SELECTED ELEMENTS OF THE METHODOLOGY AND METHOD OF DESIGNING AMPHIBIOUS FLOOD RESCUE VEHICLES

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Summary

The methodology of designing amphibious flood rescue vehicles at the preliminary stage of the design process has been presented. The study has been focused on the properties of such vehicles when afloat, with their on-land behaviour and performance characteristics having been left aside. In the study, a general assumption has been made that the amphibious flood rescue vehicles should be designed as, above all, watercraft that additionally can be driven on public roads and in off-road conditions. In the introduction, the solutions currently applied in the field of flood rescue transport facilities in Poland have been briefly defined. This has been followed by description of the methodology of designing amphibious flood rescue vehicles, supplemented with presentation of elements of the method of designing such vehicles that is based, firstly, on the assessment of vehicle performance and behaviour when afloat and, secondly, on the assessment of accident risk. The final part of this paper includes some remarks about modelling the shape of the hull of a modern amphibious flood rescue vehicle at the preliminary stage of designing such a vehicle. The methodology has been worked out with bearing in mind the planned further publications that would deal with computational models used for the designing of amphibious flood rescue vehicles.

Keywords: amphibious flood rescue vehicle, designing, methodology of designing, designing method.

1. Introduction

The issues addressed in this paper are related to the methodology and methods of designing amphibious flood rescue vehicles. The said methodology and methods must be known to designers of vehicles of this kind. This is because such a vehicle must have

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three fundamental features for its purposes to be satisfactorily fulfilled, i.e. it should be functional, effective, and safe.

Observations of the flood situations that occurred in Poland in 1989, 2009, and 2010 have shown that a large number of modern floating vehicles including amphibians must be used to ensure the safety of people, their property, and natural environment as well as the effectiveness of rescue operations during flood.

As regards the floating vehicles used now for flood rescue purposes, the following may be said about them from the point of view of the carrying out of a well-organised and quick rescue operation:

1. They are insufficiently functional.
2. They may be insufficiently effective in difficult terrain and weather conditions.
3. They are often dangerous in use.

The flood rescue operation methods used until now are based on the following watercraft:

1. Amphibious vehicles possessed by individual units of the Armed Forces of the Republic of Poland, subordinated to the Ministry of National Defence;
2. Watercraft possessed by individual units subordinate to the Ministry of Internal Affairs and Administration;
3. Watercraft possessed by other State services such as:
- The State Fire Service;
- The Police;
4. Watercraft being at disposal of local communities and natural persons:
- Motor boats;
- Rescue rowboats.

2. Elements of the methodology of designing amphibious flood rescue vehicles

In general, an assumption has been made that the amphibious flood rescue vehicles should be designed as, above all, watercraft that additionally can be driven on public roads and in off-road conditions.

Such a complex technical system as an amphibious flood rescue vehicle should have a set of special features related to the following aspects:

1. Functionality;
2. Effectiveness;
3. Safety of vehicle operation.

Before the designing process is started, it is very important that appropriate information should be collected and the technical and economic data on a similar or model vehicle should be analysed.

Adequate similarity of the newly designed vehicle to that taken as a reference (comparable)

may be considered to have been achieved if the following vehicle characteristics are more or less identical:
1. Vehicle type, size, and range of application;
2. Principal dimensions (length, width, height, draught, displacement);
3. Space division, crew spaces;
4. Volume of watertight compartments;
5. Vehicle properties when afloat;
6. Vehicle construction and structural material;
7. Vehicle propulsion system and speed;
8. Vehicle outfit.

It is worth remembering that the basic design requirements to be met by amphibious flood rescue vehicles cover the following factors:
1. Intended vehicle use;
2. Technical solutions applied, materials used, and vehicle weight;
3. Vehicle performance (displacement, deadweight capacity, as well as on-road, off-road, and on-water speed of the vehicle);
4. Vehicle properties in the general sense of this word (mobility).

The methodology of designing amphibious flood rescue vehicles at the pre-design stage is based on the applying of module approach and the designing process consists of the following stages, in the order as below:
1. Defining of intended vehicle use;
2. Estimating of principal vehicle dimensions;
3. Defining of vehicle construction type and basic structural material;
4. Estimating of vehicle weight;
5. Estimating of volumes of internal vehicle spaces (compartments);
6. Estimating of power capacity of the propulsion system;
7. Estimating of vehicle buoyancy, including the reserve buoyancy necessary in the event of vehicle damage;
8. Estimating of vehicle stability;
9. Estimating of vehicle behaviour when afloat, including its weatherly qualities and mobility;
10. Estimating of vehicle manufacturing cost;
11. Preparing of engineering design specifications.

The design criteria should be aimed at the achieving of the following goals:
1. The lowest possible vehicle weight;
2. The watercraft propulsion system being as modern as possible;
3. The best possible hydromechanical properties of the vehicle when afloat.

The process of designing amphibious flood rescue vehicles, from the point of view of the intended use of such vehicles (floating and fording), consists of three major modules:
1. Module A, general;
2. Module B, related to the solving of problems of static nature;
3. Module C, related to the solving of problems of dynamic nature.

The design issues addressed within individual modules may be grouped as follows:

Module A, general
1. Principal technical specifications and dimensions of the vehicle;
2. Vehicle shape;
3. Space division of the vehicle;

Module B, static issues
1. Vehicle hull (shell, major structural components);
2. Vehicle propulsion system (main propulsion system, auxiliary propulsion systems, drive shafts and axles);
3. Vehicle on-land rolling system (steering system, suspension system, road wheels);
4. Vehicle weight (vehicle, crew, fuel, reserves, outfit);

Module C, dynamic issues
1. Vehicle performance and mobility when driven on land (on paved roads and in off-road conditions);
2. Vehicle performance and behaviour when afloat.

The above issues should be addressed with taking into account the aspects related to the on-land behaviour and performance characteristics of automotive vehicles [7].

3. Method of designing amphibious flood rescue vehicles

When an amphibious flood rescue vehicle is being designed, a method based on the assessment of vehicle performance and behaviour and on the assessment of accident risk should be employed [3, 10]. A schematic diagram of such a method has been shown in Fig. 1.

For the vehicle performance and behaviour to be assessed, the hydromechanical characteristics and properties of the vehicle must be evaluated in specific vehicle operating conditions, with the vehicle condition and environmental state (water conditions, topographic features) being taken into account.

The most important problems that should be solved at the pre-design stage and that are related to the performance and behaviour of an amphibious vehicle when afloat include the following [2]:
1. Vehicle buoyancy (longitudinal and lateral balance of the vehicle);
2. Vehicle stability;
3. Vehicle mobility (power-resistance and manoeuvring characteristics of the vehicle);
4. Vehicle unsinkability (reserve buoyancy and stability of the vehicle when damaged).

The risk assessment is a formalised method of analysis that may be used to assess the risk at both the vehicle designing and operating stage; it integrates the risk analysis with risk reduction, which is treated as a design objective like other design or operating objectives. In the method based on risk assessment (risk analysis), the so-called

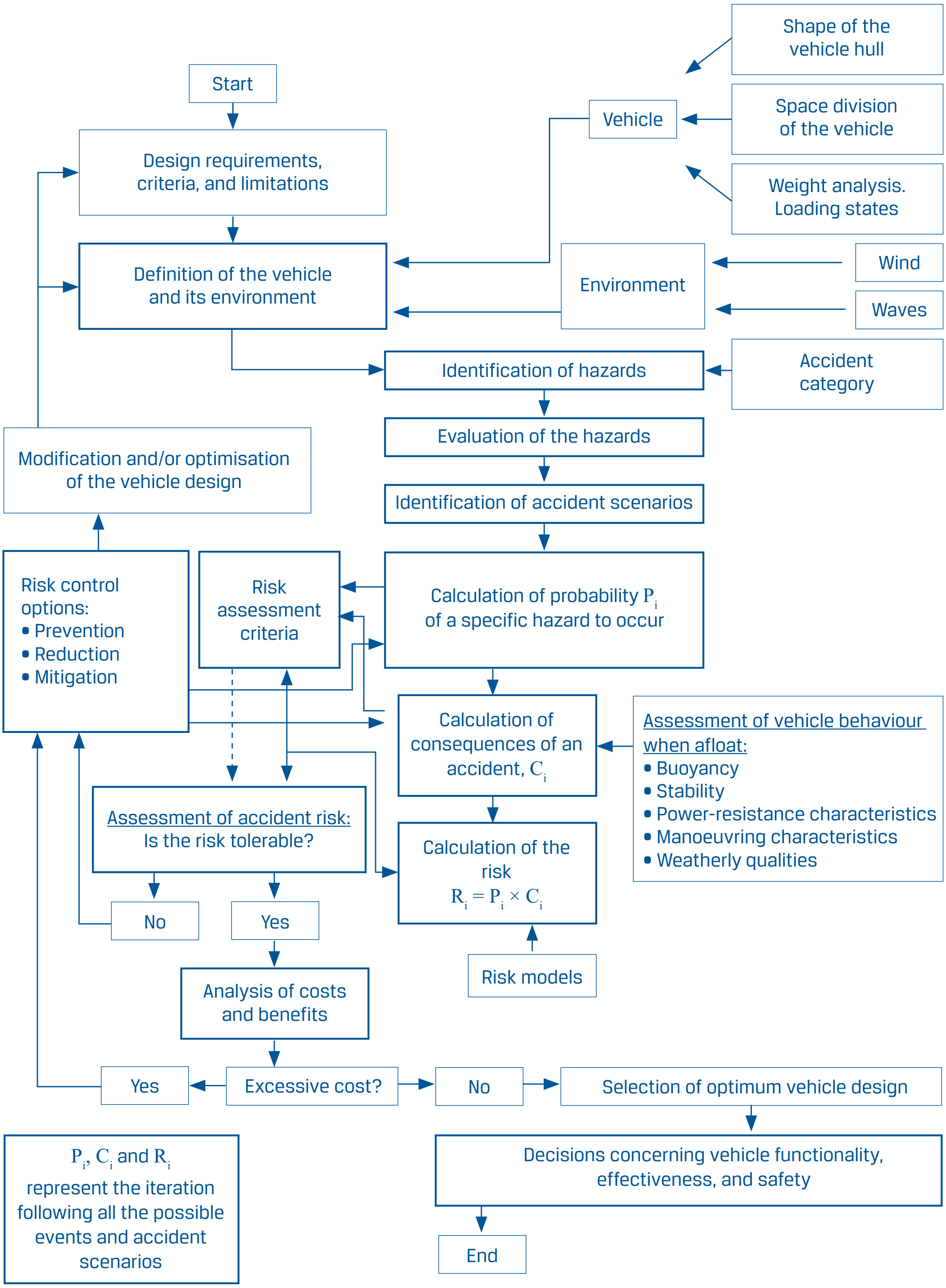

Fig. 1. Structure of the method of designing amphibious flood rescue vehicles at the pre-design stage

"integrated" approach is adopted, where the risk reduction measures are combined with the assessment of vehicle performance and behaviour [2]. The risk analysis is connected with identification of all the possible hazards, evaluation of the hazards, identification of possible accident scenarios, calculation of the risk (which in turn is connected with estimation of the probability of a hazard to occur and of its consequences), and with risk assessment and control. The risk assessment should be based on risk assessment criteria. The risk control measures and options may be preventive and/or reducing the consequences of an accident. In the method proposed, the vehicle safety is assessed in qualitative terms (safety is a qualitative characteristic) and this should be based on risk assessment, which has the quantitative nature [2].

According to the structure of the method as presented in Fig. 1, an essential element of the method is the assessment of vehicle behaviour when afloat, covering the following vehicle behaviour factors in succession:
1. Buoyancy;
2. Stability;
3. Power-resistance characteristics;
4. Manoeuvring characteristics;
5. Weatherly qualities.

The vehicle design cannot be analysed within the scope as specified above without the shape of the vehicle hull being precisely described. Therefore, basic information about modelling the shape of the hull of an amphibious flood rescue vehicle within the method under consideration has been presented in Section 4. The modelling concerns the method elements related to defining the vehicle as shown in Fig. 1. In Section 5, basic information is provided regarding the assessment of behaviour of an amphibious flood rescue vehicle.

4. Modelling of the shape of the hull of an amphibious flood rescue vehicle

Modelling methods

The modelling of the vehicle shape consists in the creation of a realistic vision of a vehicle that might be put into service. The designing of a utility model of the vehicle to be launched is a process that makes it possible to develop, from design basis through sketches and computer modelling (CAD) to realistic visualisations, a vehicle picture that would be an outcome of studies, tests, and engineering calculations [4 7].

The modelling method chosen

The designing of the body shape of an amphibious vehicle is a complex task. The vehicle design should comply with the user ergonomics principles and with the preliminary functional requirements related to the intended vehicle use. The selection of starting-point

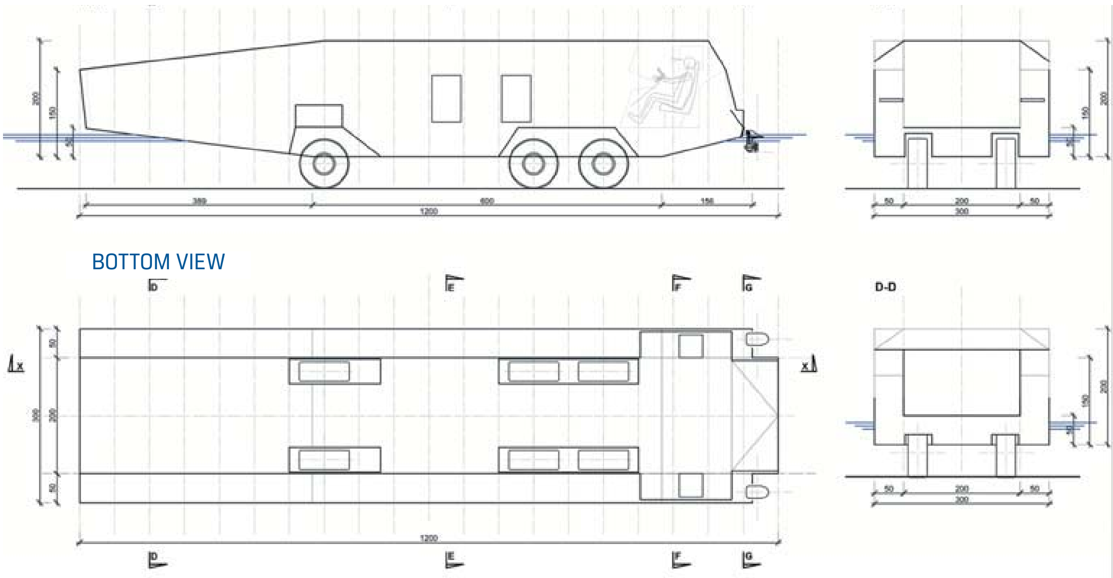

Fig. 2. Initial shape of an amphibious vehicle

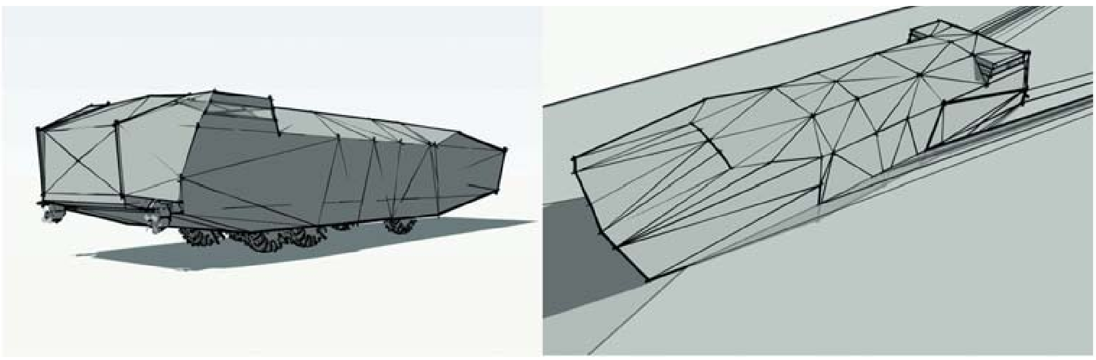

Fig. 3. Sketch of an amphibious vehicle when on land (left) and afloat (right)

parameters makes it possible to visualise the initial structure of the vehicle as shown in Fig. 2.

In result of an analysis of the above criteria, a preliminary vehicle shape may be defined, as presented in Fig. 3.

The preliminary vehicle shape is visualised in the form of a sketch, which is subjected at the next stage to analysis and is more precisely defined in a three-dimensional digital space (CAD). During the creation of a geometrical vehicle structure in the space, the model may be subjected to virtual measurements and an optimised preliminary vehicle shape may be obtained, which has been shown in Fig. 4.

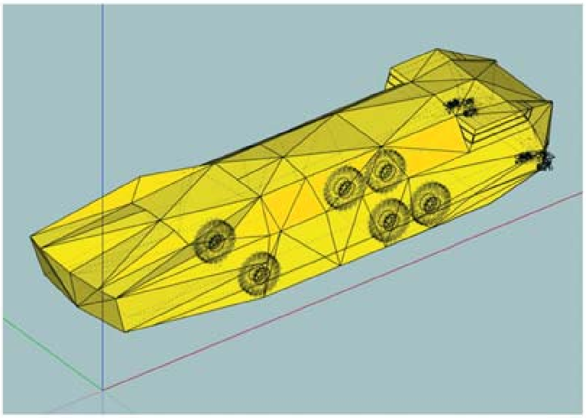

Fig. 4. Three-dimensional model of an amphibious vehicle

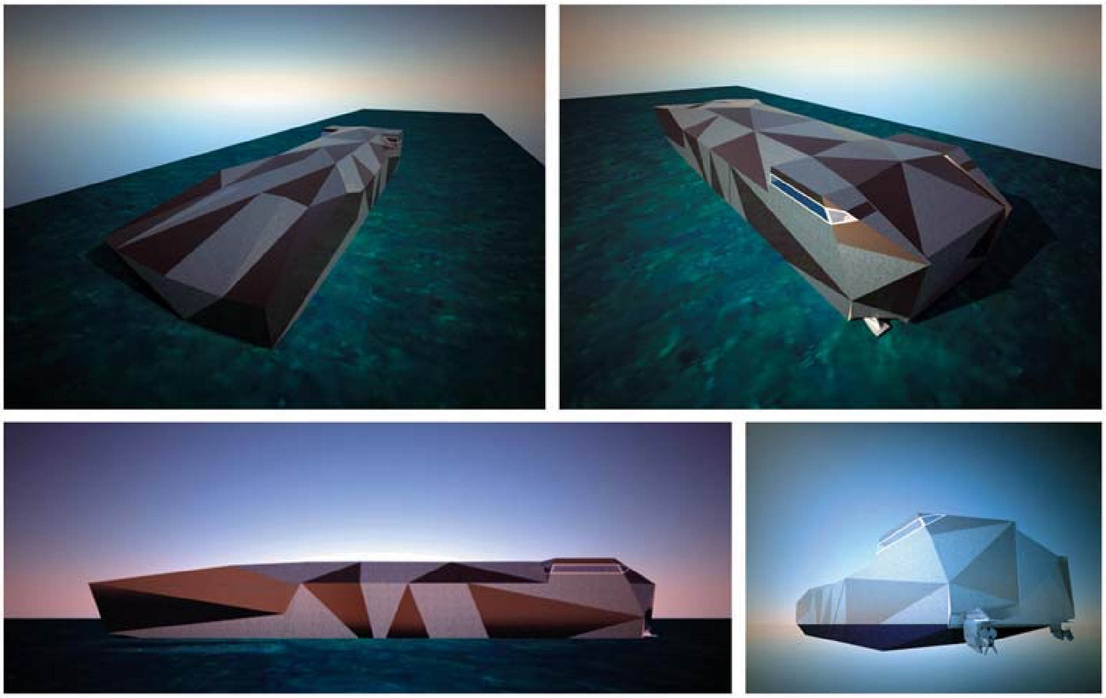

Fig. 5. The vehicle as viewed from the front (top left), rear (top right), left (bottom left), and bottom (bottom right)

The final outcome of the preliminary designing process may be presented in the form of realistic visualisations. At first, a colour scheme of the vehicle designed is prepared and then the vehicle is placed in a virtual environment, as it can be seen in Fig. 5.

5. Selected problems related to the assessment of behaviour of an amphibious flood rescue vehicle in operating conditions

Vehicle buoyancy

For the condition of stable equilibrium in the vertical direction to be met, two forces, i.e. the gravity force P and the hydrostatic buoyant force D, should be balanced [1, 2]:

$$\sum_i \vec{F}_{zi} = \vec{P} + \vec{D} = 0 \qquad (1)$$

where:

$\vec{P} = \vec{g} \cdot Ms$;

$\vec{D} = \rho_w \cdot \vec{g} \cdot V$;

$\vec{g}$ – gravitational acceleration [m/s^2];

Ms – total mass of the watercraft [kg];

ρ_w – mass density of water [kg/m^3];

V – volume of the immersed part of the watercraft hull [m^3].

Such a balance enables the watercraft to stay on a free water surface, i.e. to keep buoyant. If $\vec{P} > \vec{D}$ then the watercraft sinks or goes somewhat down into water providing that it have reserve buoyancy. Conversely, if $\vec{P} < \vec{D}$ then the watercraft goes up until the decreasing buoyancy force drops to a value just sufficient to balance the watercraft weight.

In practice, the watercraft buoyancy is ensured by the application of empty tanks or spaces filled with polyurethane foam. To increase the reserve buoyancy, flexible air tanks may be used.

Insufficient reserve buoyancy may result in a loss of stable equilibrium and shortening of the watercraft sinking time. This may prevent the carrying out of a successful rescue operation, where the time required for evacuation must be shorter than the sinking time. It may be stated, therefore, that the ensuring of the appropriate type of equilibrium in the vertical direction is an essential measure of the safety of a watercraft present on a free water surface. It is recommended that the calculation of sinking time and evacuation time should be a part of the designing and operating procedures related to the assessment of watercraft safety. Alas, the maintaining of buoyancy may prove to be insufficient for the carrying out of a successful rescue operation because of a possibility that the watercraft would prematurely lose its stability.

Vehicle stability (static stability)

The stability of a watercraft is defined as the capability of the watercraft heeled over to one side to return to the position originally occupied before the heeling moment was applied.

A basic characteristic of the watercraft stability is the metacentric height h_0, also referred to as "transverse metacentric height." It is also defined as a measure of the initial watercraft stability. It may be written down in two ways [1, 2]:

$$GM_0 = KM - KG = KF + FM - KG \tag{2}$$

or

$$h_0 = z_M - z_G = z_F + r_0 - z_G \tag{3}$$

where:
z_M – ordinate of the metacentre [m];
z_G – ordinate of the centre of gravity of a watercraft [m];
z_F – ordinate of the centre of buoyancy of a watercraft [m];
r_0 – small metacentric radius [m].

A graphic interpretation of the above characteristics has been presented in Fig. 6.

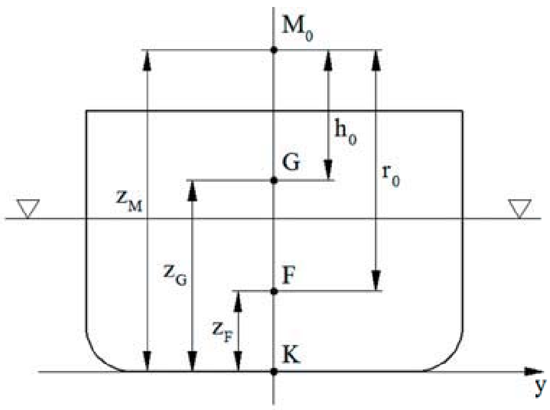

Fig. 6. Characteristics of the static stability of a watercraft

Point M_0 is referred to as "metacentric point" or simply "metacentre." The small metacentric radius is determined as follows:

$$r_0 = J_x / V \tag{4}$$

where:

$J_x = (2\int y^3 dx)/3$ – moment of inertia of the area of the floating waterline of the watercraft around the longitudinal axis x;
V – volume of the underwater (immersed) part of the watercraft hull.

A measure of the static stability is the value of the righting moment, which causes the watercraft to return to its original position when the heeling moment disappears.

For small angles of heel, the righting moment is defined by equation:

$$M_w = -D \times l = -D \times h_0 \times \sin \varphi \tag{5}$$

where:
D – buoyancy force determined in accordance with Archimedes' principle as $D = \gamma \times V$;
γ – specific weight of water.

Equation (4) is often referred to as "metacentric formula." It is a basic formula used to solve stability problems at small watercraft heel angles, generally of up to 10°.

Power-resistance characteristics of the vehicle

The total resistance of the watercraft to motion may be defined as follows:

$$R_T = R_F + R_W + R_S + R_{App} + R_{AA} \tag{6}$$

where individual components of the resistance are:
R_F – frictional resistance;
R_W – wave-making resistance;
R_S – spray resistance;
R_{App} – appendage resistance;
R_{AA} – air and wind resistance.

When dividing both sides of equation (6) by $(1/2 \times \rho \times v^2 \times S)$, where "ρ" is mass density of water, "v" is watercraft speed when afloat, and "S" is cross-sectional area of the immersed part of the watercraft hull, we obtain the following dimensionless form of equation (6):

$$c_T = c_F + c_W + c_S + c_{App} + c_{AA} \tag{7}$$

The value of coefficient c_{TRZ} (index "RZ" means "in real conditions") may be determined by testing a physical model of the watercraft in a towing tank, with using the Froude method.

The value of coefficient c_{TRZ} thus obtained for specific watercraft speeds makes it possible to determine appropriate watercraft resistance value by multiplying the value of this coefficient by $(1/2 \times \rho \times v^2 \times S)_{RZ}$, which is also determined for real conditions:

$$R_{TRZ} = (1/2 \times \rho \times v^2 \times S)_{RZ} \times c_{TRZ} \tag{8}$$

In general, when multiplying the value of the total resistance R_{TRZ} by the corresponding watercraft speed we may obtain the power demand value:

$$N_{0RZ} = R_{TRZ} \times v_{RZ} \tag{9}$$

From the practical point of view, the most important thing is to know the watercraft resistance at the operating speed, because the power demand at this speed is taken as a basis (i.e. the first iteration) for the selection of the power capacity of the main propulsion system of the amphibious vehicle used as a watercraft.

The watercraft resistance R_{TRZ} may also be calculated with the use of methods of computational fluid dynamics (CFD), but this lies beyond the scope of this study.

Weatherly qualities of the vehicle when afloat

For the vehicle behaviour when afloat to be assessed, the vehicle characteristics such as buoyancy, stability, and behaviour under the impact of internal and external inputs must be analysed.

As an important part of the assessment of vehicle behaviour, the accompanying phenomena should be taken into account, the precise description of which determines to a significant extent the correctness of calculations. The determining of the impact of these phenomena on watercraft motions is important inasmuch as they directly result in the inputs specified below as the forces and moments acting on the watercraft [1, 2]:

- Gravity force;
- Forces and moments caused by the action of wavy water surface undisturbed by the presence of any watercraft;
- Reaction forces and moments related to the interference introduced by the oscillating watercraft to the wavy water surface;
- Forces and moments caused by the action of wind and water current;
- Forces and moments caused by the action of water flowing into and out of e.g. a flooded watercraft compartment;
- Forces and moments caused by the action of water present in the watercraft hull;
- Forces and moments caused by the flooding of watercraft surfaces;
- Forces and moments caused by people displacements or cargo shifting;
- Forces and moments caused by the action of air cushions;
- Forces and moments caused by the functioning of watercraft propulsion and steering systems.

For adequate accuracy of the computations connected with the assessment of watercraft behaviour, all the impacts mentioned above must be precisely modelled.

The behaviour of a watercraft under the influence of inputs received from inside (the impact of free water surfaces in tanks and holds, cargo shifting) and from outside (waves, wind, water current) may be assessed with the use of a hybrid mathematical model based on equations of watercraft motion where the influence of inputs received from various sources is taken into account. These inputs include the internal and external factors mentioned above as well as the factors that may result from the phenomena related to both the watercraft hull flooding process and the watercraft motions caused by the impact of waves, wind, and water current.

Another reason for which the model proposed may be considered as a hybrid one is the fact that quasi-static, quasi-dynamic, or dynamic models may be used to describe the behaviour of water and/or fuel in watercraft compartments.

The model used for the assessment of watercraft behaviour includes:

A. Elements of general type, i.e. definition of watercraft shape, space division, hydrostatic characteristics of hull shape, geometric characteristics of watertight compartments of the watercraft;

B. Elements related to watercraft statics, i.e. states of loading of the watercraft when undamaged, lateral and longitudinal balance of the watercraft when undamaged, definition of watercraft damage, buoyancy of the watercraft when damaged, watercraft stability at various stages;

C. Elements related to watercraft dynamics, i.e. waves, equations of motion, inputs applied.

The watercraft motion in various watercraft states may be described with the use of a system of six differential equations directly stemming from Newton's laws. The equations of translations of the centre of mass of an object are formulated in an inertial coordinate system moving with the average velocity of the object, with the x axis of the system having the direction of the vector of velocity of the translatory motion of the centre of mass G of the object; the equations have the form as follows (see Fig. 7) [1, 2]:

$$\begin{aligned} m \cdot \ddot{x}_1 &= F_{x1} \\ m \cdot \ddot{y}_1 &= F_{y1} \\ m \cdot \ddot{z}_1 &= F_{z1} \end{aligned} \tag{10}$$

On the other hand, the equations of rotation of an object are usually formulated in a coordinate system rigidly connected with the object [1, 2]:

$$\begin{aligned} I_{SWx} \cdot \ddot{\Phi} &= M_x \\ I_{SWy} \cdot \ddot{\Theta} + (I_{SWz} - I_{SWx}) \cdot \dot{\Phi}\dot{\Psi} &= M_y \\ I_{SWz} \cdot \ddot{\Psi} + (I_{SWx} - I_{SWy}) \cdot \dot{\Phi}\dot{\Theta} &= M_z \end{aligned} \tag{11}$$

In these equations:

m – mass of the watercraft;

I_{SWx}, I_{SWy}, I_{SWz} – principal central moments of inertia of the watercraft relative to the longitudinal, lateral, and vertical axes going through the watercraft's centre of gravity G (x_G, y_G, z_G).

However, a decision was made to write down these equations in the following form for i = 2, ..., 6 [1, 2]:

$$\sum_{j=2}^{6} (M_{ij} + A_{ij})\ddot{x}_j(t) + B_{ij}\dot{x}_j(t) + F_j(t) = F_i^E(t) + F_i^{AC}(t) \tag{12}$$

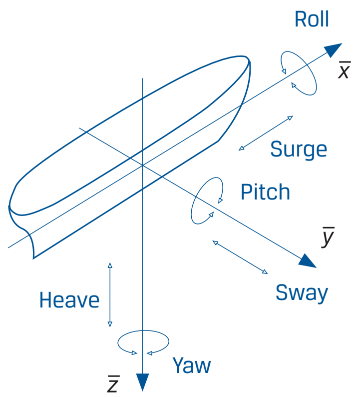

Fig. 7. Degrees of freedom of a watercraft on a free water surface

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$$\sum_{j=2}^{6} (M_{ij} + A_{ij})\ddot{x}_j(t) + B_{ij}\dot{x}_j(t) + F_j(t) = F_i^E(t) + F_i^{AC}(t) \tag{12}$$

where:
M_{ij} – mass matrix;
A_{ij}, B_{ij} – matrices of radius-related coefficients;
F_j – restoring (hydrostatic) forces;
F_i^E – hydrodynamic loads caused by waves;
F_i^{AC} – forces resulting from movements of the water present in flooded watercraft compartments.

The hydrostatic forces are calculated with the use of the hydrostatic pressure integration technique. The viscous damping coefficient for the watercraft roll is approximated with the use of a linear coefficient. It should be determined by model testing. At an assumption that the vehicle movements are not dynamic and that the impact of waves is negligible at the determining of this coefficient, a statement may be made that the damping of the six motions described above cannot be counted among the most important factors having an impact on the vehicle behaviour.

6. Recapitulation

The methodology of designing amphibious flood rescue vehicles at the pre-design stage has been presented here. The methodology covers two groups of issues. The first one includes problems related to the defining of the features and characteristics that determine the functionality, effectiveness, and safety of a vehicle of this kind. The problems concerning pure vehicle design, which are connected with the defining of vehicle shape and its space division and with the statics and dynamics of the vehicle when afloat, constitute the second group. The paper presents a method of designing amphibious flood rescue vehicles, with a schematic diagram of the method having been shown in Fig. 1; elements connected with the modelling of shape of one of the amphibious flood rescue vehicles being currently designed have also been discussed. The most important issues concerning the buoyancy, stability, power-resistance characteristics, and weatherly qualities of amphibious flood rescue vehicles have been dealt with as well.

The study has been focused on the properties of such vehicles when afloat, with leaving aside the fact that amphibious vehicles can also be driven on land.

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