ISSN 2658-5014 (Print) ISSN 2686-7044 (Online)
http://siit.ugatu.su 2025. Vol. 7, no. 4 (23)
SYSTEMS ENGINEERING & INFORMATION TECHNOLOGIES
Scientific paper

UDC 519.622.1 DOI 10.54708/2658-5014-SIIT-2025-no4-p116 EDN TZRHBS

SOME PROBLEMS OF HOVERCRAFT MODELLING

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The article deals with the calculation of the aerodynamics of airspace flows for various types of models of hovercrafts. Static stability is considered, and various modes of air jet flow are described, which are characterized by a jet splitting coefficient equal to the ratio of the flow rate entering the area with in-creased pressure to the total flow rate. Approximation of the results of accurate calculations and the application of an approximation formula in the mathematical model of the hovercraft based on the results of numerical investigations is proposed. As an example, the approximation of the pressure force of the nozzle wall on the flow in the problem of flow from a nozzle with a remote inner wall is considered. It is emphasized that the formulas derived from approximate theories are suitable for engineering calculations of hovercrafts, unlike methods that rely on exact solutions of the problem. The approaches described allow constructing mathematical models of the processes of the hovercraft movement, which sufficiently correspond to the experimental data..

Aerodynamics, hovercraft, air jet flow mathematical model, chamber scheme, jet scheme, static stability, flexible fence.

Цитирование: Sherykhalina N. M., Shaymardanova E. R. Some problems of hovercraft modelling // СИИТ. 2025. Т. 7, № 4(23). С. 116–123. EDN TZRHBS.

Cite: Sherykhalina N. M., Shaymardanova E. R. “Some problems of hovercraft modelling" // SIIT. 2025. Vol. 7, no. 4 (23), pp. 116-123. EDN TZRHBS.

INTRODUCTION

In 1927 K. E. Tsiolkovsky for the first time theoretically justified the principle of movement on airspace and derived a relationship of the power required to maintain the device with the height of its hovering over the screen and other parameters [Tsi27]. In the case of a chamber scheme the device is a valve cover that is raised when the pressure force in the airspace area exceeds the weight of the device. The air flow coming through the supercharger to the airspace area (chamber) is vented through the gap h formed between the lower edge of the flexible fence and the screen (the surface of the ground or water).

The aerodynamic flow in the airspace is typically calculated using several simplifying assumptions. Given that the excess pressure (P_{as}–P_a) is generally low and the Reynolds number is high—exceeding the range typical for laminar flow—the airflow is modeled as a jet of ideal, incompressible, inviscid, and weightless fluid. Furthermore, because the overall dimensions of the hovercraft are significantly larger (by one or two orders of magnitude) than the gap h, the flow is approximated using a flat cross-sectional model.

POWER CONSUMPTION FOR HOVERCRAFT MAINTAINING

The total flow rate Q for the chamber scheme under the assumption of complete dispersion of the supercharger jet in the chamber is obtained from the solution of the problem of the flow of an ideal fluid from under the shield [Gur79]

$$Q = K_\theta h \Pi \sqrt{\frac{2}{\rho}(P_{as} - P_a)}, \quad (1)$$

where ρ is the air density, K_θ is the outflow coefficient depending on the angle θ (the ratio of the asymptotic width of the jet to the size of the gap), θ is the angle of inclination of the wall of the fence to the vertical, Π is the perimeter of airspace.

Along with the chamber scheme the jet (nozzle) scheme is widely used, in which the increased pressure in the airspace region is used due to the inertial properties of the air jet flowing along the perimeter of the airspace (jet curtain).

In this case, the size of the gap h is equal to the distance necessary for the jet to turn under the action of the pressure difference and move further along the screen from the airspace region to the surrounding space. The calculation of the characteristics of the jets that create the airspace and flow from the nozzles of various configurations is reduced to solving the boundary problems of the ideal fluid hydrodynamics [Gur79, Zhi79, Zhi80a, Zhi80b, Zhi90]. These characteristics are usually presented as the dependencies

$$Q_0(\sigma) = \frac{Q}{h\Pi\sqrt{2\,(P_{as} - P_a)/\rho}},$$

$$\bar{h}(\sigma) = \frac{h}{\beta}, \qquad \sigma = \frac{P^* - P_{as}}{P^* - P_a},$$

where β is the nozzle width, P^* is the total pressure in the jet.

One of the main parameters of the hovercraft is the power required to maintain the pressure in the hovercraft $N = (P^* - P_a)\,Q$. Let us consider the dimensionless quantity

$$N_0 = \frac{N}{(P_{as} - P_a)h\Pi\sqrt{\frac{2}{\rho}(P_{as} - P_a)}} = \frac{Q_0}{(1-\sigma)^{3/2}}. \tag{2}$$

For the chamber scheme

$$Q_0 = K_\theta\sqrt{1-\sigma},\ N_0 = K_\theta/\sqrt{1-\sigma},$$

for the jet scheme for $\theta = -\pi/2$

$$Q_0 = \frac{1}{2}\left(1 - \sqrt{\sigma}\right), \quad N_0 = \frac{1}{2}\frac{1}{\sqrt{1-\sigma}\left(1 + \sqrt{\sigma}\right)}. \tag{3}$$

In the jet scheme $N_0(\sigma)$ has a minimum for $0 < \sigma < 1$, and in the chamber scheme it increases monotonically with increasing σ. It is due to the fact that in the jet scheme an increase in P^* and σ leads to an increase in the inertness of the jet. In the chamber scheme the increased pressure $P^* - P_{in}$ is lost due to the scattering of the jet. This also explains the lower flow rate with the same gap in the jet scheme.

Experiment [Zha90] demonstrates that internal friction and partial dispersion of the jet curtain—effects that become more pronounced as the ratio of the nozzle's outer wall length to the jet width (β) increases—lead to actual values of Q_0 being higher than those predicted theoretically. These influences can be accounted for by applying correction coefficients, as suggested in [Ste63].

Neglecting the jet thrust we can assume that the weight of the hovercraft is balanced by the pressure in the airspace

$$G = (P_{as} - P_a)S_{as},$$

where S_{as} is the area bounded by the lower edge of the fence. Then the power required maintaining the hovercraft can be determined by formula similar to [Tsi27]

$$N = N_0\frac{\Pi}{\sqrt{S_{as}}}\sqrt{\frac{2}{\rho}}h\frac{G^{\frac{3}{2}}}{S_{as}}.$$

These relationships indicate that power consumption is directly proportional to the gap h. However, reducing this gap negatively affects the hovercraft's performance characteristics, as discussed in the following sections.

STATIC STABILITY

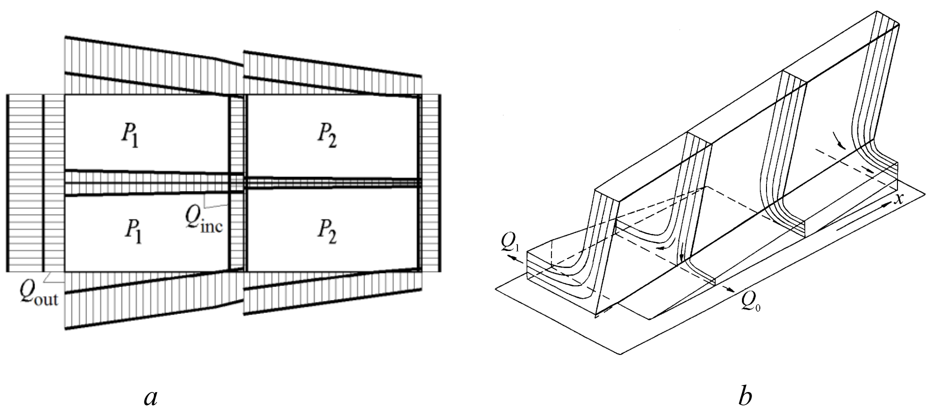
In the symmetric, non-inclined position, pressure beneath the hovercraft is uniformly distributed across the screen, and the jets within the jet curtain operate in a steady, single mode. When the hovercraft tilts, the size of the air gap between the lower edge of the flexible enclosure and the screen changes along the perimeter.

The key factor contributing to the static stability of the hovercraft is the shift of the pressure center relative to the center of mass, which generates a restoring moment. This effect results primarily from the redistribution of pressure beneath the hovercraft's bottom and enclosure, caused by changes i n flow behavior through the varying gap. Additionally, vertical and horizontal displacements of the lower edge of the flexible enclosure—effectively shifting the geometric center of the air cushion—further influence stability.

Introducing sectioning baffles into the air cushion area can enhance static stability by creating significant pressure differences between the compartments.

To analyze airflow parameters for a hovercraft with a jet scheme in an inclined state, one relies on known jet flow regimes [Kom81, Kom83]. In this scenario, each section of the hovercraft perimeter experiences different flow conditions, depending on the local gap (the distance from the nozzle edge to the screen) and the pressure difference between the section and the ambient environment. Where the gap is smaller, the jet splits and part of the flow enters the hovercraft region—this is known as the splitting mode. In areas with larger gaps, the jet curtain lifts above the screen, allowing flow to escape beneath it into the atmosphere, this is the leakage mode. Between these zones lies the equilibrium or deflected jet mode, which is particularly important when determining the hovercraft's parameters in its stable, non-inclined position.

Figure 1, *a* illustrates the flow distribution diagrams (epures) within the jet curtain, depicting the incoming airflow into the airspace, denoted as Q_{inc}. In this case, the flow rate in the jet curtain of the air entering the airspace Q_{inc} in the leakage mode has a negative sign. In this case, the stationary mode of hovering is carried out at a zero balance of the total consumption included in the hovercraft.



a *b*

Fig. 1 Hovercraft schematic:
a – airflow distribution diagrams (epures);
b – three-dimensional representation of the jet curtain

Since the jet thickness and the gap size are significantly smaller than the overall dimensions of the hovercraft, and the inclination angle \vartheta is relatively small, the flow in each segment of the jet curtain closely approximates a two-dimensional (planar) flow—except near the corners, whose contribution to the overall balance is typically negligible. Therefore, as a first approximation, the problem can be treated as two-dimensional, and the transition to a three-dimensional case is achieved by integrating the planar jet flow rates across all segments of the enclosure (see Fig. 1, *a*).

The problem of jet outflow from nozzles with parallel walls has been completely solved in studies [Zhi79, Kom77, Kom84a], while configurations with non-parallel walls are addressed in [Zhi79]. These works show that the gap height h can be treated as an independent parameter in modeling jet flow onto the screen. This parameter determines the jet flow regime, characterized by the **jet splitting coefficient** K, defined as the ratio of the flow rate Q_1 entering the region of increased pressure to the total flow rate Q.

In the **equilibrium mode** (where $K = 0$), the jet flows entirely outward, and the corresponding gap $h = h_0$ depends on the jet width ratio σ and the nozzle's geometry. As shown in Fig. 2, when $K = 0$, the jet shape corresponds to the condition $h = h_0$.

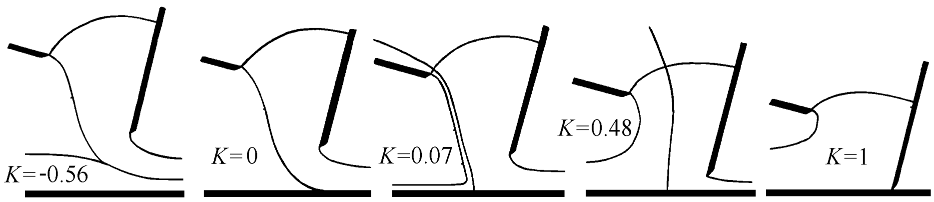


Fig. 2 Jet flow modes

If $h < h_0$, the jet does not fully deflect under the influence of the transverse pressure force before contacting the screen. As a result, it splits into two opposing streams that flow along the screen in opposite directions—this is known as the **splitting mode** (see Fig. 2 for $K = 0.07$ and $K = 0.48$). As h decreases, both Q_1 and K increase. When the nozzle's right edge is close enough to the screen, the **touching mode** occurs, where $K = 1$.

Conversely, when $h > h_0$, the jet curtain lifts off the screen, allowing a portion of the jet to pass beneath it and escape into the atmosphere—this is referred to as the **leakage mode** (Fig. 2, $K = -0.56$). In this regime, the outflow rate increases with the growing difference $h - h_0$.

For values $h \geq h_0$, jet curtain parameters such as flow rate Q, wall pressure, and nozzle exit conditions show relatively weak dependence on h [Zhi80a].

These properties of the jet flowing on the screen are a consequence of the conservation laws and take place for jets flowing out of various nozzle devices with rectilinear and curved walls, in particular, for the flexible nozzle considered in [Zhi90].

The same flow modes take place in different sections of the spatial jet curtain (Fig. 1, *b*). At small angles of rotation of the hovercraft wall (1...3°), the flow parameters in these sections can be determined from the solution of the plane problem.

It is worth noting that, by applying conservation laws along with certain simplifying assumptions, one can develop **approximate methods** for calculating jet curtain behavior. While these methods do not offer complete detail—such as precise velocity and pressure distributions along boundaries or within the flow, or the exact shape of free surfaces—they are valuable because of their simplicity. These simplifications are inherent to the assumptions used and the physical characteristics of the phenomenon.

Formulas derived through approximate theories are considerably more straightforward and well-suited for **engineering applications** in hovercraft design. In contrast, methods based on exact solutions enable in-depth analysis of flow characteristics but are often too complex—both in formulation and in computational implementation—for routine engineering use.

An effective strategy involves using exact solutions to derive **approximation formulas**, which can then be integrated into mathematical models of hovercraft dynamics. However, this becomes challenging in complex models where many parameters vary simultaneously, making the derivation of such approximations from exact solutions a non-trivial task.

In some cases, though, simplifications and approximate expressions can be developed based on **numerical simulations**. For instance, in the scenario of flow from a nozzle with a distant inner wall, it is beneficial to consider the **pressure force** D exerted by the nozzle wall on the jet. Numerical results indicate that this force varies only slightly with changes in the inclination angle θ_1 of the nozzle wall. Therefore, D can be effectively approximated as a function of two variables:

$$\overline{D} = 2D(\sigma, K)/(\rho v_0^2 \beta)$$

and then substitute in the impulse's equation, as in the approximate methods [Kom81]

$$\overline{h} = 2\frac{\sqrt{\sigma}(1-|K|) - \sigma\sin\theta_1 - \sigma K - \overline{D}\cos\theta_1}{1-\sigma}, \quad (4)$$

$$\overline{Q} = Q/\beta v_0 = \sqrt{\sigma}.$$

A nozzle with a removed inner wall simulates flows in flexible fence with hinged elements, which are usually used as peripheral barriers. For sectioning partitions, as a rule, symmetric structures are used, for which other approximations are obtained in [Kom83].

So, for $K = 0$

$$\overline{Q} = \overline{Q}_0 = \sigma^{1/(4-(1-\sigma)^2)}, \ \overline{h} = \overline{h}_0 = 2\overline{Q}_0/(1-\sigma).$$

For $K < 0$ $(\bar{h} > \bar{h}_0)$

$$\overline{Q} = \overline{Q}_0, \qquad K = -\frac{\overline{h} - \overline{h}_0}{2\overline{Q}_0}\sqrt{1-\sigma}.$$

For K > 0 $(\bar{h} \leq \bar{h}_0)$

$$\overline{Q} = \begin{cases} \overline{Q}_0, & (1-\alpha)\overline{h}_0 \leq \overline{h} \leq \overline{h}_0, \\ \overline{Q}(\alpha, \sigma, \bar{h}), & 0 \leq \overline{h} \leq (1-\alpha)\overline{h}_0, \end{cases}$$

$$K = \frac{1}{2}\left[\frac{\overline{h}_0}{\overline{Q}_0} - \frac{\overline{h}}{\overline{Q}}\right]\sqrt{1-\sigma}.$$

Thus, an approximate mathematical model of the hovercraft can be developed based on the results of exact solutions, while maintaining consistency with them.

However, numerical results obtained through exact methods often diverge from experimental data. This discrepancy is mainly attributed to the influence of viscosity, which reduces jet momentum and leads to flow separation from the inner wall.

In simplified models, these deviations can be accounted for by incorporating both theoretical and experimental data into the impulse equations. For instance, in [Wes67], energy loss during jet movement along the nozzle wall is modeled using basic assumptions, while in [Ste63], losses occurring after the jet separates from the nozzle edges are considered. Since the discrepancy between exact theory and experiment is typically within 5–20%, depending on the nozzle geometry, the introduction of such correction factors enables the development of sufficiently accurate approximation formulas suitable for use in hovercraft mathematical models.

The set of characteristics of jet curtains obtained in this way (4), (5) is sufficient for the development of a hovercraft model with the simplest flexible hence construction.

Then the calculation of the airspace parameters at a given angle of inclination ϑ is reduced to the selection of the pressure values in the lowered and raised sections (P_{as}^{down} and P_{as}^{up}) and the gap in the middle part hm, satisfying the equations for the balance of rate in both sections and the weight balance

$$\oint Q_{inc}^{down} dl = 0, \oint Q_{inc}^{up} dl = 0, (P_{as}^{down} - P_a)S_{as}^{down} + (P_{as}^{up} - P_a)S_{as}^{up} = G, \quad (5)$$

where Q_{inc}^{down}, Q_{inc}^{up}, S_{as}^{down}, $S_{as}^{up}$are rates and squares of hovercraft corresponding to the lowered and raised sections.

The numerical studies of the stability of hovercraft with various flexible barriers are given in [Mis86]. The results of research into the development of analytical estimates are given below.

The main parameter that characterizes the static stability is the ratio M_ϑ of the restoring moment M to the angle of inclination of the hovercraft ϑ. It should be noted that the dependence $M(\vartheta)$ is, generally speaking, nonlinear, but in hovercrafts with consumable partitions, the nonlinearity is in the area of large inclination of the hovercrafts, when the screen touches the edge of the fence of the lowered section. Therefore, as M_ϑ we can take the value of the derivative $\frac{dM}{d\vartheta}$ for $\vartheta = 0$. The metacentric height $m_\vartheta = \frac{\lambda}{G}\frac{dM}{d\vartheta}$ is often used, which is equal to the height of the application point of the equivalent supporting force above the screen. In a stable construction m_ϑ must be greater than the distance from the center of mass to the screen.

Due to the non-linearity of the jet curtain characteristics, it is generally difficult to obtain a direct estimate of m_ϑ. For the chamber scheme these characteristics are much simpler and this estimate is obtained in [Pet83].

For the jet scheme, under certain assumptions [Kom84b], it has been possible to determine the dependence of m_ϑ on some construction parameters of the hovercraft, such as the pliability of the flexible fence, the elongation $\lambda = L/B$, (L and B are the length and width of the hovercraft), and h is the gap. It is interesting that although the values $m\vartheta$ for the chamber and jet schemes are different, the form of dependence of m_ϑ on the listed parameters is the same, as was established in [Kom84b].

The parameters that characterize the flexible fence are its vertical and horizontal pliability

$$l_v = \frac{1}{B}\frac{dH}{dK_p}, \qquad l_h = -\frac{1}{B}\frac{dB}{dK_p}, \qquad K_p = \frac{P^* - P_a}{P_{as} - P_a} = \frac{1}{1-\sigma},$$

$l_v > 0$, $l_h > 0$ (H is the height of the flexible fence). In [Pet83, Kom84b] it was assumed that the entire lower edge of the fence is in the same plane (however, the fulfillment of this condition contributes to a decrease in the resistance during the movement, which is discussed below). In this case, the value of the metacentric height of the hovercraft with a flexible fence m_ϑ is determined by the metacentric height of the same hovercraft with a rigid fence m_ϑ^0 according to the formula

$$m_\vartheta = m_\vartheta^0 \frac{1 + 2K_p l_h}{1 + 8K_p l_v m_\vartheta^0/B}.$$

In the case of different pliability of different sections of the fence, the average values of pliability along the perimeter of the hovercraft are used.

The relationship of the metacentric height with the geometric parameters of the airspace is determined by the expression

$$m_x^\vartheta = B\frac{\sqrt{S_{as}}}{h}\frac{1}{\sqrt{\lambda}}\frac{\lambda + 1/2}{\lambda + 1}\varphi(K_p),$$

where $\varphi(K_p)$ is some function, which depends on the characteristics of the flat jets flowing from the nozzles of the peripheral fence and sectioning partitions. For this formula we use stronger assumptions (about the impermeability of the partition), for the chamber scheme [Pet83]

$$\varphi(K_p) = \frac{K_p - 1}{4K_p} = \frac{\sigma}{4},$$

for the jet scheme

$$\varphi(K_p) = \frac{1}{4}\left[\frac{K_p}{h}\frac{dh}{dK_p}\right]^{-1} = \frac{1}{4}\left[\frac{1-\sigma}{h}\frac{dh}{d\sigma}\right]^{-1}.$$

For a real hovercraft φ is not a function of K_p only. However, calculations based on the exact model [Mis86] show that in a rather wide range of parameters the dependence φ on λ and h is insignificant.

CONCLUSIONS

To solve each of the problems described of the hovercraft theory, it is necessary to use the results of the investigation of the characteristics of flexible fence and jet curtains. It is of interest to study the more complex flows of air jets in the flexible fence, as well as the interaction of the jets with the flexible walls of the fence. The results of solving such problems are given in [Zhi13, Zhi82a–Zhi90, Kom79, Kom86,], and the methods of their post-processing, accuracy increasing and error estimation in [Zhi21a–Zhi21c].

The problems listed above do not fully cover the problems of the hydrodynamic and aerodynamic theory of hovercrafts (for example, the issues of calculating the characteristics of the supercharger, air ducts, etc.). Nevertheless, the approaches described allow us to construct mathematical models of the processes occurring during the movement of hovercrafts, which sufficiently correspond to the experimental data.

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МЕТАДАННЫЕ

Заглавие: Некоторые проблемы моделирования аппаратов на воздушной подушке.

Аннотация: В статье рассматривается расчет аэродинамики потоков воздушного пространства для различных типов моделей судов на воздушной подушке. Рассмотрена статическая устойчивость, а также описаны различные режимы течения воздушной струи, которые характеризуются коэффициентом расщепления струи, равным отношению расхода, поступающего в зону с повышенным давлением, к общему расходу. Предложена аппроксимация результатов точных расчетов и применение аппроксимационной формулы в математической модели судна на воздушной подушке на основе результатов численных исследований. В качестве примера рассмотрена аппроксимация силы давления стенки сопла на поток в задаче течения от сопла с удаленной внутренней стенкой. Подчеркивается, что формулы, выведенные из приближенных теорий, пригодны для инженерных расчетов судов на воздушной подушке, в отличие от методов, опирающихся на точные решения задачи. Описанные подходы позволяют строить математические модели процессов движения судна на воздушной подушке, которые в достаточной степени соответствуют экспериментальным данным.

Ключевые слова: Аэродинамика, судно на воздушной подушке, математическая модель течения воздушной струи, схема камеры, схема струи, статическая устойчивость, гибкое ограждение.

Language: Английский.

Статья поступила в редакцию 2 июня 2025 г.

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METADATA

Title: Some problems of hovercraft modelling.

Abstract: The article deals with the calculation of the aerodynamics of airspace flows for various types of models of hovercrafts. Static stability is considered, and various modes of air jet flow are described, which are characterized by a jet splitting coefficient equal to the ratio of the flow rate entering the area with in-creased pressure to the total flow rate. Approximation of the results of accurate calculations and the application of an approximation formula in the mathematical model of the hovercraft based on the results of numerical investigations is proposed. As an example, the approximation of the pressure force of the nozzle wall on the flow in the problem of flow from a nozzle with a remote inner wall is considered. It is emphasized that the formulas derived from approximate theories are suitable for engineering calculations of hovercrafts, unlike methods that rely on exact solutions of the problem. The approaches described allow constructing mathematical models of the processes of the hovercraft movement, which sufficiently correspond to the experimental data..

Key words: Aerodynamics, hovercraft, air jet flow mathematical model, chamber scheme, jet scheme, static stability, flexible fence.

Language: English.

The article was received by the editors on 2 June 2025.