Hydrodynamics of new high-speed surface systems

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Abstract. Until recently, high-speed surface vessels consisted mainly of hydrogliders, airfoil boats, hydrofoil and air-cushion craft. Their hydrodynamic characteristics are well understood and the vessels involved have high speeds and excellent sailing qualities. In recent years, however, there has been some expansion of this group of vessels by means of high-speed surface objects on wheels (baggies) and tracks (snowmobiles), in some cases at speeds far exceeding those of hydrofoil and air-cushion craft. Information on the hydrodynamic characteristics of these vessels is not available in the literature. This prompts us to study their hydrodynamic parameters and to consider the practical use of these vessels. The report describes conditions for water rolling of wheeled and tracked systems with grousers, simulates this phenomenon, derives the dependence of draft and bearing capacity of wheeled systems on the Froude number, and presents the dependence of tracked traction on the dimensionless parameter equal to the ratio of absolute speeds of the lower part of a track and the above-water part of a model.

1. Introduction
The idea of water rolling on wheels agitates inventors, dreamers, and thrill-seekers about one and a half hundred years [1-4]. Numerous cases of water rolling of buggies, snowmobiles and motorcycles make us to return to study this issue and probably to think of its practical use. Vessels on wheels and tracks have a number of advantages. First of all, it is a high roll speed on water. The speed of hydrogliders and hydrofoil craft makes about 60÷70 km/h, that of air-cushion craft – 100÷110 km/h. And it is possible to roll on wheels and tracks on a smooth water surface at the speed of 100÷200 km/h and, perhaps, quicker (however, at slower speeds, such vessels will move as displacement boats, but to reach the "high-speed mode" is a separate question). Such vessels will be demanded in emergencies (e.g., floods), in search and rescue operations, in emergency medical aid in the remote districts, including consider rolling motion of surface systems on a smooth water surface. Rolling conditions are described, this phenomenon is modeled, dependences of draft and bearing capacity of wheels on the Froude number for several values of the system dimensionless mass are obtained, and the position of a stable rolling area border line for in the Arctic conditions. So we have numerous cases of water rolling on wheels and tracks, but there is no general theory of this issue yet, though the first steps were taken in 1965 [5]. This article, wheel systems [6, 7] and tracked traction is evaluated.
2. Modeling of the rolling phenomenon

To figure out conditions when wheel vehicles can steadily roll on a free water surface, we must choose a system of parameters which determine a set of dynamically similar movements, and separate out their possible dimensionless combinations.

We will consider water rolling of a wheel with grousers (like a buggy wheel). The feature of the phenomenon of rolling motion on a water surface for such a wheel is the fact that the supporting force is caused by dynamic reaction of water, similar to gliding, and a vertical component value of the hydrodynamic force is practically the same as for water rolling of a smooth cylinder [5, 7]. However, the considerable difference for such wheels is the fact that they are simultaneously propulsion units. Vehicles of that kind may not only slide on water at high speed, but also go on shallow water, and they are not inferior to off-road vehicles ashore.

The established rolling motion of a wheel vehicle on a water surface at high speed is determined by the following parameters [6-8]:

\[ V, m, D, \rho, g, B, h, \]

where \( V \) - speed, \( \rho \) - density of water, \( g \) - free fall acceleration, \( m \) - mass of a vehicle, \( D \) and \( B \) – diameter and width of wheel treads, \( h \) - height of grousers. At the motion speed of about 100 km/h, the draft is small in comparison with diameter of wheels \((\Delta = D)\), and the liquid separation occurs in the lower point of a wheel. In this case, the main dimensionless parameters which characterize the rolling motion (except geometrical ones) are the Froude number \( VgD \) and dimensionless mass \( m/M \).

In a flat case, the expressions for dimensionless draft \( \Delta/D \) and dimensionless bearing capacity of a cylinder \( Y/mg \) are as follows [6]:

\[
(\Delta/D) = C(m/M) / F_r^2, \quad Y/mg = m/M ,
\]

where \( M = (\pi n/4) \rho D^2 B \) - characteristic mass of a wheel system, \( n \) - number of wheels, \( C \) – similarity factor depending on a form of the cylinder side surface (number and dimensions of floats, pattern of wheel treads, etc.). For a smooth cylinder, \( C = 1 \) [5].

3. Dependence of an average wheel draft on the Froude number and system mass

Figure 1 shows dependences of dimensionless draft \( \Delta/D \) on the Froude number for a number of dimensionless mass values. Circles (curve 1) represent experimental data obtained at towing of cylinders with floats in a tow basin (a flat case, \( m/M=0.12 \)). The dashed line is a solution of I.T. Yegorov [5]. Squares and triangles (curves 2, 3) comply with experimental data obtained at rolling of a heavy self-propelled model \((m_1=3.0 \text{ kg}, m_1/M=2.05 \text{ and } m_2=3.9 \text{ kg}, m_2/M=2.69, \text{ accordingly})\). At rolling of a self-propelled model, the flow is not flat. In this case, the dependence of dimensionless draft on the Froude number is better described by the following formula:

\[
\Delta/D = C(m/M) / F_r^{3/2}
\]
As shown below, the similarity factor value $C$ in formula (2) is approximately as follows: $C=2.57$.

4. Similarity factor and estimation of bearing capacity of a wheel system

We will evaluate a value of bearing capacity $Y$ for a 4-wheeled all-wheel drive self-propelled model. At the established movement, the lifting force impacted on the model is equal to $Y=mg$ ($m$ – mass of the model) or, in the dimensionless form, $Y/Mg=(m/M)$, i.e. we obtain from formula (2)

$$Y/Mg = \frac{1}{C}(\Delta/D)Fr^{3/2}$$

(3)

Figure 2 shows the dependence of similarity factor $C$ on the Froude number. When $0<Fr<3$, the experimental data are shown as circles ($m/M\approx0.12$), when $9<Fr<15$ - as squares ($m/M\approx2.05$) and triangles ($m/M\approx2.69$); the dashed line shows the similarity factor arithmetic mean $C=2.57$.

For the Froude number $3<Fr<9$, no experimental data is available. In this range, lighter self-propelled models should be used which are currently unavailable. None of available models can slide on water in this range (they will sink). Despite the wide spread of experimental data, these experiments show that dimensionless coefficient $C=(\Delta/D)Fr^{3/2}/(m/M)$ is apparently a universal constant for high speed water rolling of wheels of this form. In this case, the dependence of wheel bearing capacity on the Froude number can be found.

Experiments show that the working draft of wheels makes approximately $0.1<\Delta/D<0.15$. For bigger drafts, the rolling motion becomes unstable and the movement may pass into the flotation mode.
(like a displacement vessel). For smaller drafts, the movement is possible but the speed (Froude number) must be higher. Figure 3 shows the dependences of dimensionless lifting force $\frac{Y}{Mg}$ on the Froude number, which were obtained as per formula (3) with use of all the experimental data available.

The value of parameter $C$ in calculations was accepted as equal to $C=2.57$. Solid lines represent exact lifting force values known in this case: $\frac{Y_1}{Mg}=2.05$ (lower line) and $\frac{Y_2}{Mg}=2.69$ (upper line). Experiments show that the dimensionless lifting force does not depend on the Froude number in the researched area.

![Figure 3. Dependence of the dimensionless lifting force $\frac{Y}{Mg}=\frac{(\Delta/D)Fr^{0.75}}{C}$ on Froude number $Fr$ and the system mass (● - $m/M=0.12$; ■ - $m/M=2.05$; ▲ - $m/M=2.69$).](image)

Now we will graph dependences of lifting force on the Froude number for a number of dimensionless draft values using formula (3). In figure 3, curve 1 corresponds to value of dimensionless draft $\Delta/D=0.1$, curve 2 – to $\Delta/D=0.15$, and curve 3 - to $\Delta/D=0.2$. For values higher than $\Delta/D=0.2$, the movement becomes unstable and insignificant disturbance (e.g., a wave or drastic change in relative bearing) can transfer wheel rolling to the flotation mode. Curve 3 is actually a border line for the area of stable rolling motion. For dimensionless draft values lower than $\Delta/D=0.1$, the rolling motion is only possible at a sufficient engine output. In our case, the model speed was $V\leq15$ m/s (perhaps because of insufficiency of the acceleration area length on shore). Thus setting the wheel system mass and using the above results (i.e. formulae and graphs), we can determine the model (nature) bearing capacity and the minimum speed when the rolling mode starts. Tables of experimental data for dimensionless parameters $\Delta/D$, $C$, and $\frac{Y}{Mg}$ given in figures 1-3 may be found in [6].

We will explain by an example a possible design algorithm for a wheel system rolling on the free water surface.

### 4.1. Example

Determine the range of possible roll speeds for a 4-wheeled all-wheel drive system on a free water surface if its mass, diameter of wheels, and tread width are equal, accordingly, to: $m=3000$ kg, $D=1.5$ m, and $B=0.75$ m.

**Solution algorithm.**

1) We assume that the form of wheel treads of a nature is same as that of a self-propelled model. We determine the system characteristic mass and dimensionless mass as per formulae $M = \frac{(\pi n/4) \rho D^2 B}{\rho}$ and $m/M$ ($n=4$, $\rho=1000$ kg/m$^3$, $D=1.5$ m, and $B=0.75$ m). We obtain: $M=5298$ kg, $m/M=0.566$.

2) Using the formula $m/M = \left(\frac{(\Delta/D)Fr^{0.75}}{C}\right)/C$ and considering that the maximum allowable draft is $\Delta/D=0.15$, we determine the corresponding Froude number: $Fr=4.55$. 

4
3) Now that we know the Froude number, we find the lowest allowable speed value: 
\[ V = Fr\sqrt{\frac{gD}{D}} = 17.45 \text{ m/s} \] (62.8 km/h) i.e. roll speeds must be higher than \( V = 17.45 \text{ m/s} \) (62.8 km/h). However, as mentioned earlier, the "working" wheel draft makes approximately \( (\Delta/D) = 0.1 \). Therefore, using similar calculations for \( (\Delta/D) = 0.1 \), we obtain the roll speed value in this case: \( V = 22.86 \text{ m/s} \) (82.83 km/h).

5. Evaluation of tracked traction

The above results belong to wheel systems and are the most important in terms of design. For track systems, the tractive force value is of the greatest interest since their bearing capacity is substantially provided with gliding elements always available in such structures.

Figure 4 shows the dependence of traction dimensionless coefficient \( C_T = T / \left( \frac{1}{2} \rho V^2 B h \right) \) on dimensionless parameter \( p = \left( \frac{\omega R}{V} \right) \), which is equal to the ratio of absolute speeds of the lower track part and the structure surface part. Here, \( T \) – tractive force, \( \rho \) – water density, \( V \) – absolute speed of the surface part, \( B \) – track width, \( h \) – grouser height, \( \omega \) and \( R \) – angular speed and radius of a track wheel.

![Figure 4. Dependence of traction dimensionless coefficient \( C_T \) on parameter \( p = \left( \frac{\omega R}{V} \right) \).](image)

The circles represent experimental points. The solid line shows the dependence obtained when processing experimental data by the least square method, the dashed line corresponds to the approximate formula \( C_T = (p - 1) \) for tractive force evaluation. Experimental data obtained when towing a motionless (\( \omega = 0 \)) track (drag coefficient) is in point \( p = 0 \). In the neighborhood of point \( p = 1 \), track rolling occurs without slipping, and the tractive force value shall be close to zero. No Froude number \( Fr = V / \sqrt{gD} \) \((D = 2R)\) influence on the traction value has been revealed in this series of experiments.

6. Conclusion

As a result of the research, the technique of modeling has been developed for the rolling phenomenon of wheel and track vehicles on a free water surface; measuring circuits have been suggested for self-propelled model wheel draft when towed in a tow basin and rolling on water; dependences have been obtained for dimensionless draft and bearing capacity of wheels on the Froude number at different values of dimensionless mass and for the tracked traction coefficient on the dimensionless parameter equal to the ratio of absolute speeds of the lower track part and model body.

The experiments have shown that dimensionless values of wheel system lifting force do not depend on the Froude number at a high rolling speed. An approximate position of the rolling area border line
has been found and conditions have been determined for stable wheel rolling of a vehicle on a non-disturbed free water surface.

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