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CONTROLLED WIG FLIGHT CONCEPT

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Abstract: The general problem of Wing-in-Ground effect's active usage in WIG-craft or ekranoplanes by minimization of average geometrical altitude of flight above sea waves is deeply considered in this paper. Two concepts of stabilisation of vehicle motion in longitudinal plane are discussed and compared. The necessary analytical formulae are developed for the first time. They are rather simple and may be used for approximate estimations only, however allow selecting the best motion stabilization concept. The main advantage of the used general approach consists in making important conclusions regarding the limited effectiveness of WIG-craft flight above the disturbed sea surface. Only large WIG-craft could provide the essential fuel saving in controlled flying close to the disturbed surface. For small WIG-craft, fuel saving is not great and significant in comparison with the plane mode of flight, and other advantages of WIG-craft have to be the decisive ones in competition with planes. The modern means of automatic control permit to realize any perfect dynamic features of vehicle, and it is important to recognize the best concept of flight control before developing the control laws for the certain vehicle. This task is solved in the paper and it is useful for estimating the best ways of perfection of automatically controlled WIG-craft.

Keywords: motion control, altitude stabilization, WIG-craft, sea waves, flight trajectory, flight safety.

1. INTRODUCTION

The WIG-craft or Ekranoplane is a flying vehicle with special structural features providing low altitude flight opportunity when using Wing-In-Ground effect (WIG-effect). It consists in wing lift force increment and air drag decrease when moving close to the supporting surface. In this case air cushion action between wing and supporting surface is added to normal mechanism of lift force formation due to different speeds of flow on upper and lower wing surfaces (Fishwick, 2001; Rozhdestvensky, 2000; Taylor, 2001; Opstal, 2001).

In order to make the full usage of WIG-effect and to provide high functional characteristics of ekranoplanes they usually have the following features that distinguish them from typical/standard airplanes (Fig.1,2):

- wide wing with small aspect ratio that is relatively low attached to the body, or flying wing configuration;
- boundary plates on wings that enhance wing aerodynamics when moving close to the supporting surface;
- developed tail assembly, high fin (or several fins) with rudder, horizontal stabilizer with elevator attached to the fin at the utmost height.

The advantages of WIG-craft against planes are:

- potentially higher safety of flight due to opportunity of urgent landing/ditching;
- reduced requirements for engines operation reliability and, therefore, opportunity of their fuller use of service life;
- absence of necessity for runway (dedicated infrastructure) and possibility to perform special transport operations using amphibian property;
- absence of necessity for tight cabin and special life-support systems for crew and passengers;
- possible decrease of fuel consumption due to increase of the lift / drag ratio in WIG-mode of flight.

WIG-effect is an interesting physical phenomenon with multilateral characters, having positive and negative influence for providing the flight in WIG-mode. The main control problems arising at such mode of flight at extremely low altitude correspond to the ensuring of vehicle motion stability in the circumstances of the action of non-linear aerodynamic effects attributed to closeness to surface.

The effective use of WIG-effect requires the extremely low altitude of controlled motion close to the surface. This altitude has to be permissible by the criterion of flying safety at the definite height of sea waves or other disturbances of underlying surface. The proper designed WIG-craft has the natural property of self-positioning in altitude, but only the facilities of automatic control can ensure the required functional characteristics under the circumstances of sea waves disturbances (Halloran, O'Meara, 1999; Nebylov, Wilson, 2002; Yun , Bliault, Doo, 2010).

Fig.1. Small ekranoplane "Ivolga" for 12 passengers.

Fig.2. Ekranoplane “Orlyonok” of 140 ton weight.

Trouble-free motion at the altitude of 0.5-5m close to disturbed surface may be guaranteed by the application of special methods and means of navigation and control capable to solve the following specific problems (Nebylov, 2002, 2010):
- non-contact measurement, tracking and prediction of ordinates and biases of the field of disturbances;
- precise control of the altitude of motion with error not above 3-10 cm;
- restriction of the angles of airframe inclination for the prevention of undesirable tangency of water by the extreme points of body or wing;
- ensuring of the vehicle stability as control plant.

Unfortunately, most of these problems are still not completely solved (Nebylov, Nebylov, 2008, 2013) due to their complicity and lack of WIG-craft market development. Among experts there is no consensus even on the altitude of flight that has to be stabilized in WIG-mode. Most experts believe that it is necessary to stabilize the flight altitude regarding the average level of disturbed sea, and this altitude could be measured by the integrated navigation system that includes radio-altimeters and inertial navigation unit. Other experts believe that the automatic control system has to provide only the stability of plant and to increase the stability margin, making the transition processes aperiodic, without oscillations. As for the altitude stabilisation, it has to be provided on the base of WIG-craft property of self-positioning due to decrease of lift force during increase of altitude. Some other opinions exist also.

2. MODELS OF THE PLANT AND DISTURBANCE

In this paper the authors first time suggest the reasonable criterion for altitude control of WIG-flight. It is shown that the best control law lies between rigid stabilisation of average altitude and full freedom in action of the self-positioning property of WIG-craft. Only the longitudinal motion of WIG-craft is considered.

It is assumed that the automatic control system is installed aboard a WIG-craft and provides increasing of its stability margin up to the level corresponding to simple aperiodic transition processes in the longitudinal plane. Such automatic control system could be named as damping system and it is useful for performing automatic or manual control of WIG-craft motion. To the first approximation this damped plant can be considered as the linear aperiodic unit of the first order

$$W_e(s) = k_e/(1 + T_e s) \quad (1)$$

with the time constant T_e and the gain factor k_e.

Such a very simple model of damped WIG-craft is necessary for analytical statement of the problem of T_e optimization for the most effective motion of WIG-craft in the longitudinal plane. On the other hand, this model is very close to the truth for small wave disturbances applied to the vehicle flying at the certain altitude that permits to linearise the nonlinear plant. For example, such simple dynamics could be provided for real WIG-craft by application of the PID-regulator with additional reject filters in the closed loop control.

As for k_e, it can be equal to 1 if one considers the reaction of vehicle altitude to a height of a single harmonic sea wave.

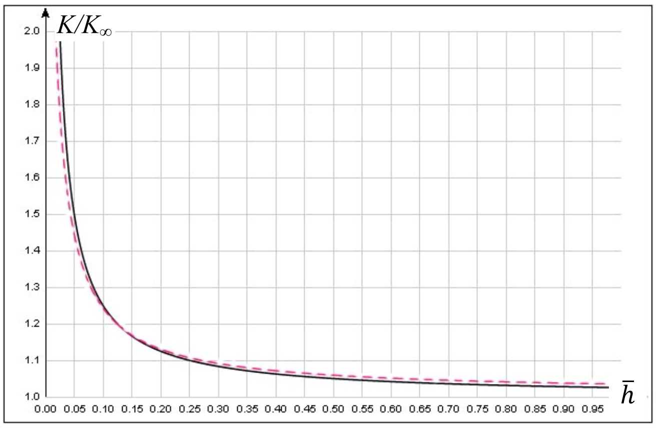

Fig.2. Dependence of normalized lift/drag ratio on normalized altitude of flight $\bar{h}$.

The feature of WIG-craft altitude self-stabilization is convincingly shown in the Fig.2 (Diomidov, 1996) where the experimental curve of dependence of normalized lift/drag ratio to the normalized altitude of flight $\bar{h} = h/b$ is represented by a full line. K_∞ is the lift/drag ratio at high altitude when WIG-effect is not appearing; b is the vehicle wing chord. It is clear that the real use of WIG-effect is possible only at very small altitudes when $\bar{h} \le 0.5$. For example, for rather small vehicle at b=4m the condition $h \le 2$m must be fulfilled, but $h \le 1$m will be better for effective flight. For famous Russian WIG-craft “Lun” with b=12.5 m the effective flight in WIG-mode requires $h \le 2 \div 6$ m. For also famous Orlyonok (Fig.2) with b=9 m the corresponding requirement is $h \le 1.5 \div 4.3$ m.

For analytical investigation of the problem it is necessary to develop the formula for description of the dependence $K/K_\infty\,(h/b)$. For this purpose the authors suggest the use of new formula

$$K/K_\infty = 1 + b/(30h) \quad \text{at } h/b \ge 0.03. \quad (2)$$

The dependence (2) is shown in Fig.3 by the dotted line and practically coincides with the full line. Naturally, at $h \to \infty$ one can obtain $K \to K_\infty$ and the WIG-effect disappears.

Now let us consider two possible concepts of WIG-craft altitude stabilization at disturbance from sea waves. For explanation the concepts we will use the simplest model of sea waves as harmonic function

$$\theta(l) = a \sin(\Omega l + \varphi), \tag{3}$$

where l is a distance along the vehicle flight path, Ω is a spatial frequency of wave, φ is the phase of harmonic wave.

Physically this model corresponds to the sea waves of swell type. More complex models of three-dimensional sea waves could be also considered (Nebylov, Wilson, 2002), but they complicate analytic transformations and are not necessary at this initial stage of investigation. It will be done in the next papers.

3. TWO CONCEPTS OF WIG-CRAFT VERTICAL MOTION AT HARMONIC DISTURBANCE

At the first concept the altitude of flight is stabilized regarding the average level of disturbed sea and the vehicle moves straight above the crests of waves with rather small clearance margin Δ (to avoid the collision with disturbed surface even at presence of some errors in motion control). If calculate altitude of flight

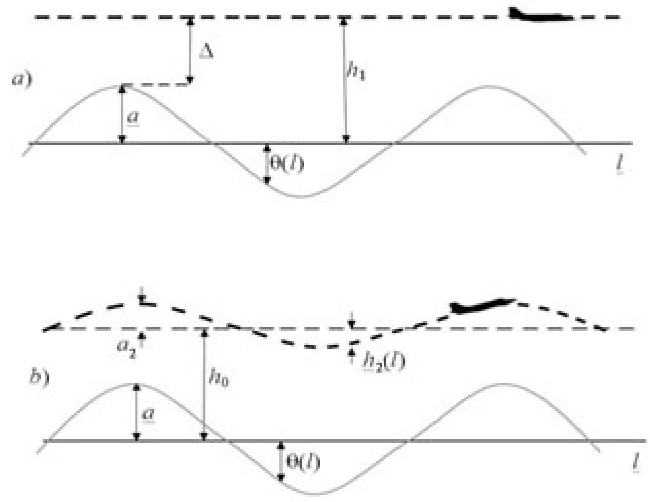

Fig.4. Trajectory of flight in longitudinal plane at harmonic disturbance: a- concept 1, b - concept 2.

regarding the average level of sea surface, it must be $h_1 = a + \Delta$, as it is shown in Fig.4,a.

The minimal geometrical altitude of flight will be Δ, the maximal geometrical altitude of flight will be $\Delta + 2a$. The average level is

$$h_1 = a + \Delta. \tag{4}$$

If it is recalculate into the values of K/K_∞ on the basis of formula (2), we will estimate the effectiveness of flight, and it will not be great.

For approximate estimation one can substitute the average value of altitude h_1 from (4) to (2) instead of h. It will give

$$K/K_\infty \approx 1 + b/(30(\Delta + a)). \tag{5}$$

For example, at a=2m, Δ=0.25m, b=4m according to (5) $K/K_\infty \approx 1.064$. It means that such WIG-mode of flight is not very effective and provides only 6.4% saving in fuel consumption.

At the second concept the stabilization of altitude of flight is not rigid and permits vehicle to track partly the wave disturbance passing them through the dynamic unit with the transfer function (1). The corresponding curves are shown in Fig.4,b.

In this case at disturbance model (3) the WIG-craft trajectory in the longitudinal plane will be

$$h_2(l) = a_2 \sin(\Omega l + \varphi + \psi), \tag{6}$$

or, passing from spatial space to temporal space,

$$h_2(t) = a_2 \sin(\omega t + \varphi + \psi), \tag{7}$$

where the angular frequency $\omega = V\Omega$, V is the ground speed of vehicle. For example, if $\Omega = 0.05\text{m}^{-1}$, V=33m/s, then $\omega = 1.65\text{s}^{-1}$. It corresponds to the length of sea wave $\lambda = 2\pi/\Omega = 125$ m.

Taking into account the plant transfer function (1), the magnitude and phase of vehicle trajectory vertical oscillation will be

$$a_2 = a/\sqrt{1 + \omega^2 T_e^2}\ , \tag{8}$$

$$\psi = \operatorname{atan} \omega T_e.$$

Initial phase φ is not essential, but phase ψ in general case will influence the WIG-mode effectiveness.

The current geometrical altitude of flight h_e can be described by the formula

$$h_e(t) = h_0 + h_2(t) - \theta(t) =$$
$$= h_0 - a_2 \sin(\omega t + \varphi + \psi) + a \sin(\omega t + \varphi), \qquad 9)$$

where h_0 is the clearance margin similar to Δ in the first concept.

When analyzing the formula (9) and Fig.4,b it becomes clear that the average value of $h_e(t)$ will be minimal at ψ=0, when the harmonic processes $\theta(t)$ and $h_2(t)$ are cophasal. As in this case the flight will be more effective, it is reasonable to require the performance of this phase synchronism from the motion control system of WIG-craft. Fulfillment of this requirement is not difficult if the prediction of wave disturbances or radar estimator of increasing wave is used.

Accepting ψ=0, from (8) and (9) obtain

$$h_e(t) = h_0 + a \sin(\omega t + \varphi) - a_2 \sin(\omega t + \varphi) =$$
$$= h_0 + a\,(1 - 1/\sqrt{1 + \omega^2 T_e^2}) \sin(\omega t + \varphi).$$

Minimal value of geometrical altitude will be

$$h_{e\,min} = h_0 - a\,(1 - 1/\sqrt{1 + \omega^2 T_e^2}), \tag{10}$$

maximal value will be

$h_{e\,max} = h_0 + a\,(\ 1 - 1/\sqrt{1+\omega^2 T_e^2})$.

The average level will be equal to h_o,

As the collision avoidance will be provided only at

$$h_{e\,min} \geq \Delta\ , \tag{11}$$

the expressions (10) and (11) give the requirement

$$h_0 = \Delta + a\,(1 - 1/\sqrt{1+\omega^2 T_e^2}). \tag{12}$$

For approximate estimation of K/K_∞ one can substitute the average value of altitude h_0 from (12) to (2) instead of h, and it will give

$$K/K_\infty \approx 1 + b/(30(\Delta\ +\ a\,(1 - 1/\sqrt{1+\omega^2 T_e^2}). \tag{13}$$

For example, at a=2m, Δ=0.25 m, b=4m, ω=1.65s^{-1}, T_e=1s according to (13) obtain $K/K_\infty \approx$1.13. It means that such WIG-mode of flight provides 13% saving in fuel consumption.

4. INVESTIGATION OF NEGATIVE EFFECTS OF VEHICLE TRAJECTORY OSCILLATION UNDER HARMONIC DISTURBANCE

In the previous section it was shown that the second concept of WIG-craft altitude stabilization provides more effectual use of WIG-effect and better fuel saving against the first concept. Low radar signature of vehicle in this mode of flight could be also considered as the advantage of second concept in special applications.

But some negative effects inherent to this concept also exist. Firstly, such vertical oscillation may be not comfortable for passengers if the frequency is large and vertical accelerations are tangible. For cargo vehicles and especially for unmanned vehicles it is not essential.

Another negative influence of vertical oscillation consists in possible energy loss due to elongation of traversed path and corresponding decrease of fuel saving. It is not easy to calculate this loss exactly, but for evaluation in the first approximation it is reasonable to compare the distance traveled in the horizontal plane with the length of sinusoid

$h_2(l) = a_2 \sin(\Omega l + \varphi + \psi)$, written in (6). Phases φ and ψ are not interesting in this task. That is why we will consider the elementary sinusoid $h_2(l) = a_2 \sin\Omega l$ and solve the task of its length calculation for one period $l \in [\ 0,\ 2\pi/\Omega\ ]$. In other words, we extend sinusoid in a straight line and estimate its length L.

Introducing the derivative of h_2 with respect to l

$\dot{h}_2(l) = \Omega a_2 \cos\Omega l,$

for the increment of L (hypotenuse when the catheti are Δh_2 and Δl) write

$$\Delta L = \sqrt{\Delta h^2 + \Delta l^2} = \Delta l\sqrt{1 + \left(\frac{\Delta h}{\Delta l}\right)^2} = \\ = \Delta l\sqrt{1 + (\Omega a_2 \cos\Omega l)^2}.$$

Moving from finite differences to differentials and integrating, obtain

$$L = \int_0^{2\pi/\Omega} \sqrt{1 + \Omega^2 a_2^2 \cos^2\Omega l}\,dl. \tag{14}$$

Taking into account the formula

$\sqrt{1+\alpha} \approx 1 + \alpha/2,\ \ \alpha \ll 1$,

obtain from (14) more simple integral

$$L = \int_0^{2\pi/\Omega} (1 + \frac{\Omega^2 a_2^2 \cos^2\Omega l}{2})dl \tag{15}$$

rightful at $\Omega a_2 \ll 1$.

Application of exact expression

$$\cos^2\Omega l = \frac{1+\cos2\Omega l}{2}$$

permits to rewrite (15) as

$$L = \int_0^{2\pi/\Omega} \left(1 + \frac{\Omega^2 a_2^2}{4} + \frac{\Omega^2 a_2^2}{4}\cos2\Omega l\right) dl. \tag{16}$$

The third summand under the integral in (16) is the symmetric alternating-sign function and it gives zero after integration. The first two summands give the final expression

$$L = \frac{2\pi}{\Omega}\left(1 + \frac{\Omega^2 a_2^2}{4}\right) \tag{17}$$

or

$$L = \lambda\left(1 + \frac{\Omega^2 a_2^2}{4}\right)$$

where $\lambda = 2\pi/\Omega$ is the length of sea wave. At a_2=0 the increasing of trajectory length disappears and L=λ.

The obtained expression (17) permits to claim that increase of the length of the path traveled in a sinusoidal way makes up a very small fraction of the length of each period of harmonic wave.

The length of the waves is typically in tens of times greater than their height, and certainly significantly more than the possible amplitude of the vertical oscillations of WIG-craft trajectory in longitudinal plane. For example, when Ω=0.05m^{-1}, ω=1.65s^{-1}, a=2m, T_e=1s (8) and (17) give a_2=1.03 m, L=125(1+6.6 10^{-4}) = 125.1 m.

However, even this small effect must be taken into account in the study of WIG-craft stabilization concepts because it could influence on the selected parameters of control law, especially at small T_e.

5. REQUIREMENTS TO WIG-CRAFT ALTITUDE STABILIZATION AT HARMONIC DISTURBANCE

In accordance with the second concept of WIG-craft altitude stabilization, it is advantageous to allow the vehicle not intensive smooth oscillations in longitudinal plane caused by the impact of long-period sea waves. The positive effect of such mode of flight is described by formula (13) and consists in increase of the average lift/drag ratio and fuel saving. The negative effect could be described by formula (17) and consists in some increasing of the length of trajectory. It is reasonable to write the joint formula that could permit the analytical estimation of WIG-mode flight effectiveness and reasonable selection of the vehicle time constant *Te* value in the model (1).

To do this, let's introduce some total measure of flight effectiveness

$$E = \frac{K}{K\infty} / \frac{\lambda}{L}. \quad (18)$$

Really the value E shows the relative advantage of WIG-mode of flight regarding the straight flight far from the surface. At E=1 such an advantage disappears. Of course, this estimation could be rather approximate, but presently nobody offers any other criterion for optimisation of the stabilisation system of WIG-craft.

Using the formulae (13) and (17), for criterion (18) write down the expression

$$E= \left(1+ \frac{b}{30(\Delta + a\,(1-1/\sqrt{1+\omega^2 T_e^2})}\right)/\left(1 + \frac{\Omega^2 a_2^2}{4}\right), \quad (19)$$

where a_2 is given by formula (8) and $\Omega=\omega/V$, V is the ground speed of vehicle.

Taking into account (8), finally obtain

$$E= \left(1+ \frac{b}{30(\Delta + a\,(1-\frac{1}{\sqrt{1+\omega^2 T_e^2}}))}\right)/\left(1 + \frac{\omega^2 a^2}{4V^2(1+\omega^2 T_e^2)}\right). \quad (20)$$

The expression (20) can be used for calculation of the values E at different values of Te, ω, a, b, Δ and V. For example, the curves $E(Te,b)$ are constructed in Fig.4 at ω=1.65s^{-1}, a=2m, , Δ=0.25 m, V= 33 m/s.

The following results can be obtained from Fig.5 analysis.

Really achievable values of E lie in the range of 1.07 - 1.6. So, it is not easy to provide the essential fuel saving in WIG-mode of flight at presence of sea waves, especially for small vehicles. Only for rather great dimension of vehicle (at b ≥12 m) the value of E could achieve 2 and even 3.

The maximal value of E is reached at $Te\to 0$. Hence the effect of the negative impact on E from increasing the path length due vehicle's vertical oscillations is weaker than the positive effect from reducing the average geometric altitude of flight.

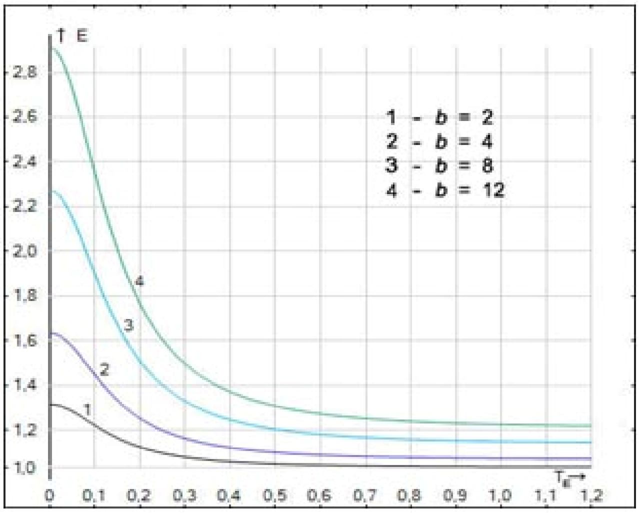

Fig.5. Dependence of criterion E on values Te and b: 1-b=2 m , 2-b=4 m, 3-b=8 m , 4-b=12 m.

It makes impossible to select the best value of time constant Te only from behavior of index E and requires use of other criteria. For example, the acceptable vertical acceleration of vehicle in oscillation could be the additional criterion for Te selection.

At motion (7) the maximal vertical acceleration is

$$A= \omega^2 a_2 = \frac{\omega^2 a}{\sqrt{1+\omega^2 T_e^2)}}.$$

If we require $A \le A_{max}$, it gives the rule

$$Te \ \ge \frac{\sqrt{\omega^4 a^2 - Amax^2}}{\omega\, Amax}. \quad (21)$$

If accept $Amax$=g/5=1.96 m/s^2, then at ω=1.65s^{-1}, a=2m formula (21) gives

$$Te \ge \frac{\sqrt{29.4-3.84}}{3.24} = 1.56 \text{ s.}$$

If consider $Amax$=g/3=3.27 m/s^2, then formula (21) permits to obtain 0.70 s and especially at

$$Te \ge \frac{\sqrt{29.4-9.7}}{6.4} = 0.70 \text{ s.}$$

At last, if accept $Amax$=g/2=4.91 m/s^2, then formula (21) permits to obtain

$$Te \ge \frac{\sqrt{29.4-24.1}}{8.1} = 0.28 \text{ s.}$$

According to Fig.5, only at Te≤0.70s and especially at $T_e \le$ 0.28s WIG– mode of flight shows the essential effectiveness against ordinary plane mode of flight in terms of general criterion E connected with fuel saving. Maximal saving of fuel could be 20-30% and it applies only to rather big WIG-craft with chord of wing b=8-12 m. For small vehicles with *b* values around 2-3 m the effectiveness of flight in WIG-mode is very small.

Of course, small WIG-craft, including UAV, may be also useful taking into account other advantages of WIG-mode of flight. But in this case it is necessary to talk only about vehicles for rivers and lakes without essential waves and remember the advantages of not using aerodromes, better safety of flight against planes and other terms.

It is essential that these outcomes are obtained at rather small clearance margin Δ=0.25m. It requires the corresponding high accuracy of flight parameters measurement and automatic control, but the modern aerospace sensors and automatic systems design methods are able to solve such tasks (Nebylov, 2013; Davila, 2008). It is possible also to use the methods of disturbance prediction for shaping the desirable dynamics of controlled plant mentioned in sections 2 and 4.

6. CONCLUSION

Among many papers on WIG-craft control problems this one had an especial purpose to estimate the potential effectiveness of controlled flight in WIG-mode above the sea waves and recommend the best concept for automatic control and stabilisation in longitudinal plane. It was done for the most general case without any detailed characteristics for the certain vehicle. Only wing chord was used for description of the vehicle dimension. The simplest harmonic sea wave was considered as a disturbance. Some other simplifications have been used also. Rather simple analytical formula for dependence of lift-to-drag ratio on the altitude of WIG-mode flight was firstly suggested. A new approach for approximate calculation of energetic loss due to vehicle trajectory vertical oscillation was firstly used. The stabilised vehicle itself was considered as the simple aperiodic unit with a single essential parameter – time constant.

All these simplifications have permitted to obtain the important general conclusions about the effectiveness of WIG-mode use. It terms of fuel consumption saving this effectiveness can be essential only for rather big WIG-craft with wing chord commensurate with sea waves height and really exceeding them several times. Such an effectiveness could be slightly increased by admission of the vehicle vertical oscillations in partly tracking the large waves, that reduces the average geometric altitude of motion. In real spectrum of sea waves different frequencies are available and the partial tracking of low-frequency waves is quite admissible. But vertical acceleration of such oscillating motion must be limited by the reasonable values.

The main conclusion consists in the necessity to develop big WIG-craft that could show really the great transport effectiveness. Development of such vehicles is more expensive, but it is a single way to obtain the class of transport with new capabilities. And of course prospective WIG-craft will require application of full spectrum of modern automatic control theories and systems (Nebylov, 2004).

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