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ROBUST CONTROL AT THE AEROSPACE PLANE TO EKRANOPLANE LANDING

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Abstract: The control system for stabilizing the lateral motion at landing the aerospace plane (ASP) onto moving ekranoplane is developed[1]. As the disturbances character applied to ASP are being changed at different weather conditions, the system analysis and synthesis are made in a wide class of disturbances. This class may be represented by some numerical characteristics – the upper bounds of derivatives dispersions. The way for estimation of such bounds by means of current observations is proposed. The algorithm for adapting the controller in accordance with the current bounds of dispersions of the input signal. It allows to increase the accuracy and reliability of docking the ASP and ekranoplane. *Copyright © 2002 IFAC.*

Keywords: motion parameters, flight control, error estimation, adaptive algorithms, accuracy, probability density function

1. INTRODUCTION

The capability of take-off and landing the ASP with use of heavy ekranoplane has been proved in (Nebylov. and Tomita, 1998a,b; Nebylov, Tomita, *et al,1999;* Nebylov, Ohkami and Tomita, 1999). The advantages of taking-off in the equatorial zone are obvious. The high initial speed of the ekranoplane should be taken into account. The ASP landing into any point of the ocean and its quick return to the base look attractively.

From the viewpoint of difficulty the landing onto ekranoplane as a quickly moving base can be compared with the landing onto aircraft-carrier . The only and substantial difference is in high speed of the base (approx. 0.5-0.6 M); no brake way by the runway (Nebylov,1994, 1995, 2001). It requires the increased accuracy in lateral and longitudinal channels, especially at the final stage (up to the several decimeters). To provide such a requirements two approaches are applicable: a) to reduce the class of the input disturbances only by the data with high reliability. Applying non–reliable data are riskful because with the wind disturbances being changed, the errors can become inadmissible and the landing become impossible; b) before the ASP landing it is necessary to gather information on disturbance character, to identify the data and to realize the adaptation control loop. The first approach was separately developed in (Kalinichenko and Nebylov, 2000). In this work the possibility of combining two approaches is investigated. The goal is to improve the control quality ensuring the guaranteed accuracy which can be attained with the first approach. It can be made by optimizing the control unit parameters with using the current bounds of wind disturbance derivation dispersions. These bounds can be given from the remote estimation unit mounted onto ekranoplane board.

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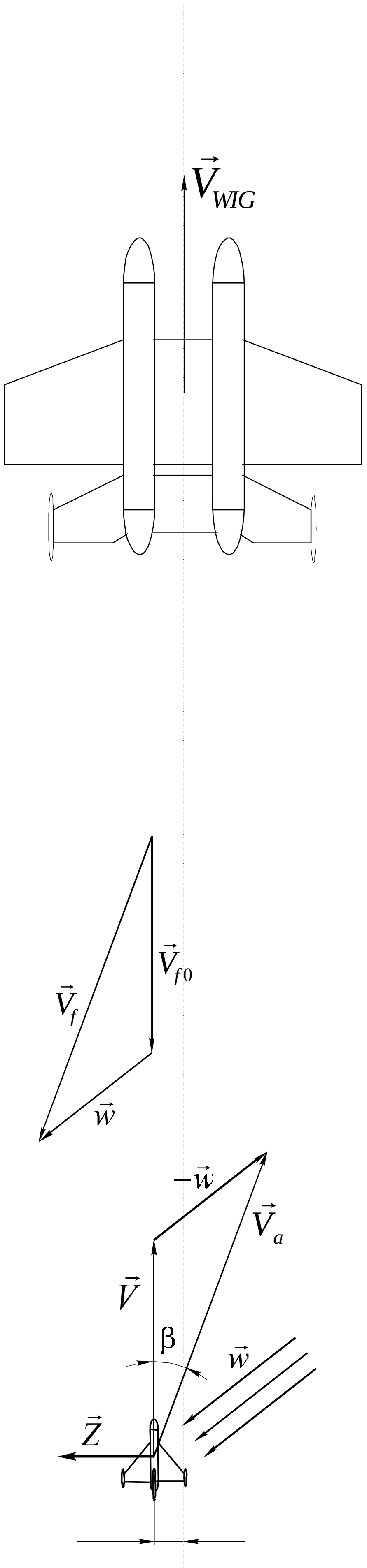

Fig. 1. Disturbances applied to ASP at landing mode.

In this work the lateral channel of ASP trajectory correction system is considered.

2. TECHNICAL SUPPORT OF LANDING MODE

The low distance navigation system can be designed basing on both radar and video scanning (VS) methods and their combinations. The integrated positioning and inertial measurers can be applied should be taken into advantage. The radar beaming method can be realized in two ways: 1) the ASP is supplied with radio beacons; their signals are used for forming the special field and for positioning ASP to ekranoplane; 2) the ASP is supplied with cube-corner reflector for increasing the power of the reflected signal transmitted from ekranoplane. Applying the radio beacons is not desirable because only the passive devices can be set on ASP board. Taking into use the second method is complicated due to low distance between ASP and ekranoplane at the final stage of docking and possible signal re-reflecing caused by the large reflecting surface. It may result in the wrong position detection and decrease of the accuracy. Thus, the preferable choice is VS. The docking zone of ekranoplane should be supplied with several (for example, three) video cameras fixed. They operate in IR range utilizing the natural property of the landing vehicle – the high temperature of airframe. It gives the possibility to attain the stronger image and to increase the pattern recognition rapidity and quality.

3. GETTING THE DISTURBANCE PRIOR INFORMATION

Let us point the way of finding the numerical characteristics bounding the input disturbances class. It is necessary to find the upper boundaries of lateral speed and acceleration dispersions to utilize them for computation the upper boundary of error dispersion and to design the control algorithm with guaranteed accuracy (Nebylov, 1998).

The basic problem at the final stage of landing is stabilizing the ASP onto the symmetry axis of ekranoplane up to the docking process starts (Fig. 1). The initial linear lateral shift z_0 is considered to be eliminated at the previous stage. The general disturbance providing the lateral shift is the wind. For designing the control system it is easy-to-use to recalculate the numerical characteristics of the wind flow into the correspondent characteristics of lateral shift of ASP relatively to the symmetry axis of ekranoplane. Let us find the RMS values of speed and acceleration of lateral shift.

First, the lateral acceleration is expressed. The lateral force applied to the ASP can be expressed by the formula $Z = c_z S\rho V^2/2$, where S – square of the wing; ρ – air density; V – ASP air speed; c_z – the coefficient of lateral force, which can be represented as $c_z = c_z^{\beta}\beta$; the coefficient c_z^{β} at the angle of slip β has a negative sign. The wing flow action to the lateral face of the ASP is not substantial comparing with Z.

According to the one of the model of atmosphere, the ASP flight at the altitude less than 400m is accomplished in the zones of homogeneity of air flight. Each zone can be characterized by its size along the ASP flight and by the vector of flow in the zone. Let the mathematical model of the flow in horizontal plane be the partly constant process $\beta(t)$ (Fig. 2). The maximal RMS angle declination is defined from the worst case when the wind flow speed w has the maximal value $w_{\max}$ and the wind direction is perpendicular to the axis of symmetry (the undisturbed motion of the ASP is supposed to be without slip). Choosing $w_{\max}$ the correspondent maximal slip angle value $\overline{\sigma}_{\beta} = arctg(w_{\max}/V)$ can be calculated. It is used as an upper bound of RMS declination β. Thus, the RMS value of Z can be expressed as $\overline{\sigma}_z = c_z^{\beta}\overline{\sigma}_{\beta} S\rho V^2/2$. Let us express the upper bound of acceleration dispersion dividing the $\overline{\sigma}_z^2$ to the ASP mass m_{ASP}:

$$\overline{D}_2 = 0{,}25\left(c_z^{\beta} arctg(w_{\max}/V) S\rho V^2/m_{ASP}\right)^2. \quad (1)$$

To make the estimation of $\overline{D}_1$ it should be noted that the speed of ASP lateral shift can be increased only by the moment of $\beta(t)$ having changed the sign. Thus, the dispersion $\overline{D}_1 = \overline{D}_2\tau_s^2$ can be found by use of RMS interval of sign changing τ_s. Let us express τ_s.

Consider the stochastic values: $\eta(t)$, ξ и $\nu(t)$, where $\eta(t)$ is the number of jumps of slip angle caused by the changing of wind direction in the zone for the time t; ξ is the number of abrupt changes of the slip angles to its sign change; $\nu(t)$ is the number of abrupt changes of the slip angle for the time t, which results in the change of the sign. It is easy to show that η has the Poisson distribution law:

$$p_{\eta}(n,t) = P(\eta(t) = n) = [\mu(t)]^n e^{-\mu(t)}/n!,$$
$$n = 0, 1, 2, ... \quad (2)$$

where $\mu(t)$ is the average number of jumps of the function $\beta(t)$ for the interval $[0,t]$. It can be found from the average zone size l_0: $\mu = Vt/l_0$.

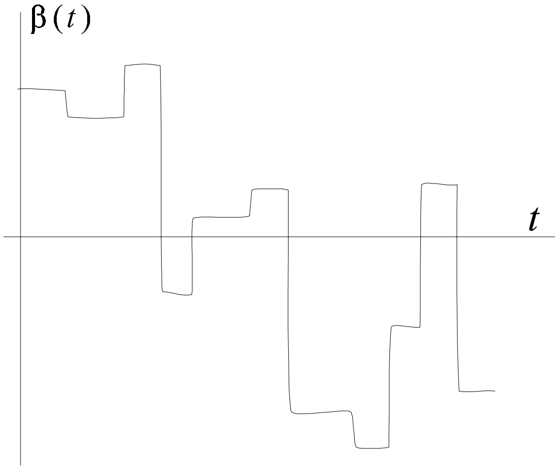

Fig. 2. Possible sample $\beta(t)$.

Concerning the stochastic value ξ let us note that its distribution is time-invariant and is the function of the number of jumps. With supposing that the probability of the sign change at each jump is equal 1/2, let us write the distribution density for ξ:

$$p_{\xi}(n) = P(\xi = n) = 2^{-n}, \quad n = 1, 2, 3, ... \quad (3)$$

The probability of the event $\nu(t) = n$ is equal to

$$P(\nu(t) = n) = P(\eta(t) = n)\cdot P(\xi = n).$$

Then, the distribution density of $\nu(t)$ can be expressed by the formula

$$p_{\nu}(n,t) = p_{\eta}(n,t)\, p_{\xi}(n). \quad (4)$$

Consider the event $\Theta(t)$ which is the change of the sign of $\beta(t)$ for the interval t and the correspondent dimensionless stochastic value θ which is the relation of the time of sign change to value $\tau_0 = l_0/V$ – the average time of overcoming the zone. Note, that

$$\Theta(t) = [\nu(t)=1] \cup [\nu(t)=2] \cup ... \cup [\nu(t)=i] \cup ...,$$
$$i = 1,2,3,... \quad (5)$$

From (2)–(5) one can find

$$P(\Theta(t)) = \sum_{i=1}^{\infty} p_{\nu}(n,t) = \sum_{i=1}^{\infty} \frac{\mu^n}{n!} e^{-\mu} 2^{-n} =$$
$$= e^{-\mu}\left[\sum_{i=0}^{\infty}\left(\left(\frac{\mu}{2}\right)^n \frac{1}{n!}\right) - 1\right] = e^{-\mu/2} - e^{-\mu}.$$

The average number of jumps of the function $\beta(t)$ for the interval $[0,t]$ is described by the formula:

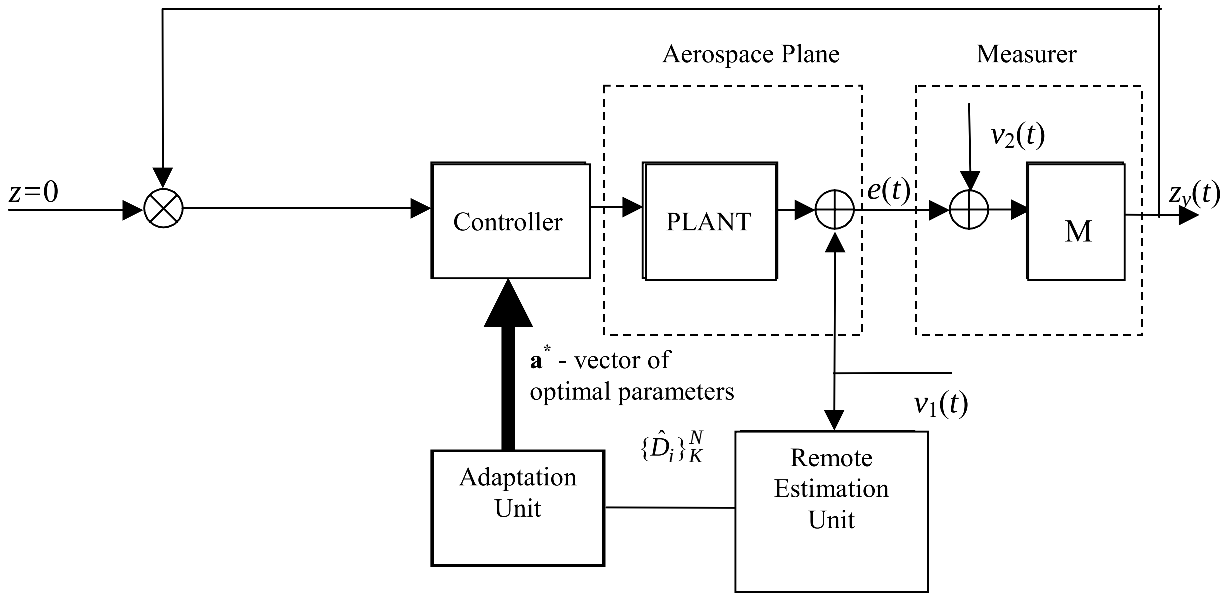

Fig. 3. The block diagram of the adaptive control system.

$$\mu = \mu(t) = t/\tau_0 .$$

Hence,

$$p_\theta(\mu) = P(\Theta(t = \mu\tau_0)) = e^{-\mu/2} - e^{-\mu} .$$

Let T_L is the duration of landing mode. The inequality $T_L >> \tau_0$ is true.

Note, that for any time moment $P(\Theta) = 1 - P(\overline{\Theta})$; with $P(\overline{\Theta}) \neq 0$. Properly speaking, the event Θ may not occur during the landing interval. To make further computation correct when finding the average interval of sign change the landing mode duration will be believed to be infinite and, hence, the probability $P(\overline{\Theta})$ is equal to zero.

The value μ_s may be found as a non-centered moment of the value θ:

$$\mu_s^2 = \int_{-\infty}^{+\infty} \mu^2 p_\theta(\mu) d\mu = \int_0^{+\infty} \mu^2 (e^{-\mu/2} - e^{-\mu}) d\mu .$$

Calculating the last integral results in:

$$\mu_s^2 = 14 .$$

Taking into account $\mu_s = \tau_s / \tau_0$, let us write:

$$\tau_s^2 = 14 l_0^2 / V^2$$

or

$$\overline{D}_1 = 14 \overline{D}_2 l_0^2 / V^2 . \qquad (6)$$

For getting current estimations of upper bounds $\overline{D}_2$ and $\overline{D}_1$ it is necessary to find the maximal speed of the wind flow $w_{\max}$ during the floating observation interval, then, to calculate using formulae (1) and (6). The duration should be chosen from the condition of overcoming the transition processes in the system.

The reliable information on observation noises may be obtained after analyzing the technical characteristics of measurers.

Note, that usually their models corresponds to the stationary noise in the wide sense with known intensity.

4. ADAPTIVE CONTROLLER

The structure scheme of stabilization adaptive loop is shown in Fig. 3. The error $e(t)$ appears generally due to the wind blows $v_1(t)$, reduced to the linear lateral shift. The signal $y(t)$ is obtained from the lateral shift measures. That signal contains the noise measurement component $v_2(t)$ which is considered to be the white noise with known intensity S_{v2}. With believing the statistic properties of disturbances flowing slowly, and control loop being linearized, the transfer functions technique is used. Let us express the Laplace transformation of the error by the transformations of $v_1(t)$ and $v_2(t)$:

$$E(s) = \frac{1}{1 + W(s)} V_1(s) + \frac{W(s)}{1 + W(s)} V_2(s) ,$$

where $W(s) = W_C(s) W_P(s) W_M(s)$, $E(s) = L\{e(t)\}$, W_C is the controller transfer function; W_P - the

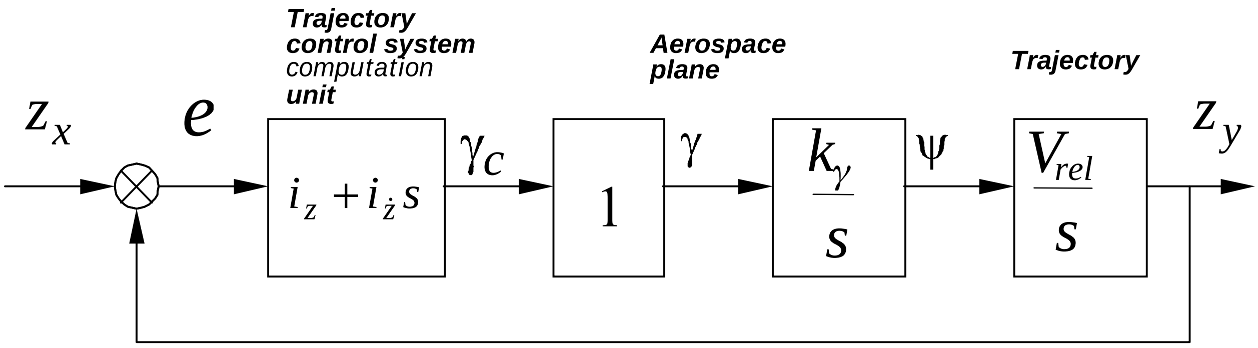

Fig. 4. The simplified block-diagram of lateral channel of ASP landing system.

transfer function of ASP; W_M - the transfer function of lateral shift measurer.

When the landing mode is on, the Remote Estimation Unit set on ekranoplane measures the wind disturbance and calculates the upper boundaries using formulae (1) and (6). Using the majorizing polynomials technique described in (Nebylov, 1998), one may conclude that the problem is typical to design the system with guaranteed accuracy. The supremum of error dispersion can be shown to be expressed by the obtained upper bounds $\overline{D}_1$ and $\overline{D}_2$ and by the value S_{v2} (Kalinichenko and Nebylov, 2000). Thus,

$$\overline{D}_e = f(\overline{D}_1, \overline{D}_2, S_{v2}, \boldsymbol{\alpha}), \tag{7}$$

where α_i are the parameters of controller to be readjusted. As the goal function (7) is complicated for calculation the value $\arg\min_{\boldsymbol{\alpha}} \overline{D}_e$ may be found only by numerical algorithms. Non-linear optimization algorithm described in (Kalinichenko and Nebylov, 2000) is used. Practically the estimated values $\hat{\overline{D}}_1$ and $\hat{\overline{D}}_2$ are used for minimization (7) which is made in Adaptation Unit (AU). The output of AU is the vector of parameter's $\boldsymbol{\alpha}$ to be adjusted. It can be chosen as $(k_C, T_C)^{\mathrm{T}}$, where k_C is the gain of the controller, T_C is one of time parameters of denominator of the transfer function W_C.

Let us consider the simplified block–diagram of the lateral channel of ASP landing system (Fig. 4). The purpose is to show that error dispersion will be bounded at any admissible input disturbance within the given class represented by upper bounds of disturbance derivatives dispersions and to show the advantages of system being implemented by adaptation loop.

Using PD–law the controller converts the input lateral shift into the roll angle γ_c which is considered to be answered inertiallessly by the ASP. The ASP response γ is transformed into the crabbing angle ψ by means of integration. The resulting lateral shift z_y is the product of integration the angle ψ. The open loop transfer function $W(s) = k(1+Ts)/s^2$, where $k = i_z$, $T = i_z / i_{\dot z}$. Let us denote $H(s) = Z_y(s)/Z_x(s) = W(s)[1+W(s)]^{-1}$ – closed loop transfer function; $H_e(s) = E(s)/Z_x(s) = [1+W(s)]^{-1}$ – error transfer function.

Error dispersion can be represented as a sum of two component:

$$D_e = D_{eg} + D_{ev},$$

where

$$D_{eg} = \frac{1}{\pi}\int_0^{+\infty} A_e^2(\omega) S_g(\omega) d\omega,$$

$$D_{ev} = \frac{S_{v2}}{\pi}\int_0^{+\infty} A^2(\omega) d\omega,$$

$A_e^2(\omega) = |H_e(i\omega)|^2$, $A^2(\omega) = |H(i\omega)|^2$, $S_g(\omega)$ is unknown spectral density of wind disturbance, S_{v2} is the intensity of measurement noise which is believed to be white Gaussian. D_{eg} is called the dynamical error dispersion caused by linear distortions; D_{ev} – noise error dispersion. Because the value D_{ev} is constant then the problem of finding the bound $\overline{D}_e$ is equivalent to the problem of finding $\overline{D}_{eg}$. In the papers (Kalinichenko and Nebylov, 2000, 2001) the dynamical error dispersion upper bound estimation algorithms for stationary and non–stationary input disturbances are given. Using those algorithms the dependence $\overline{D}_{eg}(\tilde{k}, d)$ is obtained, where $\tilde{k} = k(\overline{D}_1/\overline{D}_2)$, kT^2. It allows to find the optimal value of k and T for any $\overline{D}_1$ and $\overline{D}_2$. The family of

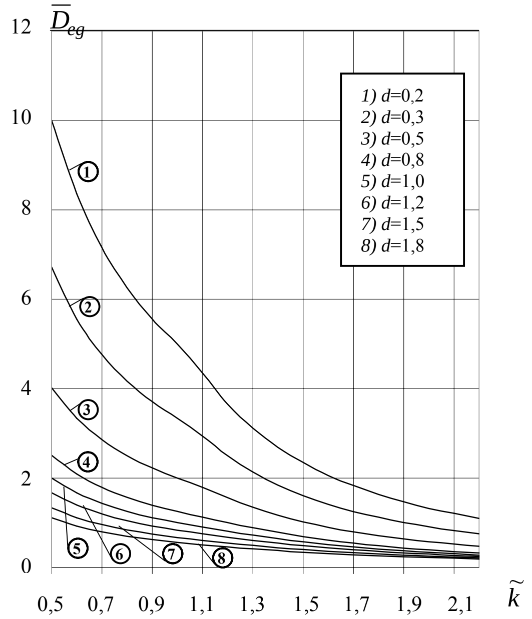

Fig. 5. Dependence $\overline{D}_{eg}(\tilde{k})$.

curves $\overline{D}_{eg}(\tilde{k})$ for different values of *d* are represented in Fig.5.

Thus, the AU is to calculate the optimal values of *k* and *d* by use of estimations $\hat{\overline{D}}_1$ and $\hat{\overline{D}}_2$.

CONCLUSION

The method of controller design based on combining the robust and adaptive approaches is described applying to the problem of stabilizing the lateral motion of ASP at its landing onto moving ekranoplane. The basic idea is in use of all accessible reliable prior information on disturbances properties. This information is being corrected during the system functioning. However, any unreliable data (in particular, the spectrum of disturbances) are not used. The more rough but adequate data (in particular, the dispersions of two derivatives) are applied. It provides the accessible guaranteed control accuracy. It is more important for many applications than hypothetical high accuracy of the "optimal" system made for some nominal full but unreliable data.

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