Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

WIG-craft Marine Landing Control at Rough Sea

Alexander Nebylov, Vladimir Nebylov

State University of Aerospace Instrumentation,
67, Bolshaya Morskaya, Saint-Petersburg, 190000 Russia
Tel.: +7 812 4947016, E-mail: nebylov@aanet.ru

Abstract: Wing-in-Ground Effect vehicle (WIG-craft) or ekranoplane landing direction optimization criteria is suggested which heeds the irregular sea waves features and provides the minimal mechanical strain on the vehicle body at hydrodynamic braking. The problem of automatic choice of the landing trajectory direction regarding the main direction of sea waves spread is under consideration. The peculiarities of marine landing at different characteristics of three-dimensional irregular model of sea waves and flying vehicle characters are investigated[1]. Recommendations concerning the implementation of ekranoplane soft landing depending on the number of sea roughness, wind velocity and vehicle landing velocity are given.

Keywords: WIG-craft, ekranoplane, flight control, landing mode, approach angle optimization, wave disturbances, hydrodynamic braking.

1. INTRODUCTION

Seaplanes and WIG-craft are supposed to take the significant part of air cargo and passengers number increment without constructing new air-strips. Both seaplanes and heavy WIG-craft can perform the cruise flight practically independently from sea state, including stormy sea. But trouble-free marine landing on disturbed sea surface requires the application of the special methods and means of navigation and motion control which are capable to solve the corresponding specific problems. Great mechanical strain on the vehicle body at hydrodynamic braking determines the necessary strength of the body and finally its weight. Too great weigh of body makes the payload capacity less and decrease the transport efficiency of the vehicle. That is why decreasing of assumed mechanical load on the vehicle body at landing is very important.

The take off and landing modes at rough sea are the most difficult and dangerous stages of sea planes and ekranoplanes (WIG-craft) flight. Theoretically the vehicle has to be able for all-weather flight, but really any marine flying vehicle is not so storm-proof to operate in the rough sea conditions of high number (Fig. 1).

Fig. 1. Ekranoplane in stormy sea.

[1]The work has been supported by the Russian Foundation for Basic Research under the project 06-08-00550-a

Thus it is important to maximize the take off and landing ability of comparatively light vehicles in the stormy sea (Nebylov and Wilson, 2002; Fishwick, 2001; Opstal, 2001; Taylor, 2001, Nebylov, 1994).

The most essential mechanical loadings directed on the vehicle body appear at the moment of bottom body contact with a water surface when hydrodynamic breaking starts. The shape of the water surface at this point is important. The spatial stochastic characteristics of sea waves have to be taken into account. It is necessary to consider also the direction of wind vector during vehicle landing. Dynamic characteristics of air and water are similar except for one of the most important parameters – density. Water is 800 times heavier than air, and at high velocity of landing motion it becomes practically rigid and gives large disturbances to the vehicle.

Landing of ekranoplane and partly of sea plane on the rough sea surface differs essentially from landing of ordinary plane on the concrete landing strip. The best direction for any "overland" plane landing approach is the direction against wind. It permits to decrease the actual ground speed at the fixed landing airspeed. It permits also to keep the zero roll and yaw angles during landing as the lateral component of wind is practically absent.

During ekranoplane or sea plane landing on the disturbed sea surface the requirements are not the same and not so simple. The pilot or automatic control system can choose any approach angle as the area for possible landing is not restricted by the strip and can belong to any suitable place in the open sea not far from the appointed destination. But of course, a direction of wind vector has to be taken into account at approach angle choice.

Landing against wind allows to lower vehicle landing velocity in relation to a surface (Fig. 2). At windy sea waves the general direction coincides with the direction of wind, i.e. aerodynamically it is advantageous to land with the direction, contrary to general direction of sea waves distribution. But at a strong wind when the waves are significant, landing against a wind gives essential wave disturbances as vehicle confronts with sea wave crests which correspond to the maximal water surface inclination. So, with the attitudes of hydrodynamics this direction exceptionally disadvantageously, since the frequency of meeting with sea waves and the bending of waves are maximal and the likelihood of vehicle crash because of excessive overloading is great.

Hydro-dynamically it is advantageous to land in the direction perpendicular to general one. Landing perpendicularly to the wind can not give the minimal landing velocity in relation to a surface, but inclination of sea wave slopes in this direction may be moderate and hydrodynamic braking will be not so hard.

That is why the optimization of the landing direction is an extreme task, and motion control at landing must be fulfilled with the allowance for current information on the characteristics of wave disturbances. Profile and the integral characteristics of sea waves can be measured together with the flight parameters of ekranoplane.

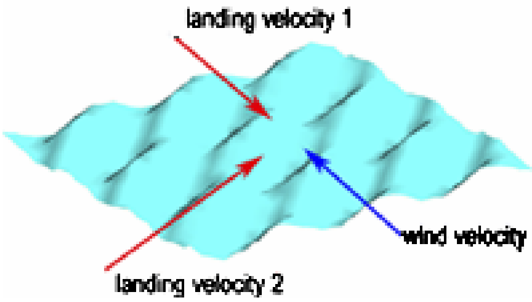

Fig. 2. Dependence on landing velocity on approach angle

So, optimization of approach angle in relation to the general direction of sea waves' extension may be the effective way of wave disturbance minimization during landing. The general direction can automatically be defined by processing of onboard radio engineering or optical sensors indications. In this case landing approach optimum mode implementation and landing itself demand using the results of numerical analysis of wave stochastic disturbances.

2. STOCHASTIC MODEL OF SEA WAVES

The disturbed by wind sea surface is a Gaussian casual field with certain temporal and spatial characteristics. Let us consider this surface as a superposition of uncountable set of elementary two-dimensional wave systems. The following representation of the waved surface ordinate corresponds to this model (Nebylov, 1994, 1995):

$$\zeta(t) = \sum_{i=1}^{\infty}\sum_{j=1}^{\infty} r_{ij}\cos(k_i x\cos\alpha_j + k_i y\sin\alpha_j - \omega_i t + \varepsilon_{ij}),\text{where}$$

$r_{i,j}$ are amplitudes, k_i and ω_i are spatial and angular frequencies, ε_{ij} are phases of elementary waves, x and y are the Cartesian coordinates.

The basic experimentally defined characteristic of completely developed wind sea waves is the power spectrum $S_\zeta(\omega)$, describing the frequency distribution of waved surface point elevation process energy, and also the law of waves energy angular distribution, usually accepted in the form:

$$\theta(\chi) = \frac{2}{\pi}\cos^2\chi, \quad \chi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right],$$

where χ is the angle in relation to a wind direction.

However, in research of sea waves influence on quickly moving at landing sea vehicle it is more convenient to use the model of the "frozen" waved surface characterized by the spatial spectrum $E(k, \psi)$ (Nebylov and Wilson, 2002)

$$E(k,\psi) = e_0(kh_{3\%})h_{3\%}^3\cos^2\psi + +e_{\pi/2}(kh_{3\%})h_{3\%}^3\sin^2\psi,\text{where}$$

$$e_0(kh_{3\%}) = \frac{1.03 \cdot 10^{-2}\pi}{(kh_{3\%})^3} \int_0^{\pi/2} \cos^4\chi' \exp\left[-\frac{0.112\cos^2\chi')}{(kh_{3\%})^2}\right] d\chi',$$

$$e_{\pi/2}(kh_{3\%}) = \frac{1.03 \cdot 10^{-2}\pi}{(kh_{3\%})^3} \int_0^{\pi/2} \cos^2\chi' \sin^2\chi' \exp\left[-\frac{0.112\cos^2\chi')}{(kh_{3\%})^2}\right] d\chi'.$$

3. CRITERION OF LANDING MODE OPTIMIZATION

According to aviation experience and physics of landing mode the "soft" landing is advisable when the bottom or landing floats of the sea vehicle slowly plunge into water without creating any great mechanical loads. In a typical landing trajectory (glissade) the velocity of immersing depends on a sea surface bias in the contact point where the vehicle touches sea surface. Therefore it is expedient to accept as the "softness" landing criterion the r.-m.-s. value of vertical velocity of vehicle bottom immersing into water

$$\sigma_V = V\sigma_\alpha, \qquad (1)$$

where V is the vehicle landing horizontal velocity, is the r.-m.-s. value of waved surface bias along the landing trajectory for which it is possible to accept the equation (Nebylov, 1996, 2007; Nebylov *et al*, 2005)

$$\sigma_\alpha^{\ 2}(\psi) = \frac{1}{\pi}\int_0^\infty k^2 E(k,\psi)dk. \qquad (2)$$

It is necessary to investigate the σ_V dependence on the landing direction relatively the wind direction and sea waves' disturbance characteristics. The minimal σ_V value will define the optimal mode of motion at landing,

4. COMPUTATIONAL EQUATIONS DERIVATION

Accepting the formulae of Neumann and Pierson-Moskowitz (Nebylov, 1994) as the basic spectral models of irregular sea waves, from equations (1), the r.-m.-s. values of waved surface bias along a landing trajectory and the expression for the spatial spectrum $E(k, \psi)$, it is possible to obtain the computational equations.

For Neumann's spectrum the resulted equation is

$$\sigma_V = (V_l - \upsilon\cos\psi)\times$$
$$\times\sqrt{\int_0^\infty \left(\begin{array}{l}\int_0^{\pi/2}(\cos^2\psi\cos^4\chi P(\chi,k)d\chi + \\ +\sin^2\psi\cos^2\chi\sin^2\chi P(\chi,k))d\chi\end{array}\right)dk}, \qquad (3)$$

$$P(\chi,k) = \frac{1.03\cdot 10^{-2}}{k}\exp\left[-\frac{0.112\cos^2\chi}{\left(k\left(3.95_{m^*c^{-5/2}}\right)(\upsilon/g)^{5/2}\right)^2}\right],$$

where χ is the angle in relation to a wind direction, k is a spatial frequency, υ a wind velocity, ψ is the angle in relation to a wind direction, V_l is the air velocity.

Calculation accordingly to the formula (3) permits to construct a plot in Fig. 3.

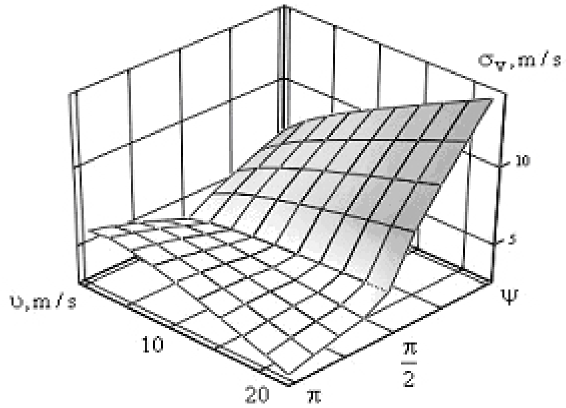

Fig. 3. The criterion σ_V for Neumann's spectrum.

For Pierson-Moskowitz spectrum the resulted equation is:

$$\sigma_V = (V_l - \upsilon\cos\psi)\times$$
$$\times\sqrt{\int_0^\infty \left(\begin{array}{l}\int_0^{\pi/2}(\cos^2\psi\cos^4\chi P(\chi,k)d\chi + \\ +\sin^2\psi\cos^2\chi\sin^2\chi P(\chi,k))d\chi\end{array}\right)dk}, \quad (4)$$

where

$$P(\chi,k) = \frac{1.03\cdot 10^{-2}}{k}\exp\left[-\frac{0.112\cos^2\chi}{\left(k(0.391)(\upsilon^2/g)\right)^2}\right].$$

Calculations accordingly the formulae (4) permit to construct the plot in Fig. 4.

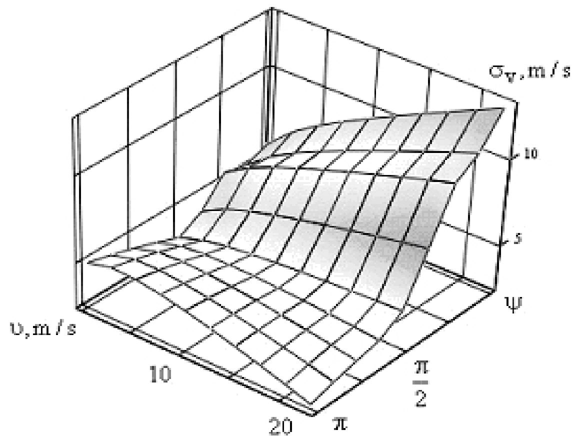

Fig. 4. The criterion σ_V for Pierson-Moskowitz spectrum.

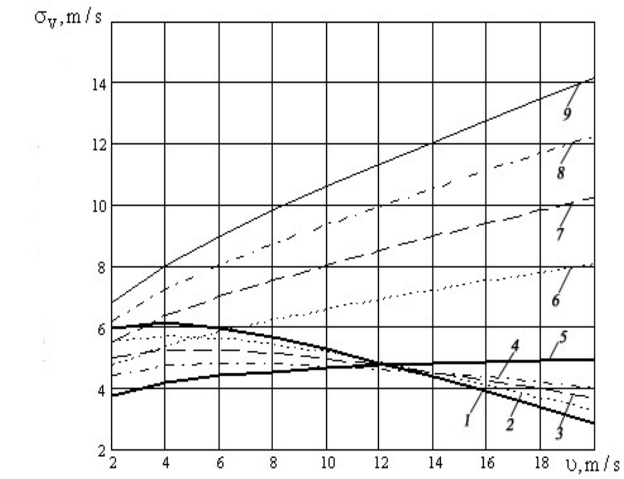

Fig. 5. The criterion σ_V for Neumann's spectrum at different landing directions: 1 - ψ =0, 2 - ψ = 30°, 3 - ψ =45°, 4 - ψ =60°, 5 - ψ =90°, 6 - ψ =120°, 7 - ψ =135°, 8 - ψ =150°, 9 - ψ =180°.

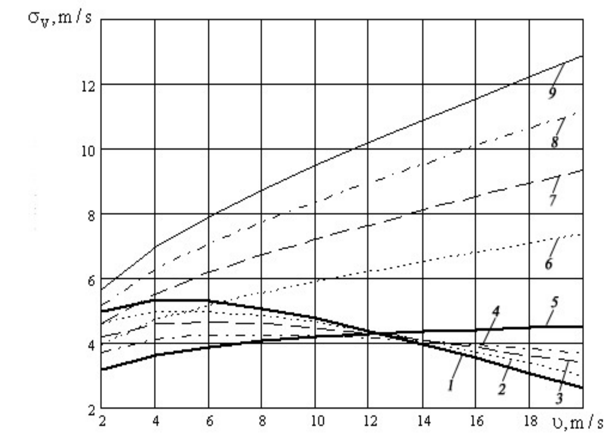

Fig. 6. The criterion σ_V for Pierson-Moskowitz spectrum at different landing directions: 1 - ψ =0, 2 - ψ = 30°, 3 - ψ =45°, 4 - ψ =60°, 5 - ψ =90°, 6 - ψ =120°, 7 - ψ =135°, 8 - ψ =150°, 9 - ψ =180°.

Values of criterion σ_V depending on wind velocity at the fixed landing velocity of the vehicle of 30 m/s at various landing directions are given in Fig. 5 and in Fig. 6.

5. OPTIMIZATION OF LANDING APPROACH ANGLE

In the executed research the vertical velocity of immersing of sea vehicle bottom in water r.-m.-s. values were deduced and calculated. It was accepted as the criterion of landing "softness" depending on a landing direction in relation to a wind direction, a landing velocity and wind velocity. At deducing the required dependence equations for a wave disturbance intensity measure, a spatial spectrum, a power spectrum of sea waves, the equation for r.-m.-s. values of the wave surface bias along a landing trajectory were used.

As a result according to the expressions (3) and (4) the 2D and 3D-plots have been constructed with MatLab application. The required parameter σ_V was calculated at an angle between a landing approach direction and a wind direction values from 0 up to π; landing velocity of 30 m/s and the wind velocity from 1 m/s up to 20 m/s with the step of 2 m/s.

The analysis of the constructed plots allows drawing a conclusion that the optimal landing approach direction depends on wind velocity which for completely developed windy sea waves defines all its characteristics. At wind absence (in the case of υ =0) the landing mode is equally favorable ball-park for all directions. At wind appearance the load of wave disturbance on the vehicle during the contact with water is higher at use of Neumann model for sea disturbance spectrum. It is connected with exceeding of Neumann spectrum values against Pierson-Moskowitz spectrum values at high frequencies that gives "rugged" waved surface. It is possible to note also that at small wind velocity and, accordingly, small power of sea waves disturbance the complexity of landing practically does not depend on a direction at Pierson-Moskowitz model also as at Neumann's model.

The most important is optimal landing conditions dependence on a direction at various sea roughness numbers. At the small disturbance at wind velocity of 2-10 m/s the most favorable landing approach direction is ψ =90°. At the moderate disturbance corresponding to the wind velocity of 10-14 m/s all directions in the interval 0-90° are acceptable for landing approach and provide rather similar conditions in the sense of mechanical loads on the body.

In rough sea, corresponding to the wind velocity of 14 m/s and above, the situation sharply varies, and the most favorable direction of landing approach will be against the wind (ψ =0). The difference in loads at favorable and adverse landing approach directions can exceed an order. The disturbance load at landing decreases approximately twice in the cases of a direction choice ψ equal to 0° or 30°, in comparison with the case of ψ =90°.

At any wind velocity the most adverse for landing approach is the direction 180°. Any direction between 90° and 180° could not be favorable at any significant disturbances. It is interesting that the approach direction ψ =60° is rather favorable at any wind velocity.

The above mentioned general outcomes are not changed essentially in the wide range of landing velocities.

6. METHODS OF SEA WAVE PARAMETERS REMOTE MEASURING

For the realization of the elaborated recommendations concerning a landing approach direction of flying marine vehicle it is desirable to have onboard a complex of instruments for estimation of intensity of sea disturbance (r.-m.-s. heights of sea waves) and the general direction of sea waves spread. There are some types of sensors, capable to solve such problems. The most well-known of them is the around-looking radar with an opportunity of estimation of width of spectrum for the radio signal reflected from the sea surface. In width of spectrum and other parameters of the reflected radio signal the intensity of sea disturbance is estimated, and the general direction of sea waves spread is defined as a direction with the maximal distinction of the reflected signal.

However, the survey radar is a rather complex and an expensive instrument, and estimation of the general direction of waves spread in this way demands significant time to finish completely even one cycle of angular scanning. Therefore it is important to estimate an opportunity of the problem decision with the use of simpler means. In (Ambrosovski and Nebylov, 2000; Nebylov, 1996) the opportunity of the use of three radioaltimeters with magnitude and Doppler channels for the general direction estimation is analyzed. Joint processing of such altimeters and inertial sensors signals allows definition in real time of the general direction of waves spread, intensity of wave disturbance, and also the altitude of vehicle flight in relation to an average level of the disturbed sea surface and roll and pitch angles.

Another way of determining the general direction of waves' propagation is correlation analysis of disturbed sea surface pictures, obtained by on-board camera (Nebylov *et al*, 2007). Permanent development and markdown of photo and video cameras, improvement of picture's quality in spectrum of photography conditions must be taken into consideration. At the same time airborne and radar devices do not have a tendency towards price reduction.

Certainly, in conditions of calm sea the high-quality images of a sea surface are unreachable, but thus the problem of optimization of landing approach is not necessary. The specified problem arises only at essential wave disturbances when the structure of sea waves is easy to be analyzed by their photos.

By considering the wave surface as a three-dimensional casual field anisotropic in a direction, the general direction can be determined as such one along which the interval of spatial correlation between eminences of a wave surface is minimal. Accordingly, the correlation interval should be maximal in a perpendicular direction.

Let's notice also that tracking of sea waves' profile under the vehicle or a little ahead it can give the information for improvement the quality of vehicle vertical motion parameters control at landing.

7. PECULIARITIES OF MOTION CONTROL AT VEHICLE LANDING TO THE SEA SURFACE

Flying vehicle landing on a sea surface has essential and specific differences from landing on concrete air-strip. Perhaps, there is only one factor facilitating landing on water – there is no necessity of strict interlinking of a point of contact with a surface and a point of full stop with any limited length and width of air-strip. The requirement of landing in the preset area desirably close to some point with known coordinates is usually put, however deviations from this point directly do not influence on the safety of landing.

Also during landing on an air-strip, the required law of change of altitude at the final stage of landing is an exponential curve, however, in conditions of the disturbed sea this curve should practically nullify the vertical velocity of the vehicle not at zero altitude (corresponding to the land surface), but at the altitude Δh where crests of sea waves can really touch the vehicle bottom. Otherwise the impact from a crest of wave can be too strong. The value Δh can be expressed through the r.-m.-s. height of sea waves by the simple formula

$$\Delta h = 3\,\sigma_{\xi},$$

or with wind velocity usage taking into account the Neumann model – in the form (Nebylov, 1994)

$$\Delta h = \text{ђ}(\upsilon/g)^{5/2},$$

where $\text{ђ}=2.25\ \text{m/s}^{5/2}$.

The curve $\Delta h(\upsilon)$ is shown in Fig. 7.

The exponential graph of the vehicle altitude desirable change $h(t)$ in the final stage of sea landing is calculated with the formula

$$h(t)=h_0 \exp(-t/T) + \Delta h,$$

and shown in Fig. 8.

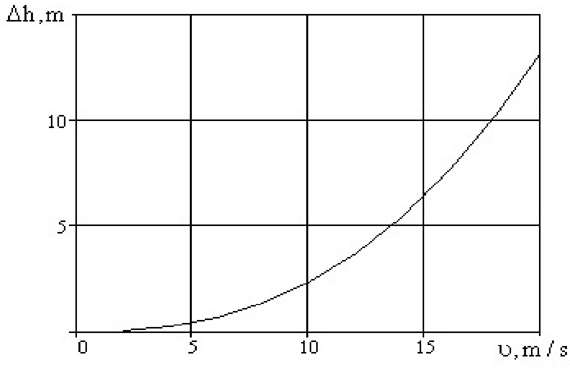

Fig. 7. Dependence of Δh on the wind velocity υ

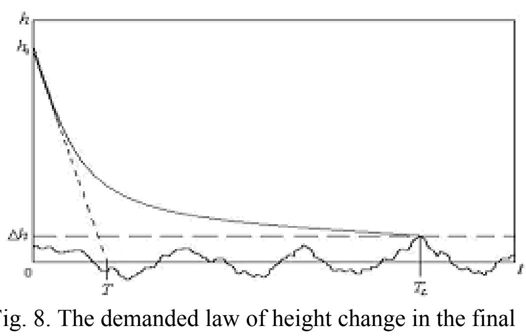

Fig. 8. The demanded law of height change in the final stage of landing

The laws for change of all rudders positions - pitch angle and engines thrust should be adhered to the most probable moment T_L of the first contact by the vehicle of the disturbed sea surface. Therefore the coordinated control of all steering bodies of marine vehicle should be realized with the single purpose of minimization of mechanical loadings during vehicle landing (Diomidov, 1996; Nebylov, 1994; Nebylov *et al,* 2007). Naturally, such control can be digital only because of its complexity.

Principles of coordinated control during landing should be developed for all steering structures of vehicle in view of an opportunity of obtaining the current information about sea wave's properties from the onboard instruments. It implies first of all to flaps and an elevator. As for slats and brake dashboards, they provide the maximal aerodynamic factor C_y and accordingly the minimal possible horizontal velocity during the moment of flattening (zeroing of vehicle vertical velocity before the moment of contact with water), not paying attention to the increasing value of factor C_x that would be inadmissible in cruising flight.

8. CONCLUSION

As a result of fulfilled investigation the technology of landing mode optimization for ekranoplanes and, probably, sea planes has been developed with the aim to guarantee the fail-safe landing during heavy sea. The outcomes of investigations show depending of the optimal landing approach direction on the number of sea roughness, wind velocity and vehicle landing velocity. The developed technology application allows ensuring the all-weather characteristics of ekranoplanes exploitation.

In the plan of further investigations are the general structure substantiation of an information-control complex of the vehicle for motion near to the sea surface including instrument and algorithmic measurement means for motion parameters, measurement of characteristics of the wave surface roughness and anisotropy, extrapolation means, an optimum desirable motion trajectory synthesizer and this trajectory realization on the base of the principle of combined control by error and disturbance.

REFERENCES

Nebylov, A.V., and P.Wilson (2002). *Ekranoplane - Controlled Flight close to Surface*. WIT-Press, Southampton, UK.

Ambrosovski,V.M. and A.V. Nebylov (2000). Flight Parameters Monitoring System for Small WIG-Craft In: *III International Conference on Ground-Effect Machines* / The RSME, Russian Branch. Saint-Petersburg, pp. 15-25.

Diomidov, V.B. (1996). *Automatic Control of Ekranoplanes Motion*. CSRI "Elektropribor", St. Petersburg, 204 pp. (in Russian).

Fishwick, S. (2001). *Low flying boats*. Amateur Yacht Research Society, Thorpe Bay.

Nebylov, A.V., S.N. Danilov, V.A. Nebylov, E.A Rumyantseva. (2005). Wing-in-Ground Flight Automatic Control Systems. *XVI IFAC World Congress*, Prague.

Nebylov, A.V. (1996). Structural Optimization of Motion Control System Close to the Rough Sea. *13th IFAC World Congress*, Vol.Q, San Francisco, pp.375-380.

Nebylov, A.V.(1994). *Measurement of parameters of flight close to the sea surface*. GAAP, Saint-Petersburg (in Russian).

Nebylov, A.V., *et al* (1995). Sea wave parameters, small altitudes and distances measurers design for motion control systems. In: *AGARD-NATO CP-556, Dual Usage of Military and Commercial Technology on Guidance and Control,* Neuilly-sur-Seine, France, pp.201-212.

Opstal, E.P.E. van, (2001). Introduction to WIG Technology. *Proceedings of the EuroAvia Ground Effect Symposium - EAGES*, Toulouse, pp.13-44.

Taylor, G.K. (2001). A Practical Guide to Building Ekranoplan (WIG) Models. *Proceedings of the EuroAvia Ground Effect Symposium - EAGES* 2001, Toulouse, pp.145-161.

Nebylov, A.V., *et al* (2007). Sea plane landing control at wave disturbances. *17th IFAC Symposium on Automatic Control in Aerospace,* Toulouse.