into five compartments - are required to assure sufficient buoyancy and stability also in case of single failure, i.e. when one of the compartment loses its buoyancy. Each single failure is to be considered. The optimization study is described below.

3.1. Cylindrical floats

The optimization procedure for cylindrical floats is relatively simple, as the diameter and length of the floats are predefined, and the only variables are: location of the float along the hull, and location of the bulkheads between the compartments. The optimization can then be done in a "guess-and-check" manner, i.e. each next iteration can be corrected based on the results from the previous one. The analyses were carried out with the use of Maxsurf Hydromax software, allowing for accurate prediction of equilibrium position of the floating body for specified loading condition. The computational model is presented in Fig.6 below.

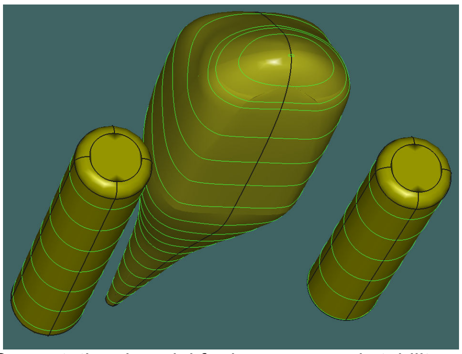

Fig.6 Computational model for buoyancy and stability analysis

The goal was to equalize as accurately as possible the maximum trim and heel angles for extreme cases. In other words - when the centre of gravity is shifted forward and the front compartment is lost, the trim by nose should be similar to the trim by tail in case when the centre of gravity is shifted aft and the aft compartment is lost. It should be mentioned that minimizing the size of aft and front compartment should be done with care, as it is also required to prevent excessive heel angle in case of loss of the central compartment. Example results of the evaluation of equilibrium condition for different failure modes are presented in Fig.7; the presented cases are (top to bottom):

- failure of front compartment, centre of gravity shifted forward;
- failure of aft compartment, centre of gravity shifted aft;
- failure of central compartment, centre of gravity shifted to the side (rear view).

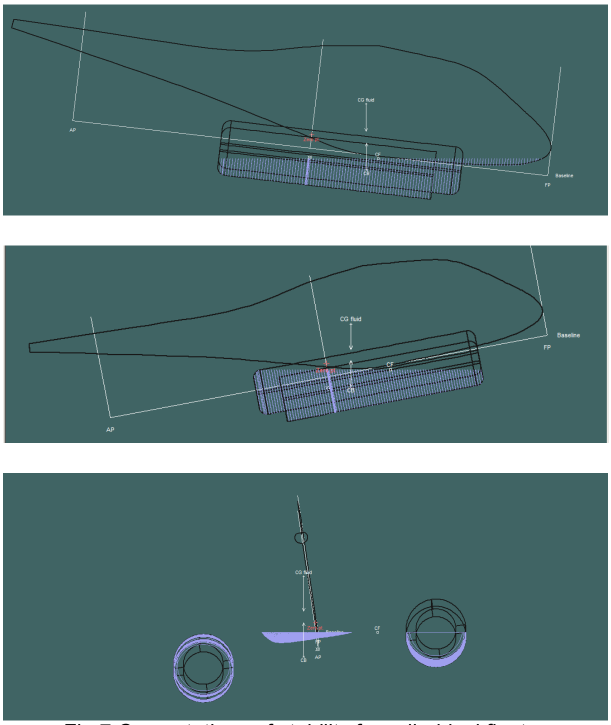

Fig.7 Computations of stability for cylindrical floats

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As a result of the optimization based on stability computations, it was possible to keep the maximum trim and heel angle ranges within the following limits:

- trim angle: 12.5 degrees
- heel angle: 7.6 degrees.

The geometry of the floats was then tested with the use of physical model to verify its performance in waves. The figure below shows the test for intact case at sea state "5min". This initial test revealed that cylindrical floats are not sufficient to prevent frequent contact of the tail rotor with water surface, which confirmed the need of further optimization with taking into account variable diameter of the floats.

Fig.8 Tests in waves with cylindrical floats.

3.2. Floats of variable diameter

The basic concept of the shape of the floats characterized by variable diameter is presented in Fig.9 below. The compartment of largest diameter is located aft. The division of the floats to five compartments is marked with colours.

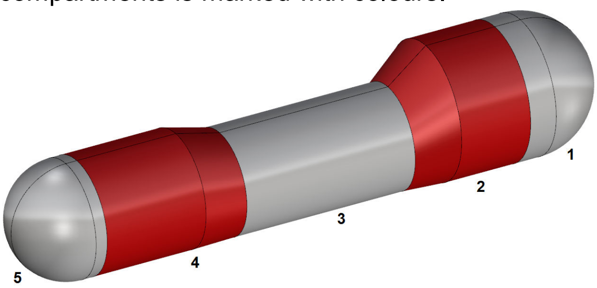

Fig.9 Float of variable diameter - scheme

Unlike the optimization of cylindrical floats, the optimization of floats of variable diameter involves much more decision variables, so the "manual" procedure consisting in subsequent corrections based on the results from previous iteration is no longer effective. Thus, formal optimization procedure was proposed to make sure that the proposed solution is actually the optimum one. The goal function, described above as minimization of the trim and heel angles over a range of loading conditions and failure modes as well as minimization of the risk of contact of the rotors with water, now needs a mathematical formulation. It was assumed that the required goal can be achieved by maximization of restoring moments in pitch and roll motion, which is obviously true for stability, but not necessarily for motion in waves, where "stiffer" characteristics of the floating body can result in shifting the natural frequency of motions closer to the maximum of the wave energy spectrum (see Fig.1), i.e. the resonance can occur. The dynamic characteristics were then not taken directly into account in the optimization; instead, the geometry optimized in respect of stability was verified afterwards by dynamic analysis.

The restoring moment of the floating body is proportional to its the metacentric height, defined as:

(1) $$h_0 = z_B + r_0 - z_G$$

where z_B is the centre of buoyancy, z_G is the centre of gravity and r_0 is the metacentric radius:

(2) $$r_0 = \frac{I}{V}$$

where I is the geometric moment of inertia of the waterplane, and V is the displacement volume. Note that this value is different for pitch and heave motion.

For given centre of gravity and displacement volume, the parameter most influenced by changes of the shape of the floats is the geometric moment of inertia of the waterplane; approximate shape of the waterplane of the floats is presented in Fig.10 below.

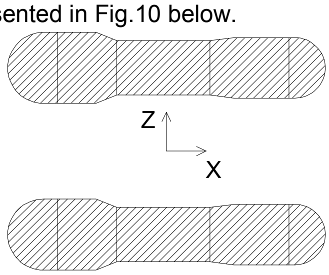

Fig.10 Waterplane of the flotation system - intact case.

It can be seen that in order to maximize the moment of inertia I_{XX} (roll motion), one has to maximize the diameter in general, while to maximize the I_{ZZ} (pitch motion), the diameter of front and aft compartment should be maximized. This, however, should be done with care, as the more volume is put to the ends of the float, the more volume will be lost in case of the compartment failure. An example of the waterplane for single failure case is presented in Fig. 11.

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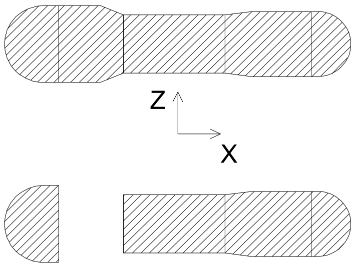

Fig.11 Waterplane of the flotation system - exapmle of single failure

The selected goal function is then the minimum value of moments of inertia for all considered failure modes; this value is to be maximized.

Optimization was carried out in the following way (see denotation of variables in presented in Fig.12):

- The lengths and diameters of two cylindrical parts (L1, D1, L2, D2) were used as decision variables;
- Proportion between the length of the conical parts (L1/2, L2/3) and adjacent cylindrical parts (L1, L3) was taken as constant.
- For each combination of decision variables (L1, D1, L2, D2), the length and diameter of third cylindrical part (L3 and D3) were computed analytically to match the assumed total length and total volume.
- The decision variables were changed within allowable limits from minimum to maximum. 50 values of each variable were checked, i.e. 6.25 millions of combinations were analysed in total. For each combination, minimum value of the moment of inertia of waterplane (of all failure modes) was compared with the values for other combinations. The combination of dimensions (L1, D1, L2, D2) resulting in largest value of minimum moment of inertia of waterplane for all considered failure modes was taken as optimum.

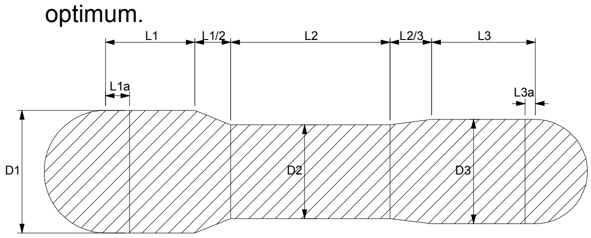

Fig.12 Denotation of variables

The procedure described above was repeated for several locations of bulkheads in the cylindrical parts, i.e. several values of L1a/L1 and L3a/L3. Figure 13 below shows how the geometry of the float changes during the optimization process (the spherical parts are marked in a simplified way with two straight lines).

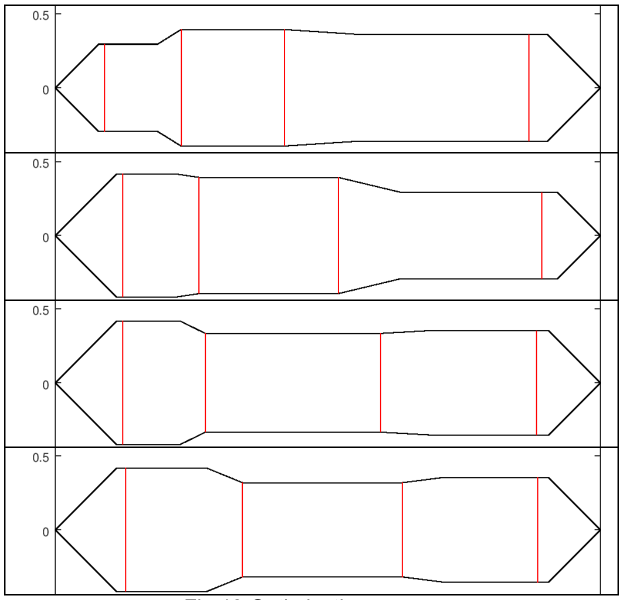

Fig.13 Optimization process

As a result of using variable diameter and the optimization, the range of trim and heel angles was reduced (compared to cylindrical floats) as follows:

- trim angle: 12.5 to 9.6 degrees;
- heel angle: 7.6 to 5.4 degrees.

4. RESULTS OF HYDROMECHANIC ANALYSES

All the analyses presented in this chapter were carried out both by means of computational and experimental analyses. This parallel approach allows minimizing the uncertainty as well as calibrating the computational models to apply them for wider range of parameters.

4.1. Buoyancy

As the computations of buoyancy are exact, i.e. no simplifications are applied in the computational model and the accuracy is limited only by the accuracy of the integration method, the comparison of the results with the experiment was done in a simplified way i.e. by visual comparison of the helicopter position relative to the surface in computational model and in the experiment. This comparison can be in fact considered the verification of correctness of physical model in respect of shape

The example comparison presented below shows the helicopter position for two extreme locations of centre of buoyancy. For each of them, most critical failure of the float was considered.

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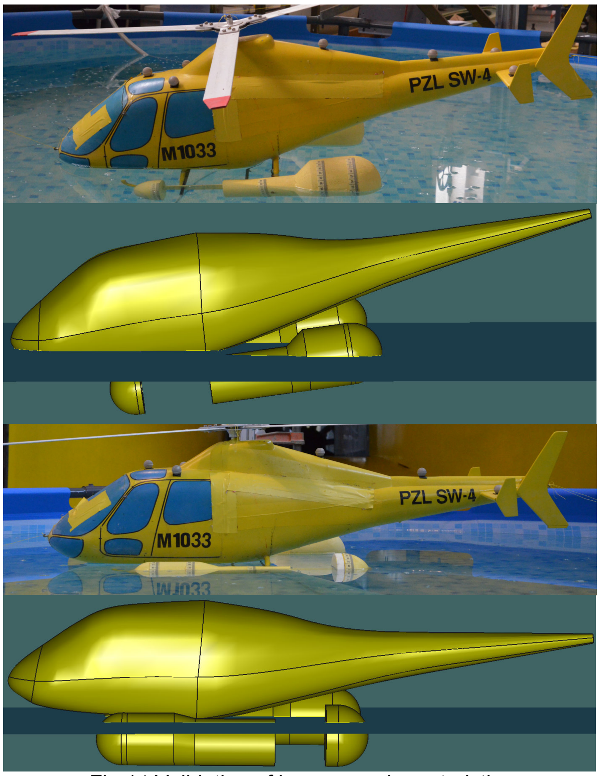

Fig.14 Validation of buoyancy characteristics

4.2. Stability

The results of computational analysis of stability included:

- helicopter's righting arm vs. heel angle;
- helicopter's righting arm vs. trim angle.

The experiment consisted in exerting specified heeling/trimming moment on the helicopter's fuselage and measuring the resulting heel/trim angle. The moment was exerted by a pair of very light lines, one attached to the top of the rotor's head, second one attached to a hook fixed to the skids (Fig.15). The vertical distance between the attachment points, is denoted as dY.

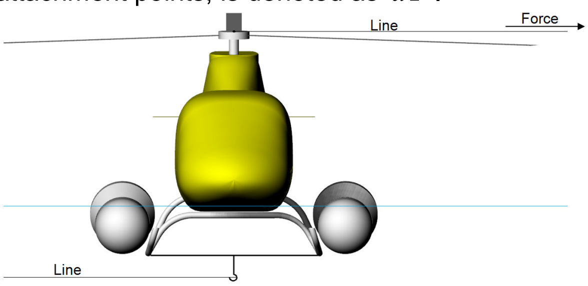

Fig.15 Large angle stability - test principle

The scheme of the measurement stand is presented in Fig.10 below. The second end of the line attached below the helicopter's skids is attached to a fixed point on the tank's side, while the line attached to the top of the rotor is led through three wheels rotating on low friction bearings, as presented in the scheme. Second end of this line hangs vertically, with a pan tied to it. In order to balance the weight of the pan, equivalent weight was used as presented in the scheme, which assures zero heeling moment when no additional weight is placed on the pan.

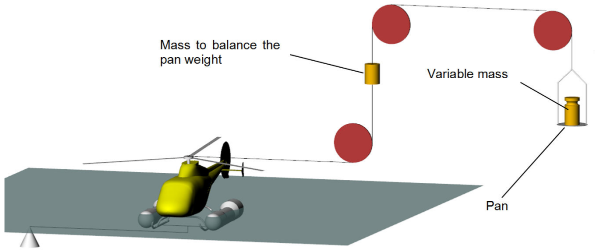

Fig.16 Measurement stand - large angle stability

The value measured directly in the experiment is the vertical displacement of the pan Y_P for given mass m.
The heel/trim angle is then evaluated according to the formula:

(3) $$\alpha = \sin^{-1}\left(Y_P / dY \right)$$

while the heeling/trimming moment is computed as:

(4) $$M = m \cdot g \cdot dY \cdot \cos(\alpha)$$

The scheme of the system kinematics is presented in Fig. 17 below.

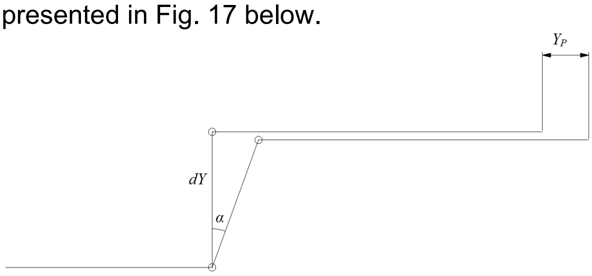

Fig.17 Evaluation of trim/heel angle

Example comparison between the results of computational and experimental analysis of large angle stability is presented in Figures 18 and 19 below. Note that the experiment can be realized only in the range of increasing righting moment value; for larger angles and constant heeling/trimming moment, the helicopter capsizes.

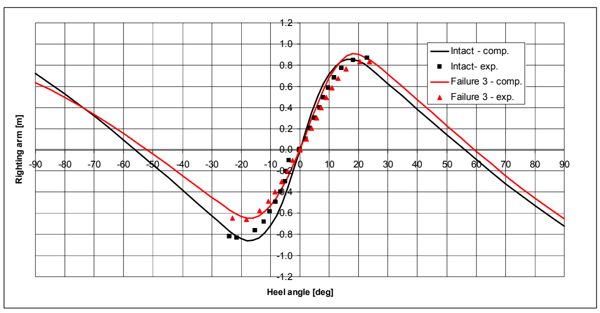

Fig.18 Large angle stability - validation, heel

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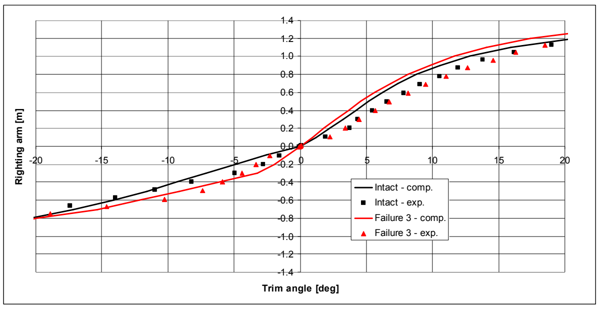

Fig.19 Large angle stability - validation, trim

4.3. Motion response to waves

Analysis of the buoyancy and stability was carried out with the use of ANSYS AQWA software, based on diffraction theory. The computational model is presented in Fig. 20 (mesh and motion for sample regular wave). The direct output of frequency domain analyses are response amplitude operators (RAOs) of analysed quantities in regular waves. Basing on RAOs, the short term predictions of absolute fuselage motions and relative motions of the rotor blades most prone to the contact with water were prepared

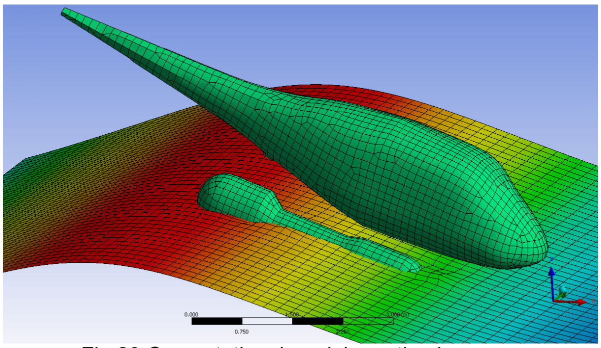
Fig.20 Computational model - motion in waves

The RAO (response amplitude operator) means the amplitude of motion response to regular wave of unit amplitude, given as a function of angular wave frequency ω. It is a transfer function for motion, i.e. characteristics of a floating object ([3]). Knowing the $RAO(\omega)$ and the wave spectral energy density function $S(\omega)$ (characteristics of the environment), the root mean square (RMS) of the response can be predicted using the formula:

$$RMS^2 = \int_{\omega} S(\omega) \cdot RAO(\omega) d\omega \quad (5)$$

where ω is the angular wave frequency. Note that this formulation is general and relates to all six degrees of freedom of motion.

Computational analyses of the helicopter motion were validated based on the experiment carried out in the Offshore Laboratory of CTO S.A. The helicopter model was exposed to wind and waves as presented in Fig.12 below. The restrictions of motion were as follows:

– the model was moored using two elastic lines to prevent the drift motion, while maintaining negligible influence of the lines on the wave frequency motion;
– the wave heading was adjusted by changing the location of the mooring points (Fig.13).

The model was exposed to irregular waves of specified spectral density functions, i.e. the root mean square of the motion response is a direct result of the measurement. The motion was tracked using the 6DOF visual QUALISYS system.

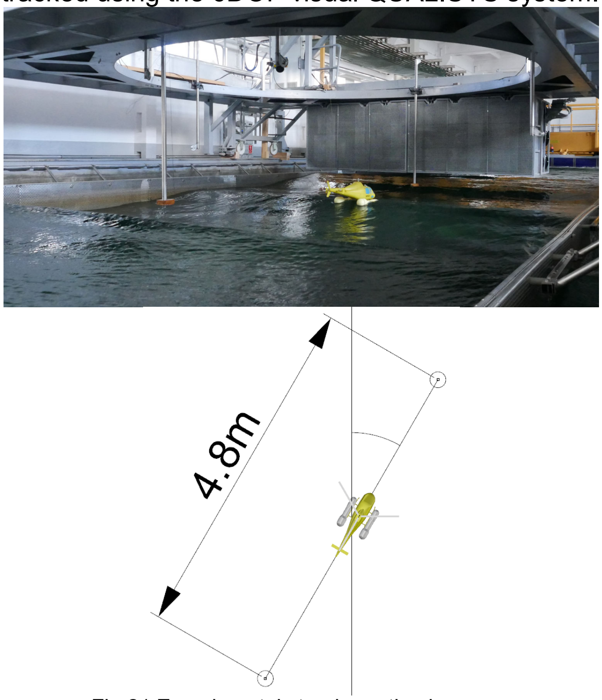

Fig.21 Experimental stand - motion in waves

Unlike the buoyancy and stability computational models, the computational model used for motion response predictions is characterized by considerable simplifications; the most important of them are:

– potential flow model: viscous effects are not directly taken into account in the computations; influence of viscous damping can be taken into account by introducing additional linear damping for selected degrees of freedom;
– linear approach: it is assumed that the response to given irregular wave is a sum of responses to harmonic waves.

It was found that while the computationally predicted heave and roll motion match well the measured values, the computed pitch motion is considerably overestimated. This was due to unphysically large values of RAO close to the

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resonance frequency. This phenomenon is characteristic for potential flow model which does not include viscous damping, and requires introducing additional linearized damping coefficient to calibrate the computational model. The difference between damped and undaped RAO values for pitch motion is presented in Fig.21. The damping coefficient was adjusted based on the results for heading angle 0°, and the computations were repeated for all cases.

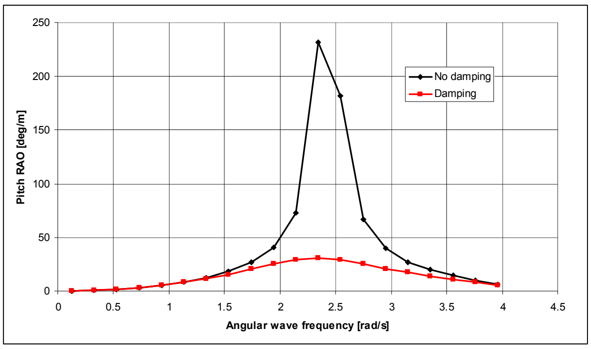

Fig.22 Pitch RAO - damped and undamped

With calibrated computational model, good agreement between computations and experiment was observed for entire range of heading angle, i.e. 0° to 90° - see figures below.

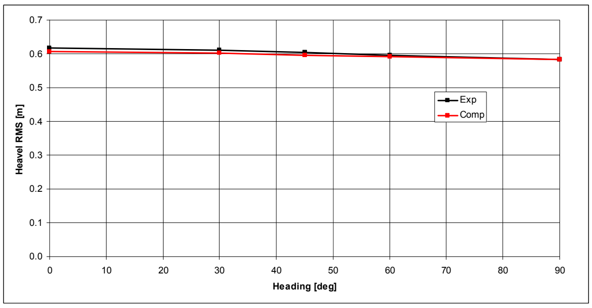

Fig.23 Heave motion - validation

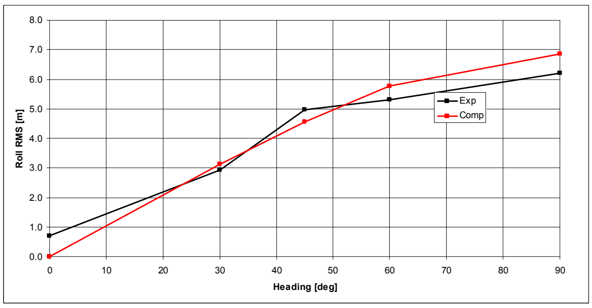

Fig.24 Roll motion - validation

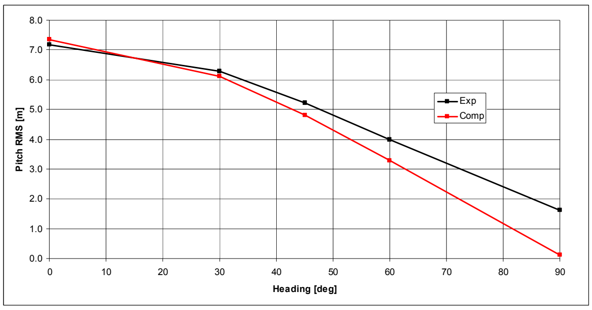

Fig.24 Pitch motion - validation

It was observed during the experiments that the motion of the helicopter with flotation system is driven mainly by the wave slope, i.e. it moves like a cork and no resonance is observed. The frequency of the contact of tail rotor with water is low, but this phenomenon was not eliminated. Further increasing of the safety would require using additional tail float. The helicopter with optimized floats tested in waves is presented in figure below.

Fig.24 Tests in waves with optimized floats

5. CONCLUSIONS AND FURTHER WORK

The results of realized hydromechanic characteristics of the helicopter with emergency flotation system yield the following conclusions:

- Considerable improvement of both hydrostatic and hydrodynamic characteristics was achieved by using variable diameter and efficient optimization of the floats;
- Qualitative validation of the computed buoyancy characteristics confirms the correctness of modelling the helicopter mass distribution;
- Validation of the computed large angle stability characteristics shows that the computations predict accurately the maximum righting arm value, while the computed maximum heel angle is underestimated, which can result partly from infinite stiffness of idealized computational model. The computations are then conservative in this respect;
- Computational model of the motion in waves requires calibration consisting in application of additional damping for pitch motion. After

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calibration, the computational model allows correct motion prediction for entire range of parameters.

Further work will include the ditching analyses, which require particularly advanced measurement stand - currently under construction.

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