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Aircraft Handling Qualities Research and Criteria Development for Nonstationary/Nonlinear Situations

Final Report of contract #SPC-94-4002

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Abstract

In this paper the "pilot-aircraft" loop in the nonstationary//nonlinear control tasks is considered. The method of creating an adaptive pilot model is suggested on the basis of assuming the existence of the internal describing model of the control object (IDMCO). On the grounds of the calculation results the criterion of the quality estimation of the control process is formulated to be used while solving the control tasks. The methods of experimental research of the abrupt changes in the aircraft dynamics on the simulator are developed. The results of the developed criterion experimental validation and its use for the analysis of the pilot induced oscillations (PIO) are presented.

Contents

1. Introduction

The problem of the pilot interaction with the flight control systems becomes more important because of the aviation technology complication, the increase of its automatization and the expanding of the flight regimes. The flight control systems of modern aircraft considerably simplify for the pilot the aircraft control letting him concentrate on the main task performance. Then the pilot can not look after the realization of the demanded characteristics of stability and control. Also he doesn't need to take care of keeping the aircraft within the limits of angle of attack and normal factor, etc. These systems demonstrate high reliability and effectiveness, but all these facts do not let us forget about the problem of safety. For example, in case of failure in the stability and control augmentation system the pilot has to control an aircraft with stability and control characteristics that differ considerably from those before the failure. Insignificant probability of the failure makes it impossible for the pilot to predict it. That is why it seems doubtful to compensate the failure results and to complete the flight successfully.

The pilot has to come across the same situation while switching the many-functional control systems with algorithms that are optimized to fulfil the concrete tracking tasks, and that are switched automatically. In this situation the high quality of the task performance greatly depends on how quickly the pilot is able to adapt to the changed characteristics and to continue the controlling. The pilot can find himself in the similar situation because of the fact that the aerodynamic characteristics are as a rule nonlinear and can change quickly. Here is a typical example: there is a nonlinear change of the aircraft characteristics while changing the angle of attack; or the change of characteristics when the aircraft reaches transonic speeds. The change of the angle of attack value can occur very quickly (it takes 1÷2 sec), and the time of the aerodynamics reorganization when the aircraft reaches the sonic speed also can be estimated in seconds. It is easy to understand that such change in the aircraft dynamics from the pilot's point of view occurs quite instantaneously, that requires his quick adaptation. Henceforth, the authors will call such situations nonstationary tasks of controlling.

From the analysis of flight accidents it is known that the most frequent reason of the emergency following the failure of the control system is the inadequate pilot's behaviour (in the civil aviation it is the cause of more then 60% of all accidents). Alongside with that the safety of the flight and the effectiveness of the controlling task performance are constantly required.

This explains the necessity of considering the closed-loop "pilot-aircraft" system under the development and choice of parameters of aviation systems, that is possible only with knowledge and ability of modelling the dynamic characteristics of the pilot performing as a regulator. It is necessary to understand some questions to model the pilot's behaviour such as the influence of psychological and physiological factors, the principles of creating internal feedbacks in a human being, the peculiarities of the input data apprehending, the influence of outer factors on the pilot's characteristics, etc. However, we think that while researching the dynamic qualities of the "pilot-aircraft" system it is important to know first of all phenomenological model of the pilot's behaviour that can describe the mean-statistic qualities, and did not try to model the mechanisms of all inner processes. Such model will help to comprehend the pilot's behaviour, to stand out the important factors for the dynamics of the "pilot-aircraft" closed loop and work out the special general engineering methods of analyzing "man-machine" systems for the nonstationary/nonlinear situations.

The problem of the estimation of the aircraft handling qualities acceptability for nonstationary/nonlinear situations has been formulated as follows:

- human-pilot controls a quasilinear object at stationary precision tracking task and pilot's Rating of aircraft Handling Qualities is satisfactory (Pilot's Ratings are equal to 1÷4 of Cooper-Harper Scale);
- the sudden (abrupt) change in aircraft characteristics takes place;
- handling qualities of the aircraft with the post-change dynamic characteristics are also satisfactory in stationary control.

The change in control object characteristics (aircraft dynamic characteristics or other) is caused by:

nonstationary effect -
    the control laws' switch,
    the control system failure,
    a fast transition from one flight regime to another, or
nonlinear effect -
    quasilinear characteristics change because of control object/control system nonlinearities.

From this point of view the problem of nonlinear control object is similar to the problem of nonstationary control object because the nonlinearity of control object characteristics is one of the reasons for the fast/abrupt change in the aircraft controllability.

This paper presents the results of the analysis of the "pilot-aircraft" closed-loop functioning, derived by computer calculations with the help of the adaptive model of the pilot's behaviour developed by the authors; and the verifying of these results by way of experiments on the simulator. The use of the adaptive pilot model allows not only to derive the techniques of analysis for the "pilot-aircraft" closed-loop in case of the abrupt changes of aircraft characteristics, but to find out the main regularities that can be used to success in the future research of the "pilot-aircraft" closed-loop.

2. Development of the adaptive pilot model and its use for the rating of the aircraft handling qualities

Under the circumstances of the real flight the pilot solves series of tasks different by their nature as well as by the character of the action. For example, the stabilization task, the tasks connected with the transitional regimes where the adaptive qualities of the pilot are displayed; and the tasks connected with the compensations of external disturbances, system failure, etc.

It is quite difficult to describe all actions of the pilot with the help of a single model of behaviour, and because of its evident complexity the use of such model may cause a lot of problems. That is why at present the simplified models are widely spread in the engineering estimations, providing the qualitative analysis of some tasks of flight dynamics. Mostly this research is devoted to the problem of mathematical models of pilot's behaviour in the stabilizing tasks [1,2,3,4], that can be explained by their domineering role in the whole body of tasks solved by the pilot. Among them there are an approach task, tracking task, height and flight speed stabilization, etc. The following tendencies of the pilot behaviour while continuous aircraft control were sorted out basing on the performed research:

- the pilot is an adaptive unit of control and strives to choose such a structure and character of control actions, so that the characteristics of the "pilot-aircraft" closed-loop suit the control task to advantage in terms of some quality criterion;
- while controlling the pilot creates closed loops alongside all the observed parameters;
- the pilot provides the stability margin of the closed-loop system, the value of which depends upon the difficulty of the control task and the type of the control object;
- in the spectrum of pilot's control actions there is some part that does not correlate with the input signal and is

case[illegible]y nonlinearity of the pi[illegible]'s characteristics (while observing and controlling) and by their nonstationarity.

The research devoted to the process of the pilot's adaptation is a special line of investigating the pilot's characteristics. The adaptive abilities of the pilot may come forward in different situations among which we usually mark out the adaptation to the abrupt change in the aircraft characteristics, to the quietly change in these characteristics, and the adaptation to the stationary control object.

In the last case the human adaptation is called studying in the process of which according to the hypothesis of sequential perception by McRuer & Krendel [1] a man passes the phases of compensatory, pursuant and predicted control. In case of slow change of the aircraft characteristics or when the change of characteristics is insignificant then the control closely resembles that of the stationary object and the pilot adapts to it not realizing his doing it.

The greatest interest evokes the process of adaptation at the abrupt change of the aircraft characteristics. Many scientists devoted their work to solving such problems, among them we can name the works of Young and his team [5], Elkind and Miller [6], Phatak & Kleinman [7,8]. In all these studies the conclusions of the adaptation process and the pilot's actions were made basing on the analysis of the transient response records.

The results of the research show that the process of the adaptation can be divided into the following periods:

1. identification of changes in the control object dynamics;
2. estimation of the new characteristics of the object;
3. modification of the pilot's own characteristics with the aim of the control loop stabilization and the correction of accumulated errors;
4. pilot's optimization of his own characteristics with the aim of achieving the highest quality of control performance. Generally the optimization process is same as that of training or studying.

The main drawback of the papers mentioned above is the lack of universalism. Each of them concerns only a certain type of control object or lacks experimental proof. The most interesting approach is stated in Phatak's paper [8], where a model of recognition and identification of the change in the aircraft dynamics is given on the basis of realizing the probabilities calculation of possible object characteristics from a certain given before set.

The main drawback of this approach is explained by the use of a given in advance set of the object dynamics models after the change — in fact in these circumstances the process of the pilot's adaptation is lost and we speak only about the method of recognition of the change in the control object dynamics.

In this paper the authors tried to create an adaptive model of a pilot with the aim of finding of the main behaviour regularities of the "pilot-aircraft" closed-loop. The discussed adaptive model takes into account the main regularities of the pilot behaviour in the regimes of a continuous control of an object with stationary dynamic characteristics while being stabilized; and this model reflects the pilot's actions in the tasks connected with changes in the object dynamics.

The main principles of the pilot's work put into the model may be characterized in the following way:

1. The pilot as a regulator adapts himself in the optimum way to a hypothetic Internal Describing Model of the Control Object (IDMCO) which he creates in his consciousness according to the observed parameters.
2. The hypothetic IDMCO is created by the pilot on the basis of the transient response after the test control signal.
3. While identifying the change in the aircraft's dynamics the pilot uses the information on the real state of the phase coordinates and on their prediction basing on the hypothetic model.
4. In the case of steady dynamics the pilot works according to the criterion of the minimum of the root-mean-square control error trying to realize some stability margins the value of which depends on the control task.

Such a model has got a series of advantages in comparison to the cited above. On the one hand, it permits to model the pilot in the stationary control as well as at the transient dynamic regimes. On the other hand, the adjustment of controller parameters in the model performed only on the basis of the vector of the observed coordinates permits to limit the amount of tasks for the pilot according to the volume of the information he gets, and also to model the pilot's behaviour when some additional (parallel to visual) observed variables emerge (on the tactile, acceleratoral or other informational channels) and when the vector of the observed phase variables is reduced (e.g., device equipment failure in the cockpit). The imitation of the discrete perception while identifying permits simultaneous modelling of the noise in the pilot observation without any additional facilities.

2.1. Model structure choice

In the model development of the pilot's adaptive behaviour it seems rational enough to proceed from the idea of Elkind and Miller [5] that a man possesses an internal describing model of the control object, and to use this model to make predictions. Elkind and Miller noted that this model wasn't precise. The IDMCO exists in the optimum model developed by Baron and Levison [9], used by Phatak [8], and precisely in the Kalman filtration block of the observed variables. However, in these papers the internal model has got a dimensional representation that is as a rule bigger than the one of the observation vector, and must coincide with the dimension of the object dynamics equations. In the same time in the real control objects the significant part of variables represent inner unobserved coordinates (e.g., the signals from the dynamic filters of the control system). It's absolutely unreal for the pilot to create such complicated models. The only way to remain within the limits of the internal model hypothesis and in the same time to avoid its unjustified complication is to create the model only on the basis of the vector of the parameters observed by the pilot.

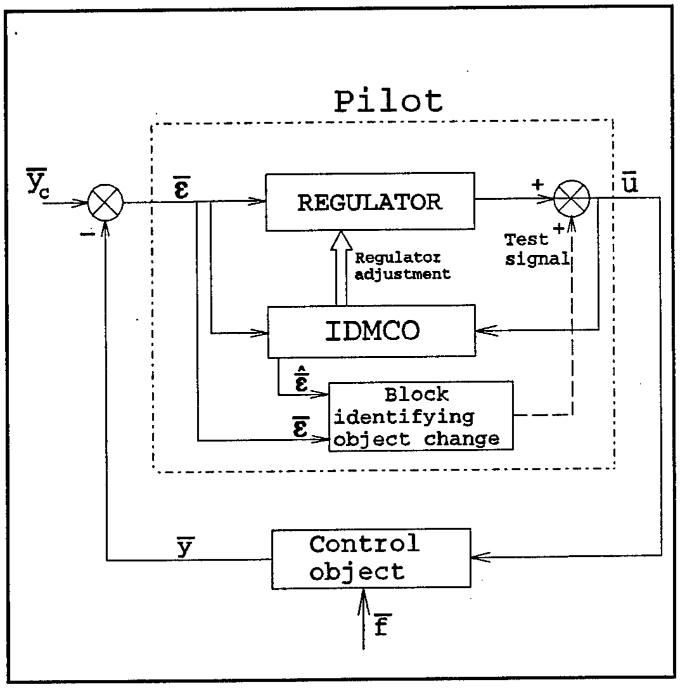

Fig.1

The structure of the "pilot-aircraft" system for the suggested model is presented on Fig.1. The control object (the aircraft with flight control system) is described by the system of linear differential equations:

$$\dot{\bar{x}} = A\cdot\bar{x}+B\cdot\bar{u} \,, \qquad (1)$$

where $\bar{x}$ - is the phase vector of the dimension representation m×1, A and B are the corresponding coefficient matrices, $\bar{u}$ - is the vector of the pilot's control having dimensional representation $l\times1$. The variables observed by the pilot are described by the equation:

$$\bar{y}=C\cdot\bar{x}+F\cdot\bar{u} \,, \qquad (2)$$

the dimensional representation n×1 of the observed vector $\bar{y}$ being as a rule smaller than the dimensional representation of the aircraft phase vector $\overline{x}$[illegible] (n≤m). As the pilot observes on the visual channel not only variable value itself but the speed of its change then we think it rational to choose the internal model in the form of:

$$\dot{\overline{z}} = M \cdot \overline{z} + D \cdot \overline{u} \ , \tag{3}$$

where the vector $\overline{z}$ is composed of the observed vector and its derivative:

$$\overline{z} = \begin{vmatrix} \overline{y} \\ \dot{\overline{y}} \end{vmatrix} \tag{4}$$

and has got the dimension (2n×1); M and D are some coefficient matrices, that have got the dimension (2n×2n) and (2n×l). The internal model adjustment is carried out by the selection of these matrices.

Thus, we suggest that the internal model of the object should be created as an equivalent system, the order of which is equal to the double order of the observed variables vector and it may not be equal to order of the equations describing real object. The necessity of including not only $\overline{y}$ but vector $\dot{\overline{y}}$ into the phase vector of the internal model is derived from the following consideration. It is known that a man adapts simply enough to control the object that is described by the double integral $W_{aircr}(p) = \frac{K}{p^2}$. If the internal model is created only on the output coordinate of the object $y(p) = \frac{u(p)}{p^2}$, then the equivalent model will have the first order:

$$\dot{z} = M \cdot z + d \cdot u \ , \tag{5}$$

In this case the pilot's adaptation must be close to the gain coefficient, and this does not provide the stability of the "pilot-aircraft" system when $W_{aircr}(p) = \frac{K}{p^2}$. So this model does not embrace the dynamic peculiarities of the object. In the same time the creation of the internal model in the form of:

$$\begin{vmatrix} \dot{y}_1 \\ \dot{y}_2 \end{vmatrix} = \begin{vmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{vmatrix} \cdot \begin{vmatrix} y_1 \\ y_2 \end{vmatrix} + \begin{vmatrix} d_1 \\ d_2 \end{vmatrix} \cdot u \qquad (6)$$

allows to describe the object $\frac{K}{p^2}$ fully by way of the choice of the parameters m_{ij} and d_i , where i,j=1,2 , that are correspondingly m_{11}, m_{12}, m_{22}, $d_2 \approx 0$; $m_{21} \approx 1$; $d_1 \approx K$.

While composing the vector oh the observed coordinates it is necessary to take into account the fact that in reality its components are distorted by man because of the non-linear effects peculiar to the organs of perception and because of their dynamics. Besides, the coordinates observed with the help of different perception organs (visual, acceleratoral, tactile, kinesthetic information, etc.) are taken into account by man with a different weight coefficient.

In the process of the pilot's adaptation to the concrete aircraft characteristics two facts should be singled out:

- identification of the aircraft's stability and controllability characteristics that is expressed in the internal model creating;
- optimization of the control laws that provide the high quality of the performance.

In correspondence to that it is expedient to divide the pilot model into the block of identification (the internal model creation) and the regulator (Fig.1). The regulator is described by the input parameters of the pilot model (the observed parameters) that in case of the stabilization task are the stabilization errors $\overline{\varepsilon}=\overline{y}-\overline{y}_c$, and in the same time it is described by their derivatives $\dot{\overline{\varepsilon}}$ and the pilot's output control effects (taking into account the dynamics of the neuro-muscular apparatus and the delay in the central nervous system):

$$\overline{u}=\frac{e^{-p\tau_p}}{T_N p+1}\cdot(K_1 p+K_0)\cdot\overline{\varepsilon} \qquad (7)$$

where K_1 and K_0 are the matrices of the dimension k×n, T_N - is the time constant of the neuro-muscular block, τ_p=0.1 - delay in the central nervous system.

Quite naturally the pilot performs the optimization of the control laws (i.e., the maintenance of the high precision control) on the basis of the internal model's structure and parameters. In other words, the pilot thinks that he controls the object that is described by the internal model equations (5), and he chooses the parameters of the regulator, i.e. K_0 and K_1 on the basis of the matrices M and D, and of the characteristics of the signal $\bar{\varepsilon}$ (Fig.2).

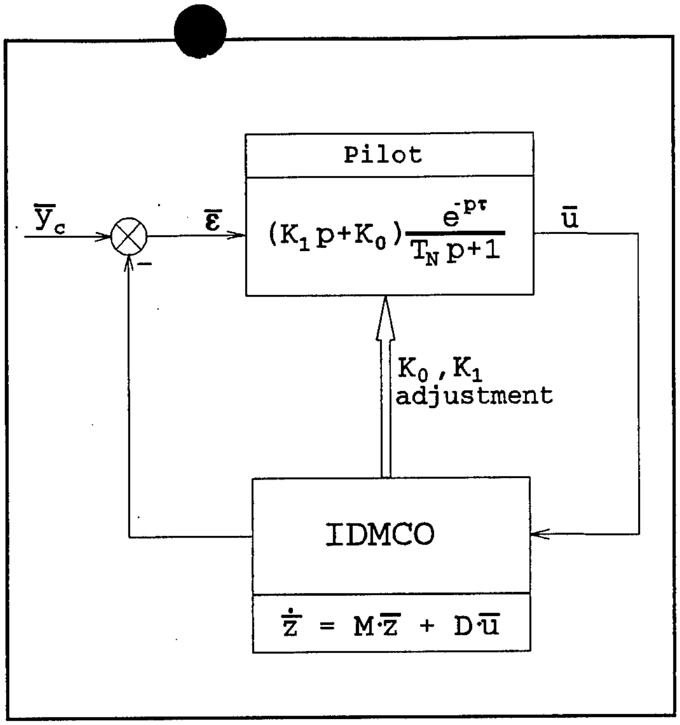

Fig.2

The pilot chooses the parameters of the IDMCO by way of a test control signal. This signal has been introduced on the grounds of the pilots' and the operators' opinion and it proceeds from experiments and paper [1]. In the moment of the test signal output the pilot would open the control loop and thus he brought to minimum the control correlation with the observed signal of the stabilization error $\bar{\varepsilon}$.

2.2. Development of the internal describing model of the control object

Let us consider the internal model developing (control object identification). This stage precedes the optimization of the regulator parameters. Generally the object identification in a closed-loop "pilot-aircraft" system (i.e., concurrently with the regulator identification) based only on $\bar{\varepsilon}$ and $\bar{u}$ signals is apparently impossible. To make it clear the integrated structure of the one-channel "pilot-aircraft" system is considered (Fig.3). Here n_1 and n_2 signals are respectively the noise caused by a pilot through control actions (remnant) and the noise or disturbances which affect the aircraft. Since the pilot can use only the control signal u and the tracking error ε, the transfer function

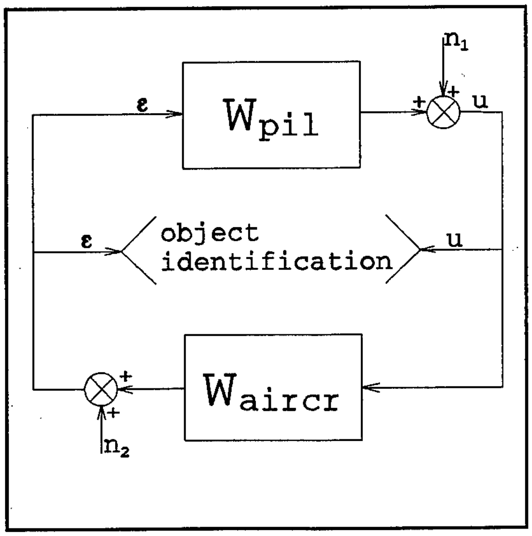

Fig.3

from $u(p)$ to $\varepsilon(p)$ can be presented as follows:

$$\frac{\varepsilon(p)}{u(p)} = \frac{n_2 + n_1 \cdot W_{aircr}(p)}{n_1 + n_2 \cdot W_{pil}(p)} \tag{8}$$

where $W_{aircr}(p)$ is the control object transfer function and $W_{pil}(p)$ is the regulator transfer function describing the pilot actions. It follows from (8) that because of the remnant the ratio $\varepsilon(p)/u(p)$ is in essence the combination of the object and the pilot-regulator transfer function, and their combining level is determined by the proportion between the remnant n_1 and disturbance n_2 noises.

It follows from this consideration that the step of the object identification (IDMCO development) can be accomplished in assumption of the presence of the test signals in control $\bar{u}$ which are uncorrelated with the input $\bar{\varepsilon}$ and are generated by the pilot to determine the object (aircraft) characteristics. Under these circumstances either the regulator loop is broken or the test signal level must be high enough so that an object response due to its input should be much more appreciable than the response caused by disturbances (otherwise the control object identification will be inadequate). It should be noted that the possibility of such test signals existence in the pilot control was mentioned in paper [1]. According to the pilots' opinion the amplitude, duration and shape of these test signals are determined by the piloting task and the control object parameters.

To verify the pilot test signals by the experiment one can use the analysis of the control time diagrams and also the analysis based on the correlation functions $K_{\varepsilon u}(t_1,t_2)$ and $K_{uu}(t_1,t_2)$. It is evident that the test signals existence leads to $|K_{uu}(t_1,t_2)|$ increase, and the regulator loop break leads to $K_{\varepsilon u}(t_1,t_2)$ reducing. However this technique did not permit to obtain ultimate results since the pilot test signals were not determined in time and particularly because of the fact that only limited statistics was available for every specific case. More interesting data were obtained in the analyses of time processes. Let us consider for example the case presented on Fig.4. As it follows from it the changes in the control object dynamics were not detected by the pilot for a long time t_{det}. The pilot identified dynamics change only after he has operated with the control stick to reduce the glide-slope speed. Since the flying regime before that was a steady descent regime, these pilot actions can be qualified as the generation of a sort of test signal resulted in the changed dynamics identification and the adaptation to it. Further in the suggested pilot model the shape of the test signal was assumed to be fixed and presented as a sequence of two stick kicks of the opposite sign. The

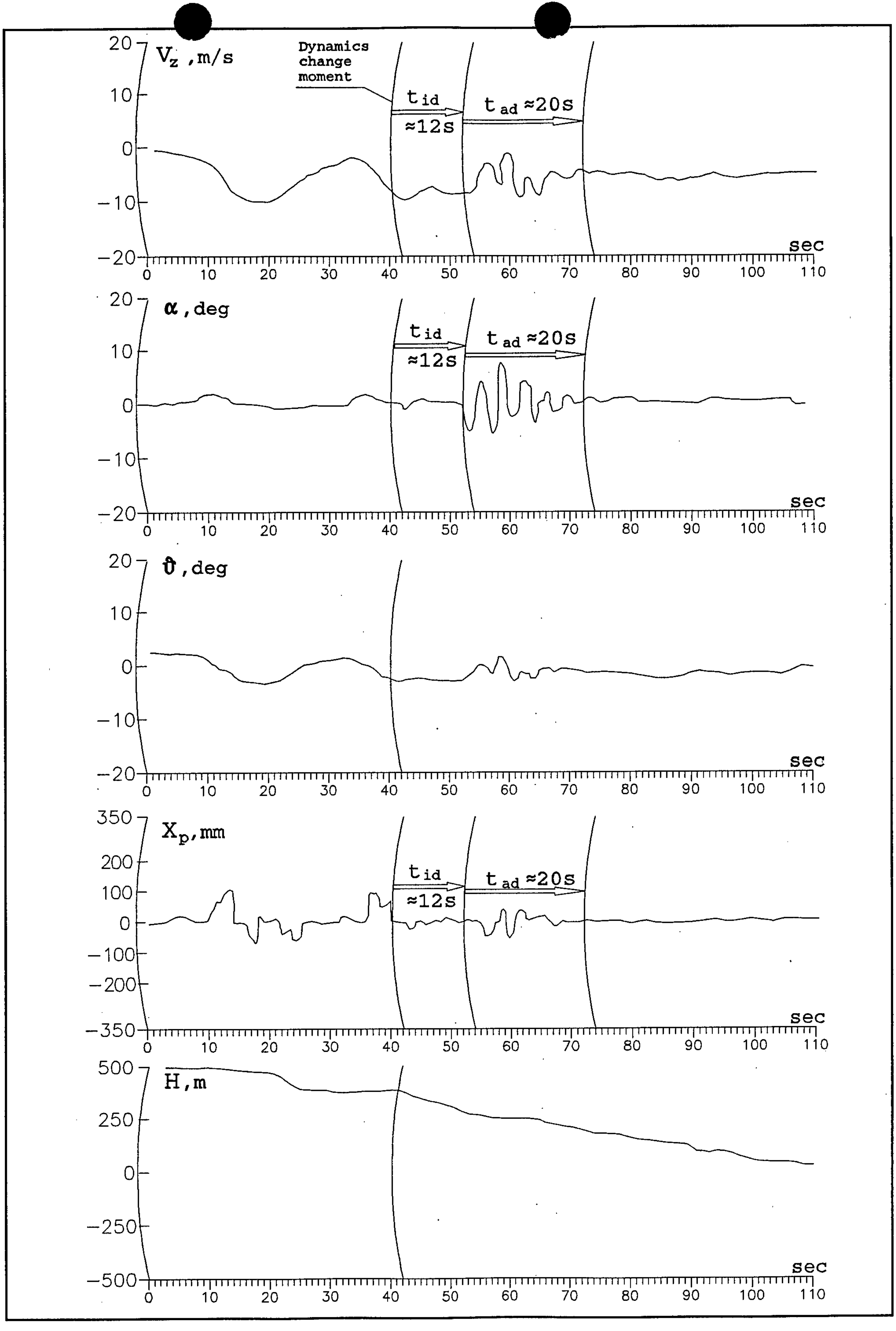

Fig.4 Passive dynamics change in the aircraft approach task.

altitude and duration of the test signals were selected by experiment.

The way of the internal model developing as well as the regulator optimization must be universal and applicable to any control object. Since the internal model structure was chosen in form (3) it is reasonable to describe the control object identification process by means of the simplest method that is a nonrecurrent method of minimum squares. The control object (aircraft) input is the pilot test signal and the output observed by the pilot is subjected to the noise due to external disturbances $\overline{f}$ acting on the aircraft and also caused by the input signal $\overline{y}_c$ (Fig.1). The nonrecurrent method of minimum squares applied to the pilot model can be presented in such a way. The control object when being identified is assumed to be stable and is described as a linearized model in terms of linear difference equation:

$$\begin{gathered}\overline{z}(k)+a_1\cdot\overline{z}(k-1)+\ldots+a_{m0}\cdot\overline{z}(k-m0)= \\ =b_1\cdot\overline{u}(k)+b_2\cdot\overline{u}(k-1)+\ldots+b_{m0}\cdot\overline{u}(k-m0)\end{gathered} \tag{9}$$

where $\overline{z}(k)$ and $\overline{u}(k)$ are the vectors of the observed parameters and the control respectively at the moment of number k measurement, the dimension representation of this vectors are (1×n) and ($1\times l$); a_{m0}, b_{m0} are the matrices of corresponding weight coefficients of n×n and $l\times l$ dimension; $m0$ is a given number of the equation terms. Substituting into the equation the measured values of input $\overline{u}(k)$ and output $\overline{z}(k)$ signals, corresponding to the observation moment number k, with accounting for the parameters a_{m0}, b_{m0} estimated after $k-1$ step, one can obtain:

$$\begin{gathered}\overline{z}(k)+\hat{a}_1\cdot\overline{z}(k-1)+\ldots+\hat{a}_{m0}\cdot\overline{z}(k-m0)- \\ -\hat{b}_1\cdot\overline{u}(k)-\hat{b}_2\cdot\overline{u}(k-1)-\ldots-\hat{b}_{m0}\cdot\overline{u}(k-m0)=\overline{e}(k)\end{gathered} \tag{10}$$

The residual $\overline{e}(k)$ on the right (after transporting all other equation terms to the left) presents an existence of the measurement errors and estimates inaccuracy for the parameters a_{m0}, b_{m0}. Then the matrix equation for the value $\hat{\overline{z}}(k)$ predicted on the basis of $k-1$ observations will be:

$$\hat{\overline{z}}(k/k-1)=i^T(k)\cdot\hat{q}(k-1) \tag{11}$$

where $i^T(k)=|-z(k-1)\ldots-z(k-m0)\;u(k)\ldots u(k-m0)|$ is the matrix of observation data, $\hat{q}^T(k-1)=|\hat{a}_1\ldots\hat{a}_{m0}\hat{b}_1\ldots\hat{b}_{m0}|$ is the matrix of the estimated coefficients. Using the designations involved the expression for the error can be represented as follows:

$$\overline{e}(k)=\overline{z}(k)-\hat{\overline{z}}(k/k-1) \tag{12}$$

where $\overline{e}(k)$ is the prediction error vector, $\overline{z}(k)$ is the measured value of the observed parameters vector, $\hat{\overline{z}}(k/k\text{-}1)$ is the measurement number k of the observed vector predicted on the basis of k-1 measurements. Extending the expression (12) for the case of j measurements from the total number of steps k one can obtain:

$$E(j)=Z(j)-\hat{Z}(j/j-1), \tag{13}$$

where

$$\begin{aligned} E(j)&=|\overline{e}(k)\,\overline{e}(k-1)\dots\overline{e}(k-j)\,|;\\ Z(j)&=|\overline{z}(k-1)\dots\overline{z}(k-j-1)\,|;\\ \hat{Z}(j/j-1)&=|\hat{\overline{z}}(k/k-1)\dots\hat{\overline{z}}(k-j-1/k-j-2)\,|. \end{aligned} \tag{14}$$

Substituting into (14) expression (11) extended to j measurements we can obtain:

$$E(j)=Z(j)-I^T(j)\cdot\hat{Q}(j), \tag{15}$$

where

$$I^T(j)=\begin{vmatrix} i^T(k-1)\\ \vdots\\ i^T(k-j-1)\end{vmatrix};\ \hat{Q}^T(j)=\begin{vmatrix} \hat{q}^T(k-1\\ \vdots\\ \hat{q}^T(k-j-1)\end{vmatrix}.$$

When the optimization criterion of matrix $\hat{Q}$ is taken to be the minimum of $V=\sum_{1}^{j}E^2(j)$ determined by the equation:

$$\left.\frac{dV}{dQ}\right|_{Q=\hat{Q}}=0 \tag{16}$$

then the final expression for the estimated coefficients matrix can be represented as follows:

$$\hat{Q}(j)=|I^T(j)\cdot I(j)\,|^{-1}\cdot I^T(j)\cdot Z(j)\,. \tag{17}$$

As mentioned above it is reasonable to take the vector of the observed parameters in the form (4). The pilot relates the value of the observed vector with its value at previous moment $\overline{z}(k-1)$ and with the values of the control vector at given and previous moments, i.e. $\overline{u}(k)$, $\overline{u}(k-1)$. Assuming that n parameters are observed and with extending to j number of measurement, one can rewrite the matrices $Z(j)$, $I(j)$ and $\hat{Q}(j)$ in the equation (15) if one-channel control task is considered:

$$
\begin{aligned}
Z^T(j) &= \left|\underbrace{y_1(k)\ldots y_1(k-j)\ldots y_n(k)\ldots y_n(k-j)\ldots \dot{y}_1(k)\ldots \dot{y}_1(k-j)\ldots \dot{y}_n(k)\ldots \dot{y}_n(k-j)}_{2n\times j}\right| \\
\hat{Q}^T(j) &= \left|\underbrace{a_{11}\cdots a_{1\,(2n+2)}\cdots a_{n1}\cdots a_{n\,(2n+2)}\cdots a_{2n1}\cdots a_{2n\,(2n+2)}}_{2n\times(2n+2)}\right|
\end{aligned}
\qquad (18)
$$

$$
I(j)=\left|\left.\underbrace{\begin{matrix}
\overset{\overset{X_{jn}}{/\!/}}{\boxed{\begin{matrix}
y_1(k-1) & \ldots & y_n(k-1) & \dot{y}_1(k-1) & \ldots & \dot{y}_n(k-1) & u(k) & u(k-1) \\
\vdots & & \vdots & \vdots & & \vdots & \vdots & \vdots \\
y_1(k-j-1) & \ldots & y_n(k-j-1) & \dot{y}_1(k-j-1) & \ldots & \dot{y}_n(k-j-1) & u(k) & u(k-j-1)
\end{matrix}}} & \begin{matrix} 0 & \ldots & 0 \end{matrix} \\
\begin{matrix} 0 \\ \vdots \\ 0 \end{matrix} & \begin{matrix} X_{jn} & \ldots & 0 \\ \vdots & \vdots & \vdots \\ 0 & \ldots & X_{jn} \end{matrix}
\end{matrix}}_{2n\times(2n+2)}\right|\right\} 2n\times j
$$

Thus the represented manipulations demonstrate the possibility to develop the IDMCO that describes control object in a sense of minimum of the error $\overline{e}^2$ or exactly describes the control process because the signal $\overline{e}$ observed by the pilot is the function of the useful control $\overline{u}$ and external disturbances $\overline{f}$, i.e. $\overline{e}=\overline{y}_c-W_{aircr}\cdot\overline{u}+\overline{f}$. It is easy to notice that the object identification accuracy depends on the proportion "useful signal/noise". Evidently, in order to obtain the highest accuracy the pilot will select the test signal (if it is possible in practice) so that this proportion will be maximum.

A certain advantage of the model proposed to describe an adaptive pilot behaviour is the possibility of including in the control loop not only the visual signals, but the acceleration information and some others; besides it is possible to take into account the dynamics and nonlinearities of the sense organs.

3. Application of the pilot adaptive model explaining the control object dynamics influence on the flying performance. The criteria development of the pilot rating of the abrupt changes in the aircraft dynamics

Let us consider the regulator parameters adaptation circuit of the adaptive model involved (Fig.2). It is easy to see that the regulator parameters depend only on the characteristics of the internal describing model of the control object. Under these circumstances the flying performance after loop closing by the adapted pilot (regulator) depends essentially on how exactly the internal model feels the real aircraft dynamics. That is why the special investigation was conducted and was aimed at disclosing the primary reasons of the flying performance change when the abrupt change of the control object dynamics takes place.

Shown on Fig.5-Fig.9 there are the pitch frequency responses for the different control object dynamics and the identification results based on the model described above. The control object pitch dynamics is described by the transfer function:

$$W(p) = \frac{\vartheta}{X_p} = \frac{\omega_0^2 (p + \frac{g}{V} \cdot n^{\alpha})}{n^{\alpha} \cdot X_p^n \cdot p \cdot (p^2 + 2\xi \omega_0 p + \omega_0^2)} \qquad (19)$$

when analyzing the parameter values X_p^n, n^{α}, V were fixed. The fundamental frequency ω_o and relative damping ξ were varied.

Let us analyze the internal model variations which take place when the control parameters ω_o ξ alter. Presented on Fig.5-Fig.9 there are the pilot ratings PR in approach task that were obtained on the TsAGI piloted simulators. It is easy to indicate that the difference between the aircraft and the internal model frequency response increases with the pilot ratings worsening. So when the pilot ratings are high (corresponding to the control object dynamics level 1) then the good phase and amplitude agreement take place in the characteristic pilot control frequency range 1-3 rad/sec. As the pilot ratings deteriorates, the coincidence range of the frequency response narrows up to its degeneration into the point for the level 3 control object dynamics.

Such difference between the pilot identified and real aircraft characteristics results in impossibility to provide (when loop closing

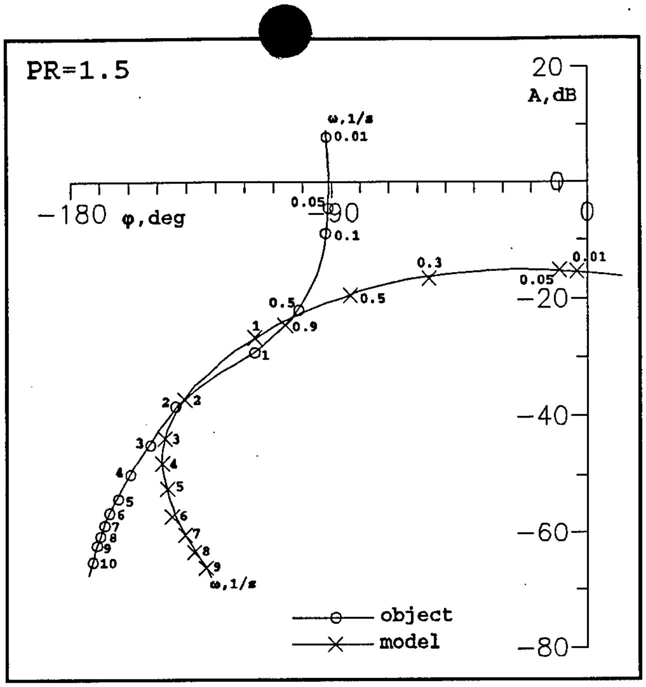

Fig.5

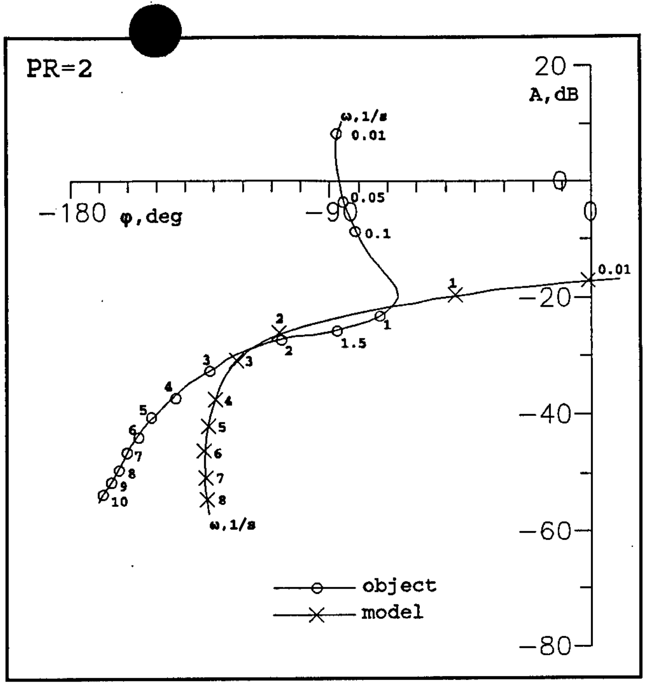

Fig.6

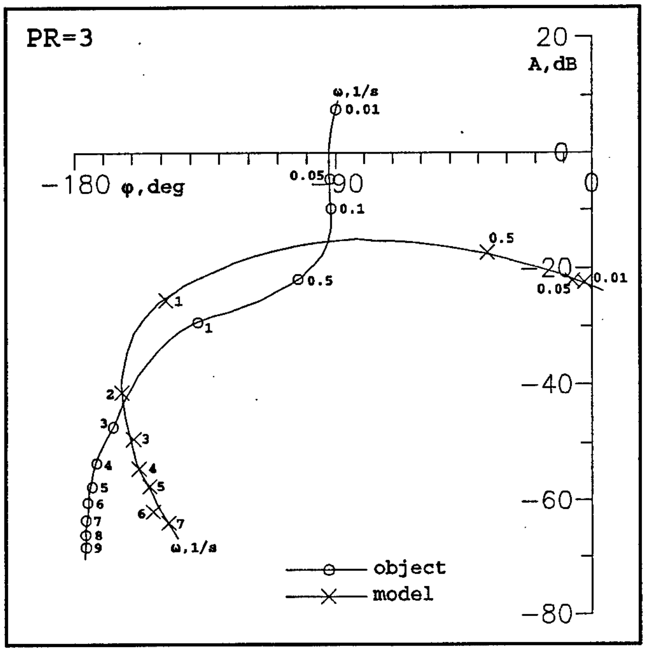

Fig.7

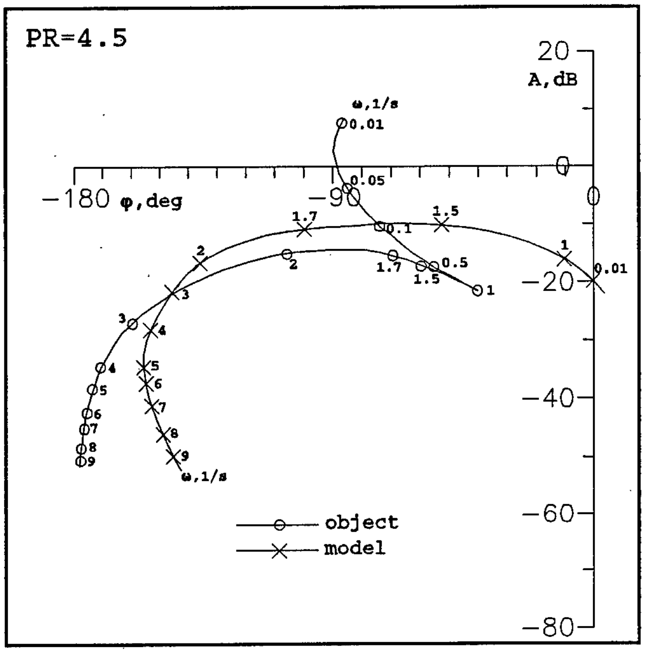

Fig.8

with the pilot-regulator is adapted in accordance with the internal model) the same dynamics and margins of the phase and amplitude as there were used in the pilot adapting. This also was obtained in the investigations based on the control object model with the transfer function $W_{aircr}=\frac{1}{p^2\cdot(Tp+1)}$. It is noted in these papers that the stability margin decreases when the time constant T approaches to the value which is a limit from the stability and controllability point of view. Similar data are presented in paper [1] where note is taken of the fact that while the control object transfer function is

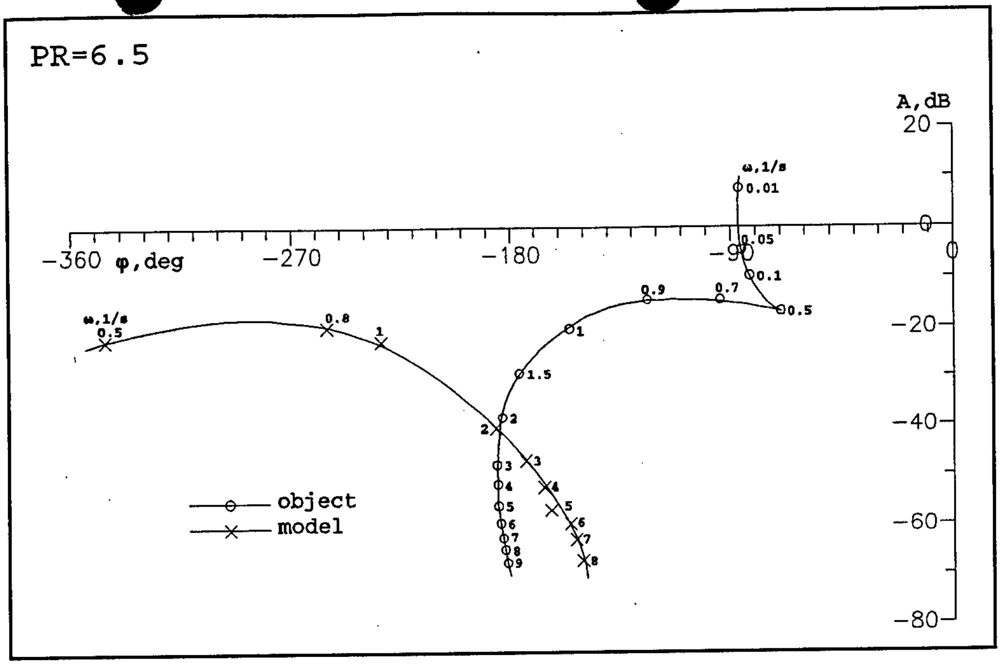

Fig.9

complicated then the closed loop stability margin decreases.

As mentioned above, the identification performance is influenced appreciably by the proportion "useful signal/external disturbances" $X_u=\frac{X(\bar{u})}{X(\bar{f})}$. So the identification accuracy drops substantially at low values of this ratio. On the other hand, a certain critical value X_u^{min} exits, since that the identification accuracy is high enough and does not vary practically during adapting, so the regulator parameters are constant too. This critical value X_u^{min} is the value, since that the pilot is able to select surely the control actions throughout noise. The dependence of the object identification accuracy on the ratio "useful signal/noise" (at the constant test signal amplitude, duration and shape) is illustrated on Fig.10. It is natural, that the identification accuracy worsening results in flying performance deterioration, as described above, and is confirmed by the experimental data.

To summarize one can draw the following conclusion. Flying quality and limit (from the stability and controllability viewpoint) of the control object dynamics can be estimated on the basis of accuracy investigation of the control object internal model. As the internal describing model displacement increases in terms of frequency response, the pilot ratings deteriorate. As a measure of the model displacement one can choose, for example, the coincidence accuracy of the phase-amplitude frequency response at the characteristic control frequency range ($\omega=1\div3$ rad/sec). Shown on Fig.11 there are the data illustrating the relations between the difference in the frequency responses of the internal describing model and the real control object

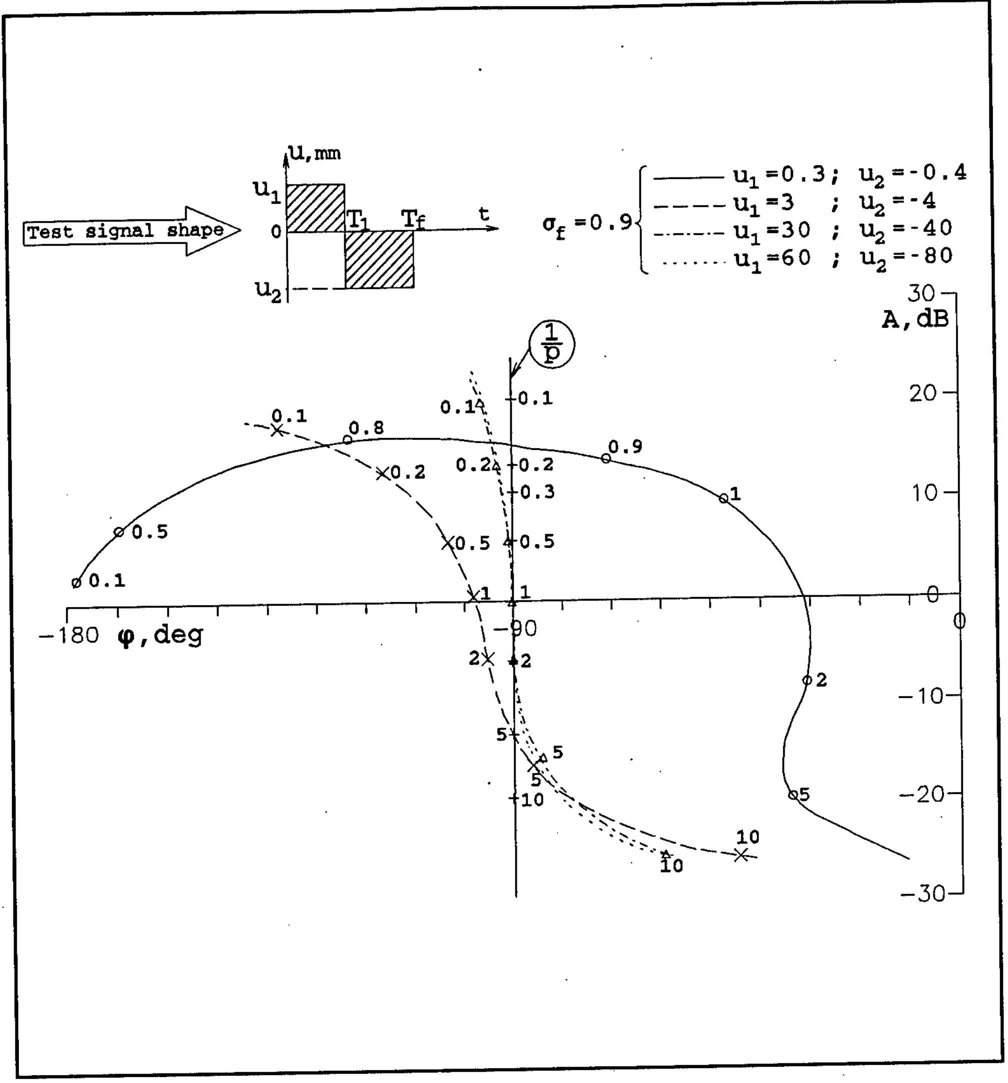

Fig.10 Dependence of the object identification accuracy on the ratio "useful signal/noise".

and the pilot ratings on the Cooper-Harper scale. Here the difference in phase $|\Delta\varphi|$ and amplitude $|\Delta A|$ is assumed to be a measure of the model displacement at ω=1.2rad/sec which is the characteristic frequency of the approach regime. As one can see at a limited number of matchings between the internal model and the real control object the following tendency takes place: the increase in the internal model displacement deteriorates the pilot ratings. However, this question demands further detailed consideration and a great number of statistic data. As the object-model mismatching $\hat{W}(p)-W(p)$ increases at the considered frequency range, the stability margin of the closed-loop "pilot-aircraft" system decreases (when the adaption of the pilot-regulator coefficients is based on the control object internal

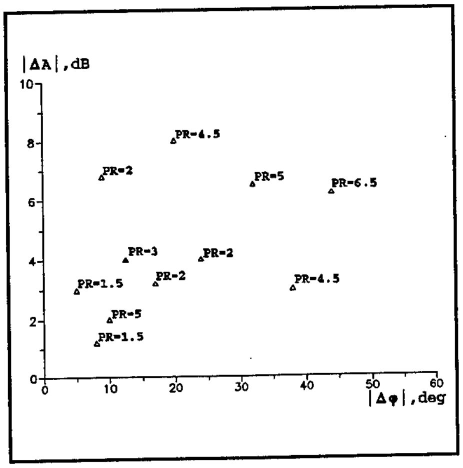

Fig.11

describing model obtained). Thus, the limiting case for the pilot dynamics capabilities in the control can be considered as the case when the real closed-loop stability is not provided with the regulator adapted in accordance with the developed internal model. This conclusion is confirmed by the data obtained for the object with the transfer function $W_{aircr}=\frac{1}{p^{2}\cdot(Tp+1)}$.

In case of a sudden change of the control object parameters the pilot must identify the new aircraft dynamics and then to adapt himself as a regulator proceeding from the identification results. The calculations based on the model use have shown that at a constrained identification time ($T_{id}<T_{reg}$) the object parameters identified in flying anew (internal describing model parameters) depend on the generation moment of the change, i.e. they depend on the initial identification conditions and the external disturbances at the beginning of the identification. Such dependence is believed to be useful in explaining the reasons of the flying regime influence on the criticality manifestation of the abrupt change. Really, if the object dynamics change is due to the one time appreciable external disturbances (active failure), then the new dynamics identification will be more prolonged. This is attributed to the fact that a great number of parameters' statistics is needed for the accurate determining of the observed phase coordinate vector; this makes it possible to compensate for displacement of their estimation at the initial time moment. On the other hand, when the identification time is limited during the pilot task fulfillment, the internal model parameters will depend on the initial conditions. This results in the different regulator adaption and, therefore, the different control process properties. These conclusions fully agree with the experimental data. For example, in the pitch stabilization task when the flight time is unlimited it was noted that with the active change (as compared to the passive change) the pilot ratings of the dynamics change criticality are practically unaltered, though the adaptation time increases.

Thus, the situations due to a sudden aircraft dynamics change can be conditionally divided into two main groups:

A) the case of high external or pilot-incited disturbances in the closed-loop "pilot-aircraft" system at the change moment;

B) the case of insignificant disturbances.

The following situations are characteristic for a group A:

1) The high level of the external disturbances at dynamics change moment (large atmosphere disturbances, active failure with the large balance deflection change δ_{el}). In this case

the internal describing model generated by the pilot at the initial time moment is considerably displaced (Fig.10) and, therefore, the pilot-regulator adjustment does not correspond to it's optimal value to maintain high flying quality. To provide a more precise generation of the model the pilot needs some time for adaptation. So the identification time increases when the object dynamics change.

2) The control object dynamics is rather poor (PR > 4.5). When the pilot tries to compensate for the dynamics change after the failure that causes the additional disturbance in the aircraft dynamics. In this situation the pilot is unable to identify the object accurately (Fig.9). That is why the larger disturbances occur and the poor flight task fulfillment is observed. In this case the pilot ratings are mainly determined by the after-change object dynamics.

The following three situations are characteristic for the group B:

1) The pilot-regulator adjustment obtained for the before change dynamics corresponds to the high control performance after the dynamics change. In this case the change does not result in some additional pilot-induced disturbances and generally may not be indicated by the pilot. The pilot rating of the change is completely determined by the stationary control after the dynamics change.
2) After the dynamics change the object is easily identified by the pilot, the control process is not hindered and is featured by a high quality.
3) The object is characterized by poor after change dynamics, but due to the absence of the disturbances the pilot identifies the changes only after his intervening into the control.

In all B-group situations the change time moment cannot be reliably determined by the pilot.

Let us present now some considerations allowing to understand the question dealing with the acceptability of the control object parameters when they change abruptly. As it has been noted above, one can expect that at the first moment of the parameters change the pilot-regulator adjustment does not vary. That is why, at the initial time moments (before the dynamics change identifying) the closed-loop instability can occur due to the mismatching between the "old" pilot adjustment and the "new" control object dynamics W^1_{co}. Alongside, with the increasing of the instability degree the disturbances caused by the pilot will also increase and finally will result in insufficient identification accuracy of the "new" object (W^1_{co}) and nonoptimum adjustment of the pilot. Thus, because of the dynamics change, it may happen that $\hat{W}^1_{co} - W^1_{co} > \Delta W_{accept}$, that leads to the instability of the new closed-loop "pilot-new aircraft control dynamics". The last can result in an emergency.

Proceeding of the mentioned above one can suggest the following scheme which allows to explain the nature of the pilot's adapting when dynamics of the control object changes and also to estimate the criticality of such changes. If the failure results in such object dynamics change that $\hat{W}^0_{co} - W^1_{co} > \Delta W_{accept}$ (pilot estimation of the "old" dynamics ($\hat{W}^0_{co}$) differs from that for the "new" one (W^1_{co}) by the value greater then ΔW_{accept}), then the large phase coordinate disturbances caused by the pilot should be expected. If the induced disturbances (or instability degree) are rather high, the pilot is not able to identify correctly the new object dynamics (to develop internal model $\hat{W}^1_{co}$) and even after the pilot-regulator readjustment in accordance with the image $\hat{W}^1_{co}$ the new closed-loop "pilot-object W^1_{co}" system will be unstable and the dynamics change will not be counteracted.

The determining factor in this situation should be the difference between the estimation of the "old" object dynamics $\hat{W}^0_{co}$ and the "new" object dynamics W^1_{co}. This is similar to the problem of the stationary control tasks where the difference between frequency responses of the aircraft and its internal model at the pilot's operation frequency range can be chosen as a measure of the acceptability of the object dynamics. The next possibility is to choose the stability margins of the closed-loop "pilot (adapted to $\hat{W}^0_{co}$) - object W^1_{co}" system as the determining factor of pilot's rate of the dynamics change. The last is much more preferable because in this case the value of the disturbances caused by the failure is predicted. It should be noted that when the object dynamics before the failure is rated rather high (PR=1÷4.5) then the internal aircraft model before change $\hat{W}^0_{co}$ can be replaced by the real aircraft transfer function W^0_{co} because of their closeness. Therefore the pilot-regulator adjustment will remain unaltering. Thus, the following criterion for the estimation of the acceptability of the abrupt change in aircraft dynamics can be formulated as:

> if the closed-loop "pilot-aircraft" system keeps its stability after the abrupt change (i.e., the failure in the control system) when the pilot-regulator is adapting to the object before the change then the change does not result in

the appreciable disturbances in the aircraft motion.

Presented on Fig.12 there is a graphic illustration of the suggested criterion. It should be noted that if the substantial increase in the stability margin takes place then the occurrence of bad pilot ratings is possible but only in those situations when the object change results in the dynamics deterioration. In other words, pilot rating of the change in this case is determined by the pilot rating of the stationary configuration after the change. Because of the difficulties in the pilot adaptation procedure it is permissible to use the simplified variant of the criterion when the timely engineer prediction of the pilot ratings is needed. In this case the pilot transfer function can be presented in the form $W_{pil}=K_0\cdot e^{-p\tau}$ with the fixed time constant $\tau=0.3$ sec and the adapted K_0 for the object dynamics before the change.

To produce the quantitative criterion of the satisfactory aircraft characteristics change let's consider the open-loop system phase-amplitude response (PhAR) curve on the plane of these parameters, see Fig.12, where the amplitude (A_{ol}) is in dB and the phase (φ_{ol}) is in degrees. Because of the stationarity of the control process before the change moment, the pilot produces:

- minimal tracking error (high accuracy) control strategy, and
- stability margin in amplitude ΔA (≈ 6 dB) and phase $\Delta\varphi$ ($\approx 50°$).

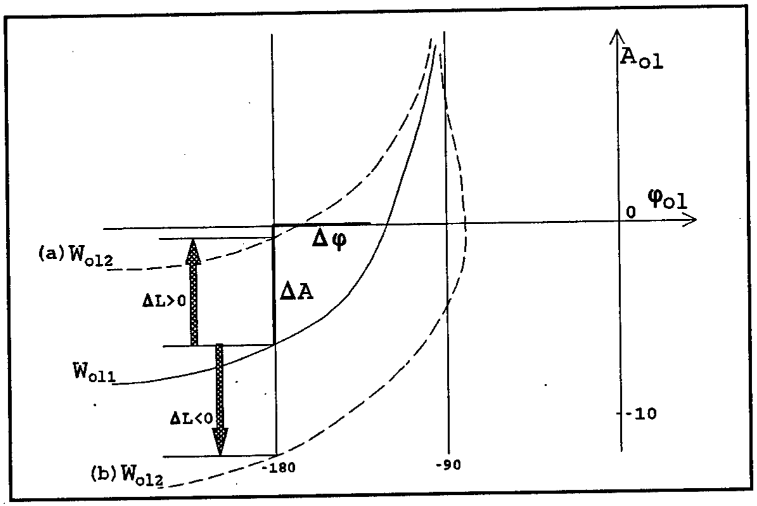

Fig.12 Phase-amplitude change.

The open-loop transfer function is defined as:

$$W_{ol(1,2)}=W_{man}(s)\cdot W_{plant(1,2)}(s)$$

On the phase-amplitude plane the PhAR curve lies so that it passes through the point ($-180°;-\Delta A$) or the point ($-180°+\Delta\varphi$; $A=0$) or both as shown in Fig.12. After the characteristics change from W_{plant1} to W_{plant2} the PhAR curve will change so that the two situations become possible:

1) PhAR curve moves in the direction of closed loop system instability, Fig.12 (a);

2) PhAR curve changes without the closed loop system stability

deterioration, Fig.12 (b).

It is rational to accept the change of amplitude stability margin, ΔL, as a quantitative criterion mentioned above. In this situation the closed loop man-machine system will become unstable after the control object characteristics change if $\Delta L>6$ dB, and the human rating of such change of control object dynamics is low. If $\Delta L<0$ there is no any problem with closed loop system stability but only the tracking accuracy degradation. Therefore the human rating of such change of control object dynamics will not be so low as for $\Delta L>0$.

4. Experimental investigation

The investigation of the unstationary control tasks which include the aircraft control under the sudden change of its dynamics impose requirements on the test conducting technique, experimental results processing and also on the objective and subjective measures of handling qualities. The experimental investigations were conducted on the TsAGI's moving base flight simulator with the angular degrees of mobility and the shadow visualization system.

Pitch control task (the tracking of the defined pitch angle) and the instrument approach were investigated as the examples of the accurate aircraft control under action of the external disturbances. If the transfer function of the control object is presented as follows:

$$W_{plant}(s) = \left\{\frac{\vartheta}{X_p}\right\} = \frac{K_c\cdot(s+L_\alpha)}{s(\omega_o^2+2\xi\omega_o s+s^2)} \quad ,$$

then according to the set problem there is an abrupt change in parameters K_c, ω_o, ξ in any possible combination envisaged by the experiment. This abrupt change occurs at some moment which the pilot is unaware of. The scheme of this flight situation is on Fig.13.

This scheme of considering the problem can be used if primary control system of aircraft breaks down and backup control system switches on or control system algorithm switches from one to another. Also this scheme can be used when the control object dynamic characteristics change

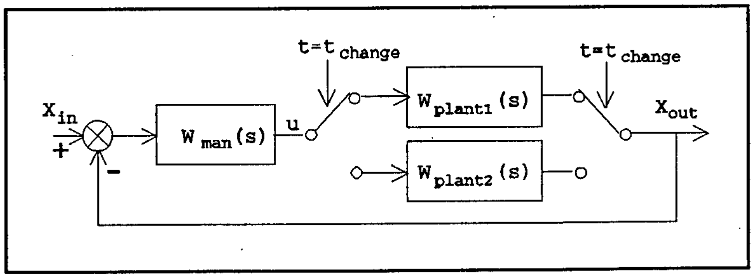

Fig.13 Man-machine system with control object characteristics change.

rapidly because of the nonlinearities. There is a typical example of such situation when the aircraft lateral-directional handling qualities change with a very fast alteration of its angle of attack. For all these cases the W_{plant1} is a transfer function of the aircraft before the characteristics change (control system failure) and W_{plant2} is a transfer function of the aircraft after the characteristics change (control system failure). The situations were simulated with the passive and active (change of the balance control surface deflection) aircraft dynamic characteristics altering.

To obtain the expert pilot-operator ratings the special pilot

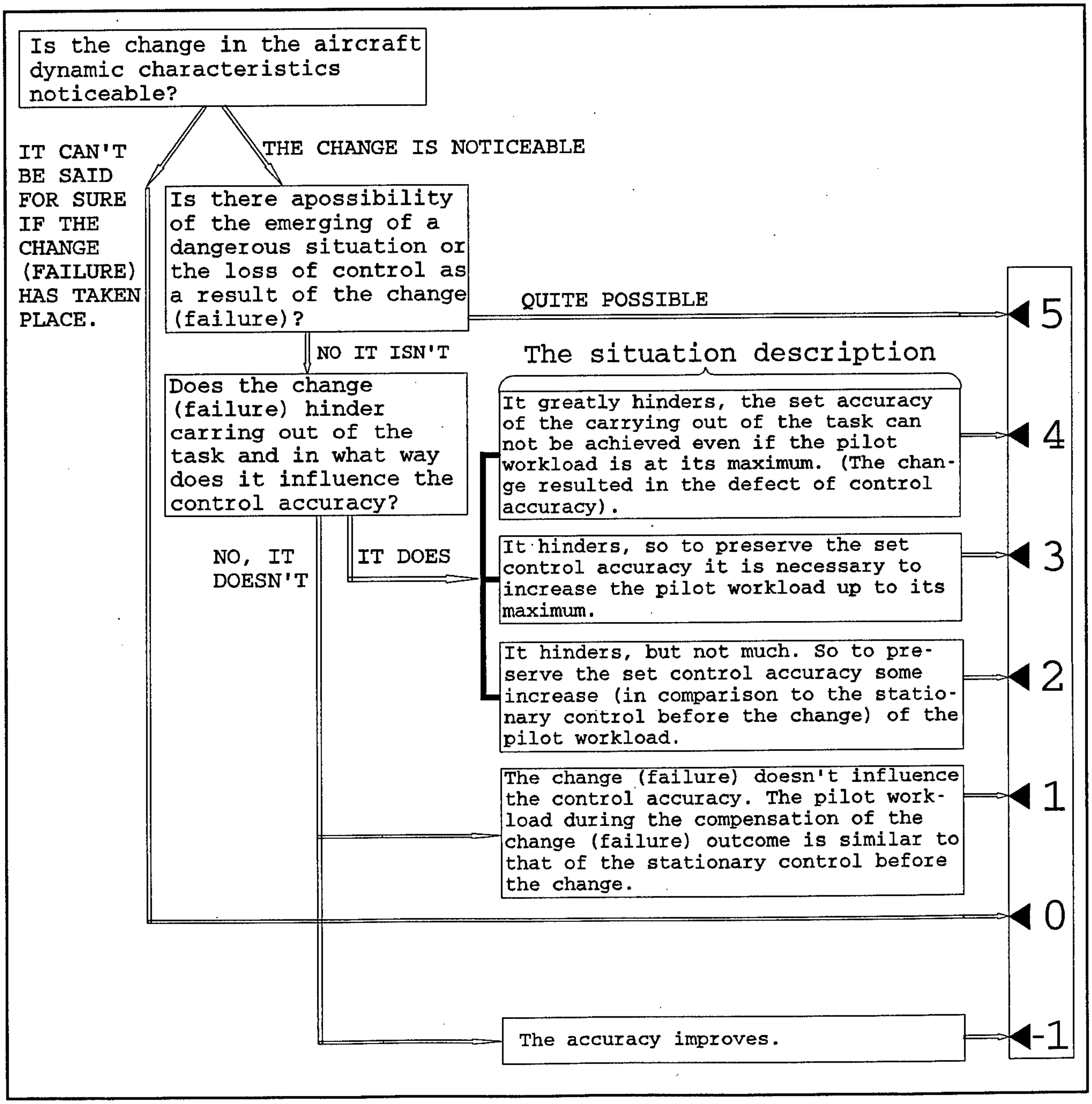

Fig.14 Pilot Rating Scale of the acceptability of the aircraft dynamics in case of its abrupt change (failure).

rating scale was developed. The scale is formed in accordance with the penalty principle (Fig.14). For statistical processing of the pilot's ratings the method was developed on the base of the Bayes rule and the probability theory. This method makes it possible to connect the aposteriory certainty probabilities of each pilot's rating to the apriory idea of such certainty, on the one hand, and with the sequence of the experimental results on the other hand.

In order to improve the certainty level of the expert rating obtained the following techniques were used:

- the background task technique,
- the random altering of the investigated flight situations,
- the psychological disorientation of the pilot.

The general feature of all the experimental data involved is that the worst pilot ratings are associated with such aircraft dynamics change that results in damping decrease, short period frequency increase, or control sensitivity increase, with the determining influence of the first parameter from the listed above.

It is easy to see that in accordance with the above-mentioned considerations concerned with the unaltering of the pilot control manner during some time after the dynamics change, the high value of resonance terms will be observed in the closed-loop "pilot-aircraft" system. So the corresponding variation of the parameter ΔL will be appreciable ($\Delta L>0$). Such kind of changes are usually identified by the pilot at once, but the adaptation to it is prolonged.

When considering the control object featured by the lesser oscillation or by the sluggish response to the control actions and the external disturbances, the level of the occurring in the "pilot-aircraft" loop disturbances is insignificant and the pilot quickly adapts himself to the changed dynamics. In a number of situations the adaptation is principally subconscious. This fact is a matter of interest in many-functional control system optimized for the specific flying tasks.

The essential factor for the task of pilot rating of the object change is the level of the external disturbances at the moment of the change. As it is noted above, the accuracy of the internal model determination ("new" object dynamics identification) at large external disturbances drops significantly. This leads to the nonoptimal pilot-regulator adjustment. In a number of experiments where the change moment was accompanied by the high level disturbances the pilot ratings of the change were groused by value of 1÷1,5 and the pilot adaptation time increased in comparison with the same situation and small disturbances, if any. It should be noted that the characteristic time of pilot adaptation to the object dynamics change is well correlated with the pilot ratings (Fig.15).

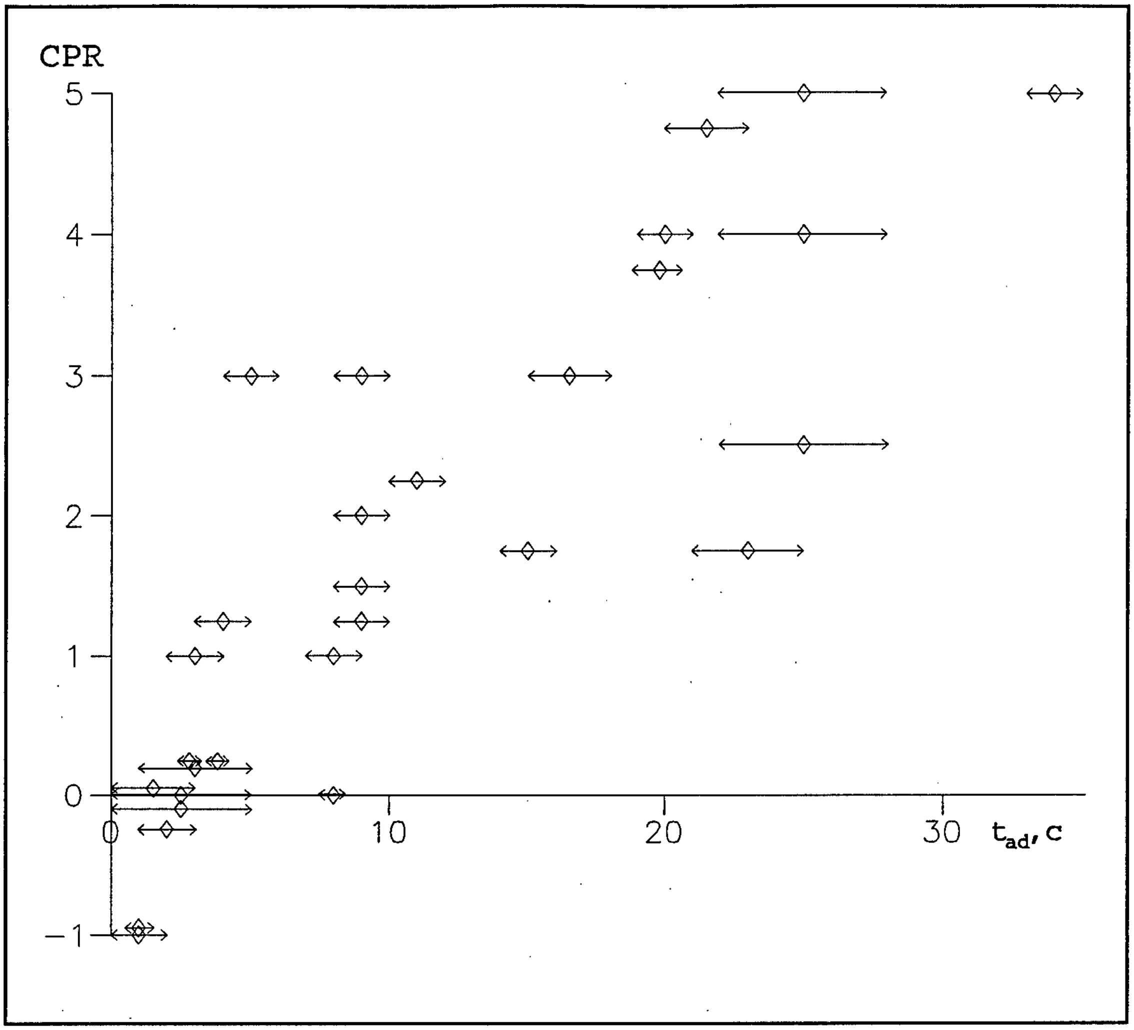

Fig.15

As it is noted above, the two kinds of changes in the object dynamics the active and the passive were investigated experimentally. According to the experimental data obtained in pitch stabilizing task the passive change was easier to counteract. This may be explained by the absence of the initial excited disturbances in the second case. Thus, one can conclude that the change type in dynamics itself governs primarily the pilot ratings.

Also the pilot rating depends essentially on the kind of the control task performed when the characteristics are changing. Such dependance is explained by different requirements to the pilot-regulator adjustment which are determined by the necessary accuracy of the controlling. For example, it was noted in approach task featured by nonstationarity and time shortage to make a decision that pilot rating deteriorates as the height decreases. At first, this is caused by the stringency increase of the requirements to the glide path holding during the glide-path set-down. Secondly, the requirements to the change counteracting become more stringent at low altitudes due to the time shortage and closeness to the surface. Usually, the dynamics change near the surface (H≈50 m) when compared to the same change at altitudes H=200÷400 meters was scored by number of 1.5÷2 lower. The passive failures in landing are extremely dangerous for the pilot . This is due to the fact that at small disturbances and small glide-path deviations the pilot can introduce the lag when intervening into control (it can reach ~10÷15 sec in the experiments), i.e. he can identify the change and try to adapt himself in close proximity to the surface. That is why to provide uniformity to the data obtained in approach task the results presented below were processed to choose those which correspond to the changes in dynamics at H=150÷350 m. However, it should be noted that problems dealing with the nonstationary flying tasks have been deficiently investigated by now and demand additional studies.

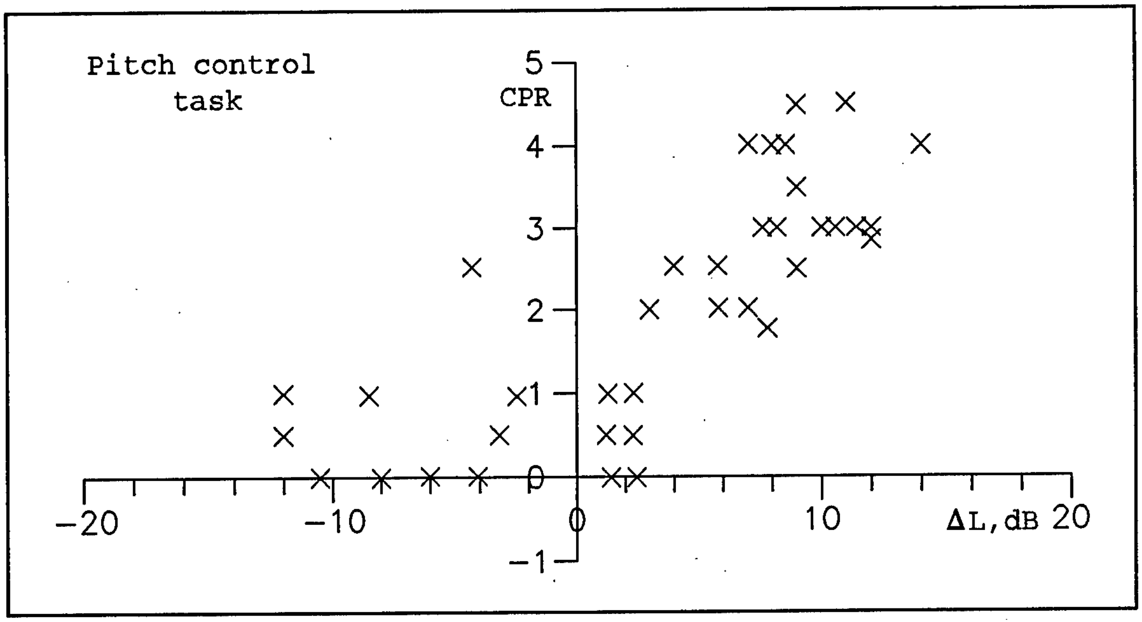

Fig.16 Experimental results - CPR versus ΔL in pitch control task (active dynamics change).

Shown on Fig.16-Fig.17 there are the results obtained in experiments processing on the basis of the simplified amplitude criterion described above. As it follows from these illustrations, the pilot rating reaches the value CPR=3 in pitch stabilizing task when parameter ΔL exceeds 7 dB. This corresponds to the appreciable disturbances in the "pilot-aircraft" loop after the change. In approaching task the pilot rating reaches the value CPR=3 beginning from ΔL=10 dB or ΔL=-20 dB. However, probably because of the task nonstationarity there is a significant dispersion in the pilot ratings.

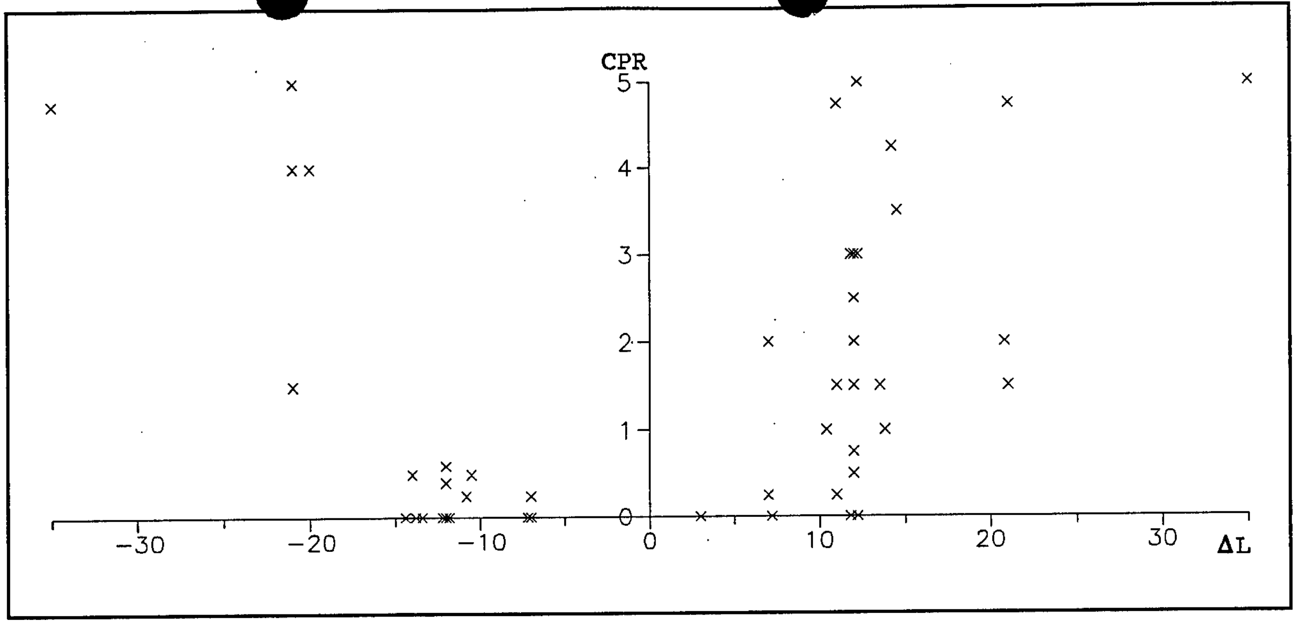

Fig.17 Pilot ratings versus ΔL in approach task.

Proceeding from the results obtained one can advance the following requirements to the parameter ΔL:

the parameter ΔL value should not exceed 7 dB in pitch stabilization task and 10 dB in landing approach (with the dynamics change at H=150÷300 m) in order to avoid the appreciable disturbance exciting in the closed-loop "pilot-aircraft" system after the change in the aircraft dynamics.

5. Use of the criterion for the PIO prediction

The other lead was to research nonlinear dynamic characteristics of the control object and the possibility of the Pilot Induced Oscillations (PIO) occurrence. We propose to consider the pitch control task as a typical aircraft control task. There are some nonlinearities in aircraft control system such as the dead zone or the rate saturation in actuators, the special rate saturations in control algorithm, the nonlinear signal transformers etc., as shown on Fig.18.

Because of the mentioned above nonlinearities the dynamic characteristics of the aircraft can change as a function of the control stick input amplitude. The pilot deals with some set of aircraft dynamic characteristics for some control stick amplitude, but if he is forced to change this amplitude the aircraft characteristics will change also. Therefore we can use the ΔL parameter to estimate the PIO tendency in the tasks when the control stick amplitude changes repeatedly during a short time period. If ΔL=4..6 dB, the closed loop system can become unstable and it will be understood as the pilot induced oscillations. The frequency of the PIO is equal to the one at

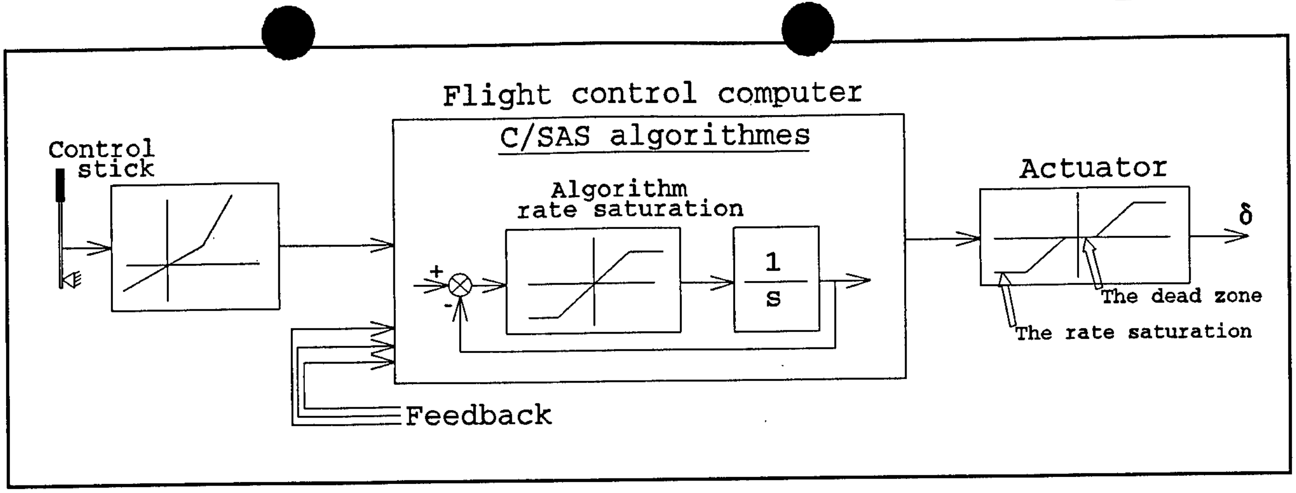

Fig.18 Some nonlinear elements in control system.

which the open loop system phase is -180°.

In the process of the research some examples of the PIO analysis of real flight situations were considered.

1) During the flight tests of the IL-96-300 control system one of the two test pilots informed about the PIO in the precision pitch control task. The control system analysis showed that because of the dead zone in the actuator there were some changes of phase-amplitude response when the pilot command amplitude varied. Particularly when the pilot command amplitude changes from ΔX=10 mm to ΔX=0.5 mm then the variation of ΔL is 4.5 dB, see Fig.19.

2) When the flight tests of some maneuverable aircraft were being carried out the PIO appeared at some flight regimes in the pitch control task. The variations of the PhAR curve on the phase-amplitude plane are showed on Fig.20. The PhAR curve moves up (ΔL>4.5 dB) when the pilot command control amplitude decreases and it is interesting to note that the phase lag is decreased in control system. The variations of the ΔL parameter are less significant at the flight regimes where the PIO tendency is absent.

3) During the landing of this aircraft the PIO appeared when the pilot produced the pitch control command with great amplitude. The PhAR curve variation is presented in Fig.21 as a function of the control stick amplitude. The main cause of this variation was the rate saturation in the actuator. The value of the ΔL parameter is more than 4 dB therefore the PIO can take place when the pilot control signal is large enough.

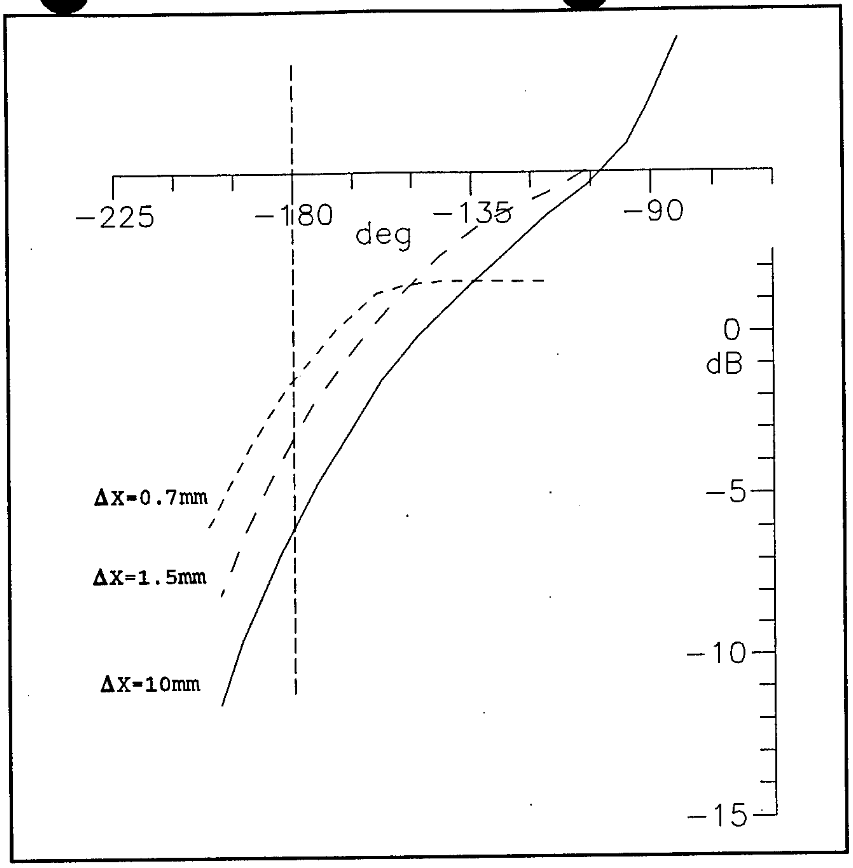

Fig.19 The IL-96 Phase-Amplitude response in pitch control task.

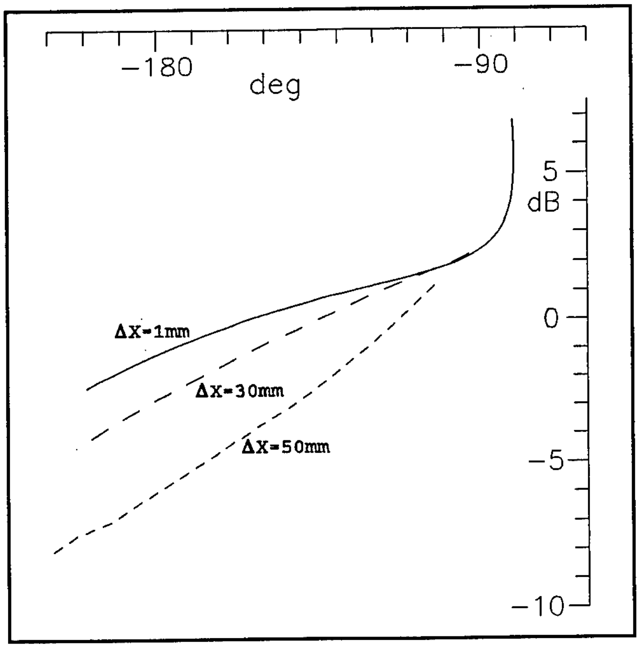

Fig.20 Phase-Amplitude response in pitch control task.

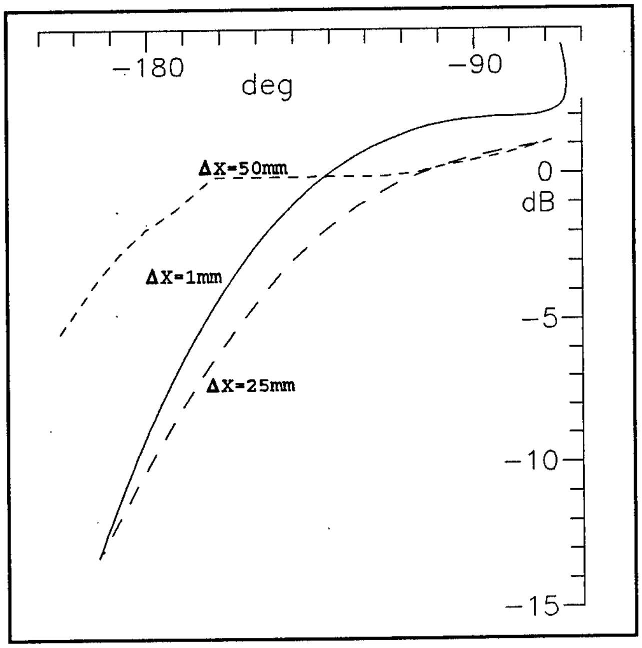

Fig.21 Landing Phase-Amplitude response.

6. Concluding remarks

The general approach is suggested for the pilot's estimation of the acceptability of a sudden aicraft dynamics change. The approach is based on the idea dealing with the pilot developing the internal control object describing model. The difference (in terms of frequency response) between the describing model and real object can be considered as the quantitative measure of aircraft handling qualities.

When conducting the engineer analysis of the acceptability of a sudden dynamics change, the simplified criterion based on the amplitude stability margin change in the closed-loop "pilot-regulator (adapted to the describing model before change) - aircraft dynamics after change"is supposed to be used.

The experimental check of the suggested simplified criterion has been conducted in situations with a sudden change in the longitudinal short-period aircraft dynamics during approach and pitch stabilizing. The criterion application in control system developing and analyzing possible failures which result in aircraft dynamics change is verified.

The criterion applicability is demonstrated while analyzing the PIO occurence caused by aircraft dynamics change due to object and control system nonlinearities.

The investigations involved have been conducted in accordance with the SPC-94-4002 contract.

7. References

1. T.B. Sheridan, W.R. Ferrel, "Man-Machine Systems: Information, Control and Decision Models of Human Performance", The MIT Press, Cambridge, Massachusetts, London, 1974.
2. "Application of Human Performance Models to System Design", Edited by G.R. McMillem etc., Premium Press, New York, 1989.
3. "Pilot as a Dynamic Element in a "Pilot-Aircraft" Closed-Loop System" (in Russian), TsAGI Review №635, 1984.
4. D.T. McRuer, W.F. Clement, P.M. Thompson, R.E. Magdaleno, "Minimum Flying Qualities. Vol.3: Pilot Modeling For Flying Qualities Applications", Technical Report №1235-1, Wright Patterson AFB, Ohio, 1989.

5. L.R. You[illegible], D.M. Green, I.I. Elki[illegible] J.A. Kelley, "Adaptive Dynamic Response Characteristics of Human Operator in Simple Manual Control", IEEE Transactions HFE, HFE-5, №1, 1964.
6. D.C. Miller, J.I. Elkind, "The Adaptive Response of Human Controller to Sudden Changes in Controlled Process Dynamics", IEEE Transactions HFE, HFE-8, №3, 1967.
7. A.V. Phatak, G.A. Bekey, "Decision Process in the Adaptive Behaviour of the Human Controllers", 5th Annual NASA-University Conference on Manual Control, NASA SP-215, 1969.
8. D.L. Kleinman, A.V. Phatak, "Current Status of Models for the Human Operator as a Controller and Decision Maker in Manned Aerospace Systems", IEEE Decision and Control Conference, 1972.
9. D.L. Kleinman, S. Baron, W. Levison, "An Optimal Control Model of Human Behaviour", Proceedings of 5th Annual NASA-University Conference on Manual Control, NASA SP-215, 1969.