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# WIG-craft flight control concept for the waved sea

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## Abstract

The problem of Wing-in-Ground effect most affective use in WIG-craft flight by minimization of the average geometrical altitude of flight above sea waves is considered in the paper. Two concepts of vehicle motion in longitudinal plane are compared. The new analytical formulae are developed. They are simple and may be used for approximate estimations only, but permit to select the best concept for vehicle altitude stabilization. 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. It is proved that only large WIG-craft could provide the essential fuel saving in controlled flying close to the disturbed surface. For small WIG-craft fuel saving against the plane mode of flight is not essential, 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 select the best concept of flight control before developing the control laws for the certain vehicle. This task of estimating the best ways for perfecting of automatically controlled WIG-craft is solved in this paper and it is useful for real designing of control law.

## 1. Introduction

WIG-effect vehicles occupy the specific place among the winged means of transportation. They use in flight the Wing-In-Ground (WIG) effect. This phenomenon consists in substantial lift force increasing and air drag decreasing when a wing is moving close to the supporting surface. In this case the air-cushion action in the space between wing and supporting surface is added to the normal mechanism of lift force formation. The velocity of WIG-flight may be around 200-500 km/h depending on vehicle dimensions. The altitude of WIG-flight has to be essentially less than the wing chord of vehicle and really lies in the range from 0.5m for small vehicles to 5-10m for big and great ones [1-8]. The most famous big vehicles were developed by the order of Russian Navy at the end of 20th century and that is why the Russian name ekranoplane is widely used for any WIG-craft. In Japan the name WISE (wing in surface effect ship) is more popular; among German scientists the term GEVs is often used.

Ground effect is essential only at altitudes which are less than 0.1-0.2 of the wing chord length [9-13]. Reasonable choice and automated maintaining of extremely low altitude is the important task in optimizing functional efficiency of WIG-craft. It is certainly necessary to take into consideration the features of sea waves at solving this task [6]. The opportunities of minimizing the average geometric altitude of WIG-craft flight above the waves and other important requirements to the automatic motion control system of WIG-craft are analyzed in the paper. It is shown that the best automatic motion control law for WIGs in longitudinal plane provides not only maintaining the altitude of flight relatively to the average height of the roughed sea surface but also the partial following, tracking of big waves` shapes.

In other words, it is reasonable to use WIG-craft auto-stabilization feature and allow vehicle to carry the smooth oscillations in the vertical plane depending on the shapes of big waves. It is proved that only large WIG-craft with the weight of 100 tons or more is able to provide a substantial fuel economy while being piloted close to the surface of the waves. For smaller WIG-craft the fuel economy in comparison with aviation mode operations is not worth and sea navigability of these small vehicles does not provide usability in the ocean. That is why it is important to choose the concept of flight control wisely prior to designing laws of control of certain piloted or automatically controlled vehicle.

Modern automatic control systems on the base of perfect onboard sensors, computers and actuators are able to embody any of the requested dynamical characteristics of WIG-craft in cruise flight and during manoeuvring [3, 4, 14-20]. Nevertheless, in accordance with the proposed concept, system of automatic motion control has to provide only the stability of WIG-craft flight and increase the stability margin, which turns the step response characteristic into aperiodic one. Concerning stabilization of altitude, it has not to be absolute and has to provide partial tracking of big waves’ shapes.

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Small waves should not (and cannot) influence the altitude of flight, but the shape of high waves must influence the movements of the vehicle in the vertical plane to reduce the average geometric altitude of flight. It is obvious that such fluctuations of the vehicle in longitudinal plane cannot be intensive to prevent overload of the crew and avionics with high acceleration (such limitation is not applicable for unmanned vehicles). Evaluation of acceptable values for the parameters of acceleration and vibration for piloted WIG-craft with passengers must be based on recommendations provided by ISO 2631. These fluctuations have not to be a result of actuators' movements and overload them excessively, but they have to be achieved by WIG-craft self-stabilization feature generally connected with the decrease of lifting force at increase the geometrical altitude. A new complex index of flight efficiency $E$ will be introduced in the paper which considers dynamic model of the WIG-craft as well as the influence of ground effect and sea waves which comply with the determined model. The graphs which show the dependence of this index to the size of the WIG-craft, parameters of its motion and other factors will be presented. The conclusion considering the fuel efficiency and other efficiency indexes of large WIG-craft will be made.

## 2. General peculiarities of WIG-craft

Flight near the underlying surface gives a lot of specific features to these vehicles, most of which are valuable for effective transportation. But flight control in WIG mode is certainly more complex and difficult in comparison with control of free flight at great altitude due to dependence of all aerodynamic indexes on the flight altitude regarding the ground or water surface. Complex character of these dependences often gives the loss of the vehicle stability at some mismatch of flight parameters values for certain vehicle aerodynamic configuration.

The idea of ekranoplane design may be considered as the inverse of hydrofoil with shallow submerged foils both of which Russian designer Rostislav Alexeev has suggested. Hydrofoil vehicle has a submerged wing, but ekranoplane has a wing above the water.

The first ekranoplane SM-1 constructed by Alexeev, was of tandem scheme and it had not serious problems with flight stability, but met difficulty in steady motion above the stormy sea. After these first experiments, the well known presently "plane-like" scheme of ekranoplane was suggested and finally realized in "Orlyonok" with take-off mass of 140 ton (Figure 1). It provided the vehicle longitudinal stability, but only in rather narrow corridor of flight parameters values. The stability can be lost at some mismatch of altitude, pitch and attack angle.

Alexeev expected to hold the mode of flight inside this permissible corridor by experienced pilots and without application of any automatic control systems.

Figure 1: Assault ekranoplane "Orlyonok" with plane-like configuration of 140 ton weight

The autopilots Smena-4 for "Orlyonok" and Smena-3 for "Lun" were created later, in seventies and eighties, mainly under the formal requirements of the Navy (Diomidov, 1996; Zhukov, 2007). These autopilots were the analogy systems for damping and stabilization of 5 main parameters of flight, but without adaptation and using the facilities of modern control theory. Unfortunately, the principles of digital control and integrated multi-channel systems were not realized in the first prototypes of Smena [1].

During three decades passed from that time the commercial rather small ekranoplanes were developed at several countries. For our opinion, the best one is Russian Ivolga-12 (Figure2), the main designer –V.Kolganov. But any serious attempts to construct the automatic control system for ekranoplanes motion control were not done. The main reason consisted in creation of the cheapest vehicles under the request of the market, and control automation means did not correspond to this concept.

Step by step it became clear that this concept cannot permit solving the problem of perfect commercial ekranoplane creation and the modern embedded means of automatic control must be the essential part of the vehicle. Automatic control system must be designed simultaneously with the vehicle design and influence on the acceptable class of

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vehicle's aerodynamic characteristics. It is especially important that vehicles without own good stability can be considered as an admissible or even optimal ones if the lift-to-drag ratio is great and fuel consumption is least. Providing of flight stability can be imposed entirely on the embedded automatic control system which reliability must be without a shadow of doubt.

Figure 2: Small Ekranoplane "Ivolga"

## 3. Statement of the problem of control law optimization

Only the longitudinal motion of generalized WIG-craft will be considered here. 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 corresponds to simple aperiodic shape of step response in the longitudinal plane. Such automatic motion control system could be named as damping system and it is necessary for performing the automatic or manual control of big WIG-craft motion. At the first approximation this damped plant can be modelled as the linear aperiodic unit of the first order with a very simple transfer function

$$W_e(s) = \frac{k_e}{1+T_e s}, \tag{1}$$

where $T_e$ is the time constant and $k_e$ is the gain factor that can be equal to 1 if the reaction of vehicle flight altitude to the single sea wave height is considering.

Such a very simple model of damped WIG-craft dynamics is useful for analytical statement of the problem of Te 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 a PID-regulator with the additional reject filters in the closed loop control.

It is clear that the best control law lies between rigid stabilization of average altitude of flight ($T_e \to \infty$) and full freedom in action the self-stabilization property of WIG-craft ($T_e = 0$).

To study the effect of self-stabilization of flight altitude $h$, it is advisable to use the formula proposed by the authors and expressing the dependence of the normalized lift/drag ratio of ekranoplane on the normalized altitude of its flight:

$$\frac{K}{K_\infty} = 1 + \frac{b}{25h} \text{ at } \frac{h}{b} \geq 0.03, \tag{2}$$

where $K_\infty$ 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 for obtaining $K/K_\infty \geq 1.2$ is possible only at very small altitudes when $h/b \leq 0.2$. For example, for rather small vehicle with $b$=4m the condition $h \leq 0.8$m must be fulfilled for effective flight. For famous Russian WIG-craft "Lun" with $b$=12.5 m the effective flight in WIG-mode requires $h \leq 2.5$m.

Let us consider two possible concepts of WIG-craft flight altitude stabilization at disturbance from sea wave's action. 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, $\Omega$ is a spatial frequency of wave, $\varphi$ is the phase of harmonic wave, $a$ is the magnitude of wave.

Physically this model corresponds to the sea waves of swell type. More complex models of three-dimensional sea waves could be also considered [6], but it complicates analytic transformation and not necessary at this initial stage of investigation. It will be done in the next papers.

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## 4. The first concept of WIG-craft vertical motion at harmonic disturbance

At the first concept of motion control 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 some errors in motion control. If calculate altitude of flight regarding the average level of sea surface, it must be $h_1 = a + \Delta$, as it is shown in Figure3.

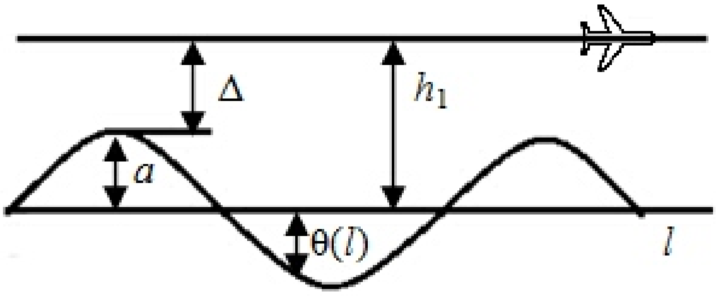

Figure 3: Trajectory of flight in longitudinal plane at harmonic disturbance at control concept 1

The minimal geometrical altitude of flight is equal to Δ, the maximal geometrical altitude of flight is equal to Δ + 2*a*. The average level is

$$h1 = a + \Delta. \qquad \textbf{(4)}$$

If recalculate it into the values of $K/K_\infty$ 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 h1 from (4) to (2) instead of *h*. It will give

$$\frac{K}{K_\infty} = 1 + \frac{b}{25(a+\Delta)}. \qquad \textbf{(5)}$$

For example, at *a*=1m, Δ=0.25m, *b*=4m according to (5) $K/K_\infty \approx 1.128$. It means that such WIG-mode of flight is not very effective and provides only 12.8% saving in fuel consumption. Certain increase of efficiency can be achieved by reducing the gap Δ, but this is possible only at very precise altitude stabilization system.

## 5. The second concept of WIG-craft vertical motion at harmonic disturbance

At the second concept of motion control the stabilization of flight altitude is not tough and permits vehicle to track partly the wave disturbance passing them through the dynamic unit with transfer function (1). The corresponding curves are shown in Figure4.

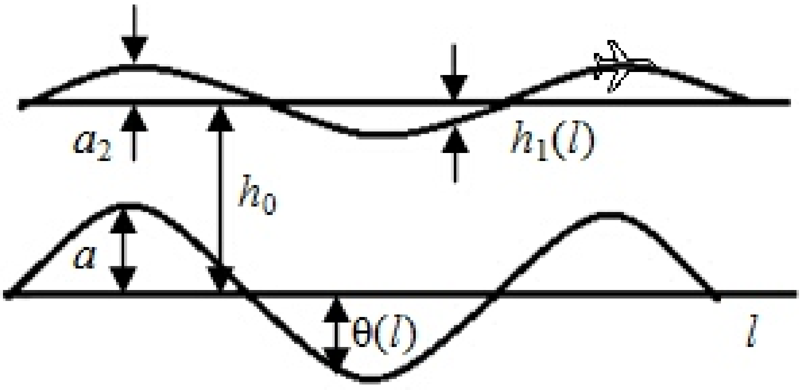

Figure 4: Trajectory of flight in longitudinal plane at harmonic disturbance at control concept 2

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

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

or, passing from spatial space to temporal space domain,

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

where the angular frequency ω=$V\Omega$ and $V$ is the ground speed of vehicle. For example, if Ω=0.05m-1, $V$=33m/s, then ω=1.65$s^{-1}$. It corresponds to the length of sea wave λ=2π/Ω=125.6 m.
Taking into account the transfer function (1) of the plant, the magnitude and phase of vehicle trajectory vertical oscillation will be

$$a_2 = \frac{a}{\sqrt{1+\omega^2 T_e^2}}, \quad \textbf{(8)}$$

$$\psi = \arctan \omega T_e.$$

Initial phase φ is not essential in this case, but the 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

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

where $h_0$ is the clearance margin similar to Δ in the first concept.
When analyzing the formula (9) and Figure4, b, it becomes clear that the average value of $h_e$(t) will be minimal at ψ=0, when the harmonic processes θ($t$) 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. Fulfilment of this requirement is not difficult if the prediction of wave disturbances or radar estimator of approaching wave is used.
Accepting ψ=0, from (8) and (9) immediately obtain $h_e(t) = h_0 + a\sin(\omega t + \varphi) - a_2 \sin(\omega t + \varphi) = h_0 + $
$+a\left(1 - \frac{1}{\sqrt{1+\omega^2 \mathrm{T}_e^2}}\right)\sin(\omega t + \varphi)$.
The minimal value of geometrical altitude will be

$$h_{e\,min} = h_0 - a\left(1 - \frac{1}{\sqrt{1+\omega^2 \mathrm{T}_e^2}}\right), \quad \textbf{(10)}$$

the maximal value will be

$$h_{e\,max} = h_0 + a\left(1 - \frac{1}{\sqrt{1+\omega^2 \mathrm{T}_e^2}}\right).$$

The average level will be equal to $h_o$,
Since only the motion over the crests of sea waves will ensure the avoidance of collisions with them, the requirement must be

$$h_{e\,min} \geq \Delta. \quad \textbf{(11)}$$

The expressions (10) and (11) require the condition

$$h_0 = \Delta + a\left(1 - \frac{1}{\sqrt{1+\omega^2 T_e^2}}\right). \qquad \textbf{(12)}$$

For approximate estimation of K/K∞ one can substitute the average value of altitude h0 from (12) to (2) instead of *h*, and it will give

$$\frac{K}{K_\infty} \approx 1 + \frac{b}{25\left(\Delta + a\left(1 - \frac{1}{\sqrt{1+\omega^2 T_e^2}}\right)\right)}. \qquad \textbf{(13)}$$

For example, at $a$=1m, Δ=0.25 m, $b$=4m, ω=1.65s-1, $T_e$=1s according to (13) obtain $K/K_\infty \approx 1.219$. It means that such WIG-mode of flight provides 21.9% saving in fuel consumption.

## 6. Study of the negative effects of vehicle trajectory vertical oscillation

In the section 5 it was shown that the second concept of WIG-craft flight altitude stabilization provides more effectual use of WIG-effect and more fuel saving against the first concept. Low radar signature of vehicle in this mode of flight could be also the advantage of second concept in special applications.

But some negative effects inherent to this concept also exist. At first, 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 so essential.

Another negative influence of vertical oscillation consists in possible energetic loss due to elongation of traversed path and corresponding decreasing 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 travelled in the horizontal plane with the length of sinusoid $h_2(l) = a_2 \sin(\Omega l + \varphi + \psi)$, written in (6). The 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 into a straight line and estimate its length $L$.

Introducing the derivative of $h_2$ with respect to $\dot{h}_2(l) = \Omega a_2 \cos \Omega l$, for the increment of $L$ (hypotenuse when the cathetuses are $\Delta h_2$ and $\Delta l$), let us 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

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

Taking into account the formula

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

it is possible to obtain from (14) more simple integral

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

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that is rightful at $\Omega a_2 \ll 1$.
Application of the exact expression

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

permits to rewrite (15) in the form

$$L = \int_0^{2\pi/\Omega}\left(1+\frac{\Omega^2 a_2^2}{4}+\frac{\Omega^2 a_2^2}{4}\cos 2\Omega l\right)dl; \qquad \textbf{(16)}$$

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

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

or

$$L = \lambda\left(1+\frac{\Omega^2 a_2^2}{4}\right), \qquad \textbf{(17)}$$

where $\lambda=2\pi/\Omega$ is the length of sea wave. At $a_2=0$ the increasing of trajectory length disappears and $L=\lambda$.
The derived expression (17) permits to claim that increasing 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 many times greater than their height, and of course significantly more than the possible amplitude of the vertical oscillations of WIG-craft trajectory in longitudinal plane. For example, when $\Omega=0.05\text{m}^{-1}$, $\omega=1.65\text{s}^{-1}$, $a=2\text{m}$, $T_e=1\text{s}$ the expressions (8) and (17) give $a_2=1.036$ m, $L=125.6(1+6.7\ 10^{-4}) = 125.7$ 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 values of time constant $T_e$.

## 7. Peculiarities of vehicle altitude stabilization at harmonic disturbance

Following the second concept of WIG-craft flight altitude stabilization, it is useful to allow the vehicle smooth oscillations in longitudinal plane caused by the impact of long-period sea waves. The positive effect of such mode of flight is clear from the expression (13) and consists in increasing the average lift/drag ratio and decreasing of fuel consumption. The negative effect could be described by the expression (17) and consists in slight increase of the length of passed 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 value of vehicle time constant $T_e$ in the model (1).
For this purpose let's introduce the integral index of flight efficiency

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

In fact this important index shows the relative advantage of WIG-mode of flight in compare with the straight flight far from the surface. At $E=1$ such an advantage disappears. Of course, this estimation can be rather approximate, but presently nobody offers any other criterion for optimization of the flight altitude stabilization system for WIG-craft.
Using the formulae (13) and (17), for criterion (18) one can write down the expression

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$$E = (1 + \frac{b}{25\left(\Delta + a\left(1 - \frac{1}{\sqrt{1+\omega^2 T_e^2}}\right)\right)} / \left(1 + \frac{\Omega^2 a_2^2}{4}\right), \tag{19}$$

where $a_2$ is given by formula (8), $\Omega=\omega/V$, $V$ is the ground speed of vehicle.
Taking into account (8), finally it is possible to obtain

$$E = (1 + \frac{b}{25\left(\Delta + a\left(1 - \frac{1}{\sqrt{1+\omega^2 T_e^2}}\right)\right)} / \left(1 + \frac{\omega^2 a^2}{4V^2(1+\omega^2 T_e^2)}\right). \tag{20}$$

The expression (20) can be used for calculation of the index $E$ at different values of $T_e$, ω, $a$, $b$, Δ and $V$. For example, the curves $E(T_e,b)$ are constructed in Figure 5 at $\omega=1.65\text{s}^{-1}$, $a$=2m, Δ=0.25 m, $V$= 33 m/s.

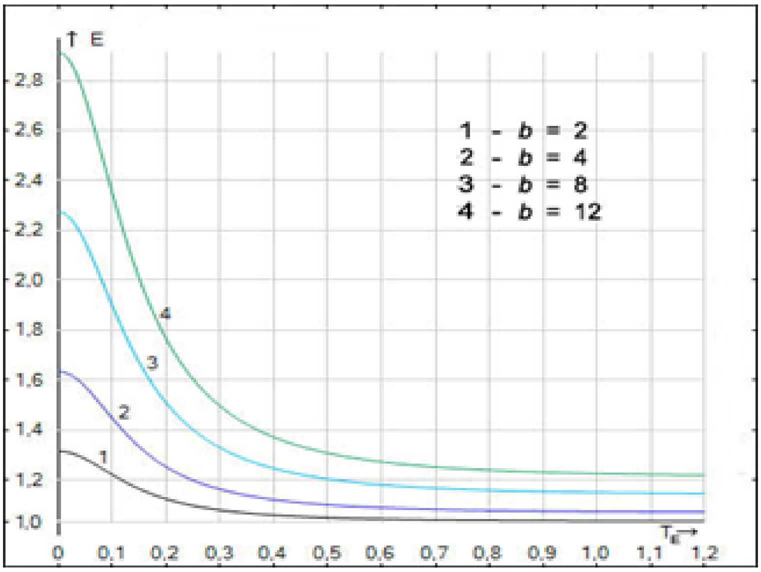

Figure 5: Dependence of index $E$ on values $T_e$ and $b$: 1- $b$=2$m$, 2- $b$=4$m$, 3- $b$=8$m$, 4- $b$=12$m$.

Analyzing the curves in Figure5, one can make the following conclusions.
In general case the achievable values of $E$ could belong to the range of 1.07 - 1.6. So, it is not easy to provide the essential decrease of fuel consumption in WIG-mode of flight at presence of significant sea waves, especially for small vehicles. Only for vehicles with rather great dimension (at $b \geq$12m ) the value of $E$ could achieve 2 and even 3. The maximal value of $E$ is reached at $T_e \to 0$. Consequently, the negative effect on index $E$ value from the increase in path length due to the vertical oscillations of the vehicle is weaker than the positive effect from decrease the average geometric altitude of flight. It makes impossible to select the best value of time constant $T_e$ only from behavior of index $E$, it requires the use of other criteria also. For example, the acceptable vertical acceleration of vehicle in oscillation could be the additional criterion for value $T_e$ selection.
At accepting the model (7) for WIG-craft motion, the maximal vertical acceleration will be

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

If one requires $A \leq A_{max}$, it gives the rule

$$Te \geq \frac{\sqrt{\omega^4 a^2 - Amax^2}}{\omega \, Amax}. \tag{21}$$

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

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

If one considers $Amax$=g/3=3.27 m/s$^2$, then formula (21) permits to obtain

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

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

$$T_e \geq \frac{\sqrt{29.4-24.1}}{8.1} = 0.28 \text{ s.}$$

According to Figure5, only at $T_e \leq 0.70$s and especially at $T_e \leq 0.28$s the WIG–mode of flight shows the essential effectiveness against ordinary plane mode of flight in terms of general criterion $E$ connected with possible fuel saving. Maximal saving of fuel could be 20-30% and it is applicable only to rather big WIG-craft with the chord of wing $b$=8-12 m. For more small vehicles with $b$ values around 2-3m the effectiveness of flight in WIG-mode is very small [21].

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 opportunity to meet the essential waves and remember the advantages of not using aerodromes, better safety of flight against planes, small radar signature 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 [11, 14-17]. It is possible also to use the methods of disturbance predicting for shaping the desirable dynamics of controlled plant that was mentioned in sections 2 and 5.

## 8. Conclusions

The problems of WIG-craft automatic motion control systems design were discussed. Only motion in the longitudinal plane was considered.

A special goal for selection the best concept of vehicle altitude of motion above the disturbed sea was set and achieved.

It was done for the most general case without detailed characteristics for the certain WIG-craft. Only wing chord value was used for description of the vehicle dimension. The simplest harmonic sea wave was considered as a disturbance. Rather simple analytical formula for dependence of lift-to-drag ratio on the altitude of WIG-mode flight was suggested and used. A new approach for approximate calculation of energetic loss due to vehicle trajectory vertical oscillation was developed. The stabilized vehicle itself was considered as the simple aperiodic unit with a single essential parameter – time constant.

All these simplifications have permitted to develop the important general conclusions about the effectiveness of WIG-mode of flight use. In terms of fuel consumption saving this effectiveness can be essential only for rather big WIG-craft with wing chord commensurate with sea wave's height and really exceeding them several times. Such 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 general conclusion consists in the necessity to develop a big WIG-craft that could show really the great transport effectiveness, especially in low fuel consumption and high flight safety, cheap infrastructure. Development of such vehicles is a single way to obtain the class of transport vehicles with essential new capabilities. And of course the design of prospective WIG-craft will require application of full spectrum of modern automatic control theories and systems [14-17].

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