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PILOT'S INFLUENCE ON DYNAMIC DESIGN OF AIRCRAFT

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PILOT INFLUENCE ON THE DYNAMIC DESIGN OF AIRCRAFT

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In connection with great variety of aircraft designs, considerable increase of flight regimes and problems which may be solved with the help of aviation, the attention of scientists is given to more through study of the aircraft dynamic and static requirements and necessary degree of the control automatization accounting for functional and physiological possibilities of the pilot[2,4]

At present two methods of solving the above problem exist.

The first is the direct simulation of specific problems on test rigs and simulators. To select the parameters of aircraft or control system, simple briefings of the pilots are used along with subjective estimates of aircraft handling qualities by the special scales (Cooper) and objective experimental measurements which characterize the quality of performing the specific handling task (stabilization accuracy, maximum deflections of the stick, etc.).

This method is a powerful tool of investigation of the aircraft and control system characteristics. It permits to obtain general results within the reasonable regions of the parameter variation. The region of reasonable values of the control and damping efficiency in the roll channel (fig. 1)[1] may be considered as a typical example. The above method is relatively simple and due to this simplicity it is of wide application. However this method has some appreciable disadvantages.

The extension of the results obtained for specific conditions of a given handling task and for specific aircrafts to other conditions and types of aircraft is difficult.

In many cases the simulation of aircraft movements in the rig tests is not full. The conditions in the cabin of the rig differ appreciably from the reality. This factor decreases the reliability of the results, obtained in the rig tests by the above method, and makes difficult the extension of the data to real conditions.

The second method, which begins to develop at present, supposes the insight into the laws of pilot functioning and his physiological state when he performs different handling tasks. The definition of the psychological and physiological basis of the pilot activity opens the way for generalization of the test results.

The two methods complement each other.

Some results obtained by the authors in developing the second method are presented below.

I. The limits of pilot adaptability used as a criterium for selection of the aircraft characteristics.

The pilot adaptability to the variation of aircraft characteristics is one of his most important properties which makes possible the effective aircraft control in a wide range of the aircraft characteristics. However the adaptability of the pilot is limited. The stability and handling requirements must account for these limits.

The promising method which enables to represent the psycho-physiological possibilities of the pilot, consists in developing his dynamics model, i.e. the mathematical description of the operation laws, the definition of the limits of their using and the variation of the parameters of these laws with aircraft characteristics and flight regimes.

This research trend has more than a half-century history to take into account numerous attempts to determine the parameters of the model (threshold values, lag time, the accuracy of tracking). However, the most reliable data are obtained (the first who obtained results of this kind was McRuer) only for the most simple problems of one-dimensional (one-channel) control. This factor shows the problem complexity.

The simplest way of obtaining the approximate description of the pilot dynamic characteristics is that in the class of linear systems.

In this case the pilot model may be obtained on the basis of so called "statistically equivalent" frequency response.

In the simplest case of one-dimensional control, when the stick deflection "X" stabilizes a single coordinate and the aircraft experiences the effect of an external disturbance "r", this frequency response is calculated as the ratio of cross spectral densities:

$$W_p(i\omega) = \frac{S_{rx}(i\omega)}{S_{ry}(i\omega)} .$$

It may be shown, that when the linear equivalent of the law of pilot actions are sought, this definition of his frequency response is the best one. In this case in the equivalent closed--loop "aircraft-pilot" system the root-mean-square deviations $\gamma(t)$ and $X(t)$ from real values are minimum.

A number of experimental studies of the stabilization of the single rolling motion has been carried out on the ground test rig. The differential operator which describes the aircraft dynamics in this handling task may be presented as follows:

$$W_{\gamma}(s) = \frac{K}{(s + 1/T_a)s}$$

The pilot frequency response multiplied by the control sensitivity "K" for various "K" values, obtained in these tests, is presented in fig.2. The stability of the product $K \cdot W_p(i\omega)$ when the control sensitivity varies in a certain range, indicates reorganization of the pilot activity, i.e. the adaptability.

The charts of the frequency response presented above show that for this handling task the pilot dynamics is rather well described by the differential operator.

$$(\mu \cdot s + \nu)\, e^{-s\tau}$$

Even this simplest linear representation of the pilot dynamics, may be used in practice for the comparative analysis of the effect of the specific aircraft and control system characteristics on the stabilization accuracy.

Tests and calculations permit to say that in this control system "pilot linear model coefficients" ν and μ approach the optimum from the condition of the minimum root-mean-square stabilization error. In the considered case this criterium completes the problem. The pilot lag time τ may be assumed constant in the range of $\tau = 0{,}2 - 0{,}3$ sec. The measured and calculated frequency responses of the pilot are compared in fig.2.

However, not only the fact of the pilot adaptability is important, but also the limits of adaptability.

The time constant $T_p = \frac{\mu}{\nu}$ which defines the advance of the pilot reaction, as a function of the time constant of aircraft T_a in the rolling motion, is presented in fig. 3.

It is evident that the value $T_\alpha = 1 - 1{,}5$ sec is the limit of the possible pilot adaptation to the phase lag of the aircraft. As it is shown in fig. 1, this value coincides esentially with a limiting value obtained by the pilot rating method.

The adaptability is also limited when the control sensitivity "K" varies. The measured variation of the total gain of the unclosed circuit "pilot-aircraft" $K \cdot \nu$ with the control sensitivity "K" is presented in fig. 4. A considerable decrease of the gain occurs from $K \approx 0{,}3^\circ/\mathrm{sec}^2\mathrm{mm}$. This value approaches the quantity which defines the minimum efficiency of the roll control.

The above data and analogous results of other investigations permit to suppose that the conditions which determine the adaptability limits may be considered as criteria to define the region of reasonable stability and handling characteristics and the characteristics of the control system.

2. Time reserves for control and limits of adaptability

The hypothesis presented above concerns the possibility of the pilot to adapt to the variation of the aircraft characteristics and flight conditions within certain limits.

It is not clear, however, what elements of the pilot activity limit this possibility.

The coefficients of the linear model can not explain this factor. Therefore, attention should be directed to certain general laws of the pilot activity. Here the hypothesis of the discrete actions of the pilot is worthy of consideration. It is reasonable also to estimate the pilot lag by the method which excludes the time required for motions.

These characteristics of the pilot may be estimated under certain assumptions about the probability properties of the processes in the "pilot-aircraft" system.

As an example let us consider the problem of the pitch angle "ϑ" stabilization.

Assume that the values of $\vartheta(t)$ and $X(t)$, where X - is the stick cut-off (t =1, 2..., N - the number of measurement) are measured simultaneously at regular and small time intervals

To estimate the lag, it is sufficiently to find the minimum of the estimate of the average conditional entropy:

$$H_{x|\vartheta}(\theta) = -\sum_i \sum_j P^{*\theta}(x_i, \vartheta_j) \cdot \ln P^{*\theta}(x_i | \vartheta_j) ,$$

where

$$P^{*\theta}(x_i, \vartheta_j) = \frac{1}{N-\theta} \sum_{t=\theta+1}^{N} \varphi_{x_i, \vartheta_j} \left[x(t), \vartheta(t-\theta) \right] ,$$

$$\varphi_{x_i,\vartheta_j}[x(t),\vartheta(t-\theta)]=\begin{cases}1 & \text{for } x(t)=x_i;\ \vartheta(t-\theta)=\vartheta_j;\\ 0 & \text{in all other cases.}\end{cases}$$

The value $\theta=\tau^*$, satisfying $\min\limits_{\theta>0} H_{x|\vartheta}(\theta)$, is the estimate to be obtained. Similarly, to estimate the intervals between pilot actions the minimum should be find:

$$H^*_{x,\vartheta'}(R)=-\sum_i\sum_j P^{*R}(x_i,\vartheta'_j)\cdot \ln P^{*R}(x_i|\vartheta'_j)$$

where R - variable submultiplicity of the multiplicity of the moments of observation of:

$$P^{*R}(x_i,\vartheta'_j)=\frac{1}{N_R}\sum_{t_i\in R}\varphi_{x_i,\vartheta'_j}[x(t),\vartheta(t-\tau^*)],$$

N_R - number of elements in R.

The submultiplicity which is met by $\min H^*_{x|\vartheta'}(R)$, includes the estimations of the discrete moments of the pilot actions which must be obtained.

The studies of the pitch angle stabilization carried out by this method permit to show, that the pilot actions are discrete and the time intervals Δt between them are distributed according to the exponential law $\lambda e^{-\lambda\Delta t}$ (fig. 5). Its exponent λ depends only on σ_{ϑ}, which is the root-mean-square value of the pitch angle derivation, so that, on the average, the same value of σ_{ϑ} meets all values of the aircraft characteristics and flight conditions for which the same value of λ

is realized in the handling process.[fig 6] Similarly, the lag depends only on σ_ϑ (fig.7), These two relations are correlated, so that the decrease of σ_ϑ from a certain value of σ_ϑ^0 results in the appearence of the nonzero lag, its increase and increase of λ .

Using these relations and the criterium $\sigma_\vartheta < \sigma_\vartheta^0$ (or respectively, $\tau > 0$, $\lambda > \lambda_{min}$) the region of the reasonable values of damping $1/T_\alpha$ and sensitivity is constructed for an aircraft which is nonstatic in the pitch angle (fig. 8). The limits of this region are found to approach those obtained from the pilot rating and the linear model.

Therefore, the region of adaptability is defined by the inequality $\sigma_\vartheta < \sigma_\vartheta^0$. Then $\tau(\sigma_\vartheta)$ and $\lambda(\sigma_\vartheta)$ show that the adaptability becomes limited when, on the one hand, the control process does not give to the pilot a certain reserve of time ($\tau = 0$), and, on the other, when the pilot is obliged to use more often the limiting intervals between the actions.

Similar phenomena occur when the pitch angle is stabilized.

3. The effect of the dynamic design on the crew comfort

The external disturbances, vibrations, turbulent reversal loads which arise in the automatic system operation, and etc., all may result in the pilot exhaustion, the need of paying uncreasing attention to the aircraft control, and finally, in the decrease of the control accuracy.

The pilot rating of the handling conditions, or, in other words, the crew comfort depends on a number of factors which include the dynamic characteristics of the aircraft. However, the analysis shows that the estimate of the crew comfort by the root-mean-square value of the acceleration due to wind σ_{n_y} may result in errors, as in this case the spectrum of the disturbances is not accounted for.

To obtain more accurate estimate of the effect of the dynamic design on the crew comfort, it is necessary to define the variations of the tolerable accelerations with their amplitude and frequency. These curves have been obtained as a result of the special studies on the movable test rigs (the frequency range $>$ 1 cps) and in flight (the frequence range $<$ 1 cps) with data reduction by statistical methods.

The curve presented in fig. 9 is characterized by a number of minima of the acceleration amplitudes as a function of the frequency of loading actions. The first minimum (the frequency range 0,2 - 0,4 cps) corresponds to the critical conditions at which a man feels sickness. At the second minimum (the frequency range 4 - 5 cps) the resonance of internals occurs. At these frequences the maximum amplitude between the upper and lower part of the body is observed. The limitation of the amplitude at high frequences makes the sight and ear less keen. The example considered below permits to estimate the importance of accounting for this relationship in determining the effect of the aircraft dynamic characteristics on the crew comfort. When the handling conditions are defined by the root-mean-square value of the wind acceleration, the turbulence is considered weak at $\sigma_{n_y} < 0,3$ strong at $\sigma_{n_y} = 0,2 - 0,3$ and very strong at $\sigma_{n_y} > 0,3$. The root-mean-square value of the acceleration can be presented in the following way:

$$\sigma_{n_y}^2 = \sigma_w^2 \int_0^\infty \left| W_{\frac{n_y}{w}}(i\omega) \right|^2 \cdot S_w(\omega)\, d\omega \;,$$

where $W_{\frac{n_y}{w}}(i\omega)$ - transfer function in the wind acceleration

S_w - normalized spectral density of the turbulence

σ_w - root-mean-square velocity of the vertical wind

By the help of this formula at a given value of σ_{n_y}, which characterizes one or another estimation of the turbulence, and known values $W_{\frac{n_y}{w}}(i\omega)$ and S_w, a particular value σ_{w_0} may be obtained.

As normally the law of the wind velocity distribution is known, the probability P_{n_y} ($\sigma_w \geqslant \sigma_{w_0}$) is estimated by this law and by the given value σ_{w_0}. The quantity defined in this fashion determines the probability P_{n_y} of the specified turbulence estimate. In fig. 10 the lines of equal probabilities are traced for the case $\sigma_{n_y} = 0,2$ (strong turbulence) as a function of the natural frequency ω_0 and relative damping ξ / ω_0. It is evident, that in the wide range of ω_0 and ξ / ω_0 the variation of the probability P_{n_y} is not high.

However, a completely different conclusion is made, if the turbulence is estimated not by σ_{n_y}, but by the root-mean-square value of the discomfort G_d defined as follows:

$$G_d^2 = \sigma_w^2 \int_0^\infty \left| W_{\frac{n_y}{w}}(i\omega) \right|^2 \cdot \left| W_d(\omega) \right|^2 \cdot S_w(\omega)\, d\omega$$

where $W_d(i\omega) = \frac{1}{n(\omega)}$ - frequency response of the pilot obtained by the inversion of the limiting curve in fig.11 .

The transfer function $W_d = \frac{1}{n(\omega)}$ defines the fact that the residence on the limiting curve (fig. 9), i.e. the pilot rating of the handling conditions in accordance to the curve designation, is expressed quantitatively by a number 1. The output amplitude W_d being less than unity, the acceleration is situated below the limiting curve; for $W_d > 1$, the acceleration is above it.

Similarly, the discomfort probability (the probability of the estimate corresponds to the curve in fig. 3) may be defined at a given value of σ_d (normally it is assumed $\sigma_d = \frac{1}{\sqrt{2}}$). In fig.11 the variation of P_d in the plane of the parameters ω_0 and ξ/ω_0 is illustrated. It is evident that in this case for the same ranges of ω_0 and ξ/ω_0 the probability P_d varies considerably more than P_{n_y} . Here the conclusion may be drawn that the automatic systems which change the natural frequency and the relative damping, may be used for increasing the crew comfort during the flight in the turbulent atmosphere. Howeever, fig. 10 shows that within the limits of the conception of the turbulence estimate by σ_{n_y} , this conclusion is impossible; on the contrary, it may be said that the effect of the dynamic characteristics on the estimate of the handling conditions is low. Thus, to obtain a correct idea about the possibility and efficiency of the methods of increasing the crew comfort, it is necessary to account for the curves of the subjective discomfort.

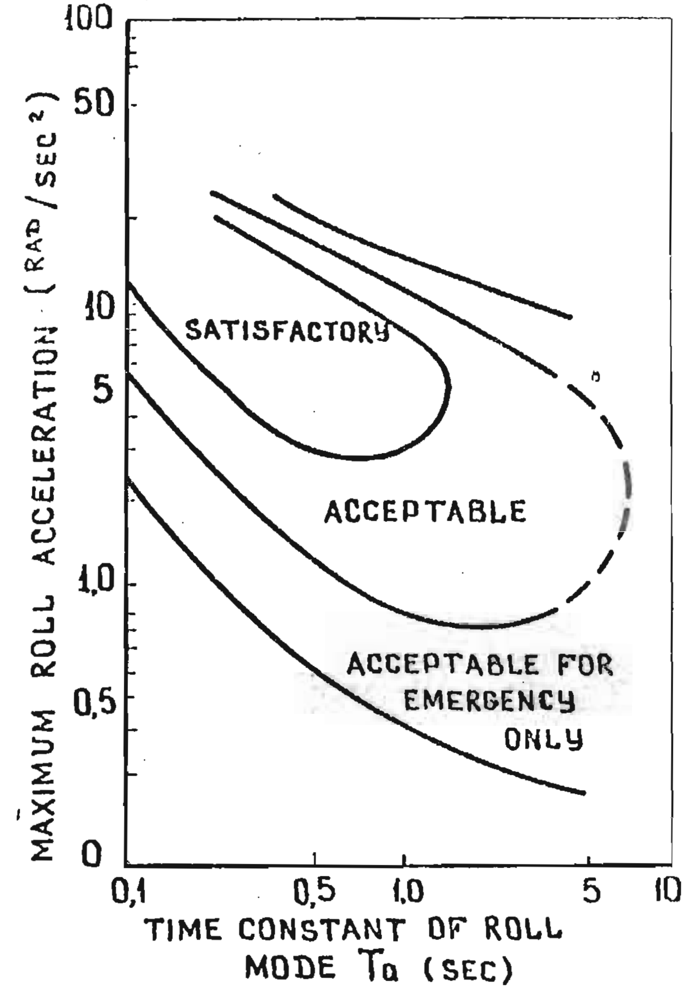
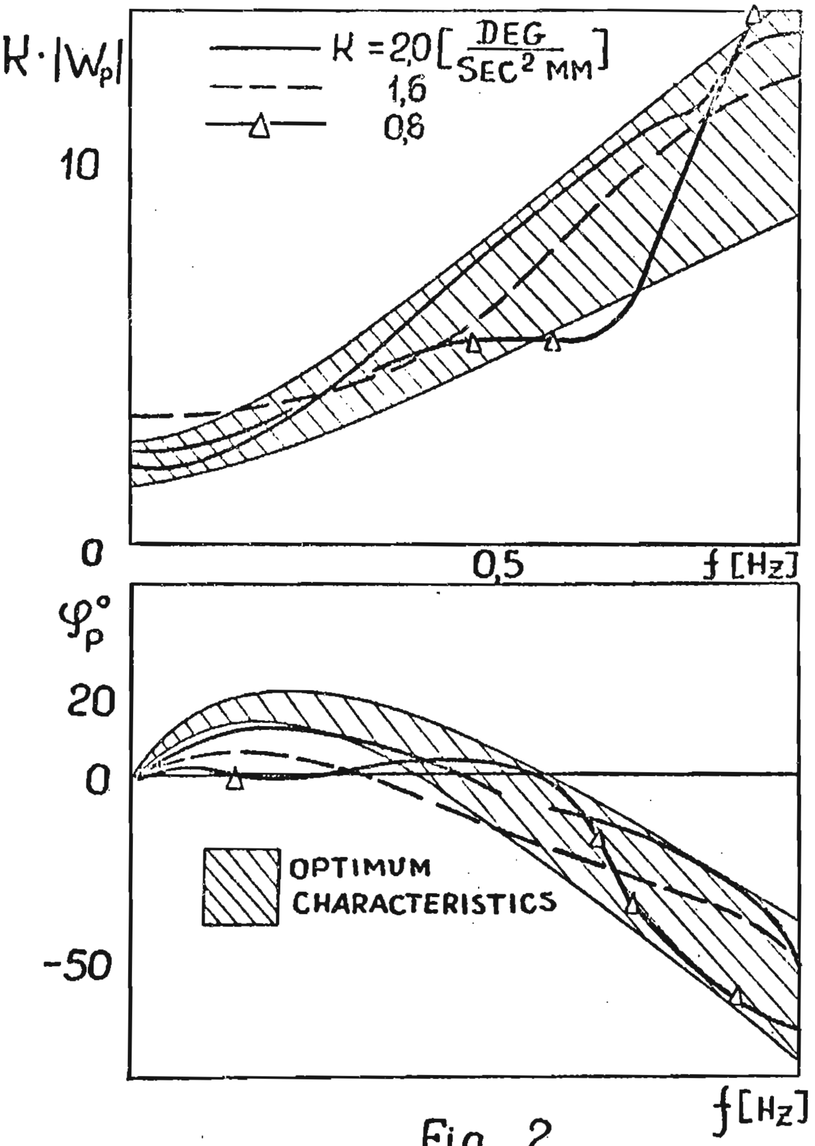

MAXIMUM ROLL ACCELERATION (RAD/SEC²)
100
50
10
5
1,0
0,5
0
0,1
0,5
1,0
5
10
TIME CONSTANT OF ROLL MODE Ta (SEC)
SATISFACTORY
ACCEPTABLE
ACCEPTABLE FOR EMERGENCY ONLY

Fig. 1



$K \cdot |W_p|$
$K = 2{,}0 \left[\frac{DEG}{SEC^2\,MM}\right]$
1,6
0,8
10
0
0,5
f [Hz]
φ_p°
20
0
-50
OPTIMUM CHARACTERISTICS
f [Hz]

Fig. 2

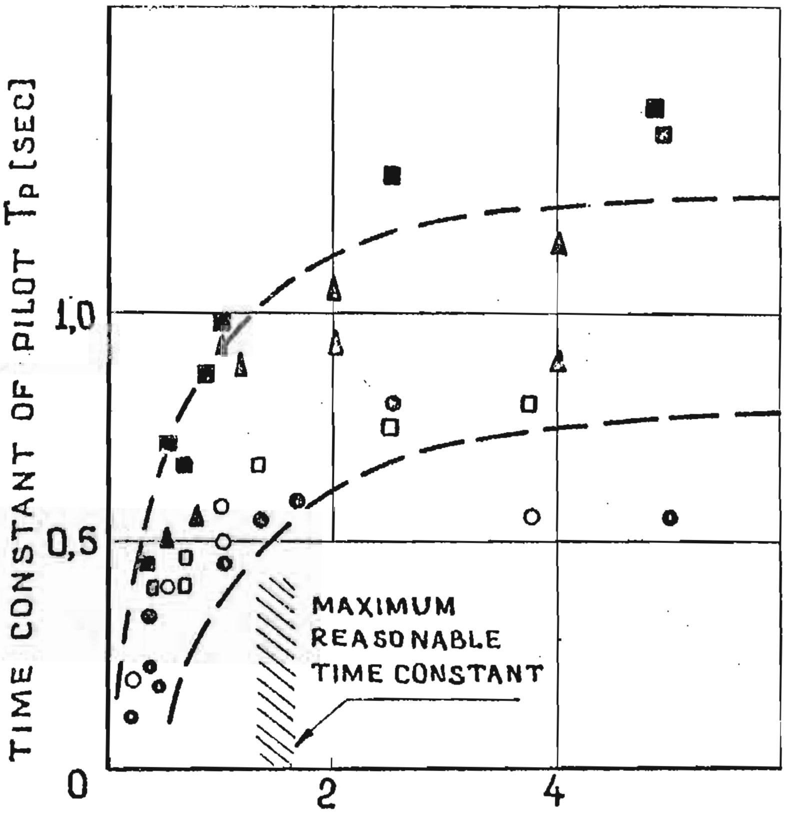

TIME CONSTANT OF PILOT T_p [SEC]
1,0
0,5
0
2
4
MAXIMUM REASONABLE TIME CONSTANT
TIME CONSTANT OF ROLL MODE T_a [SEK]

Fig. 3

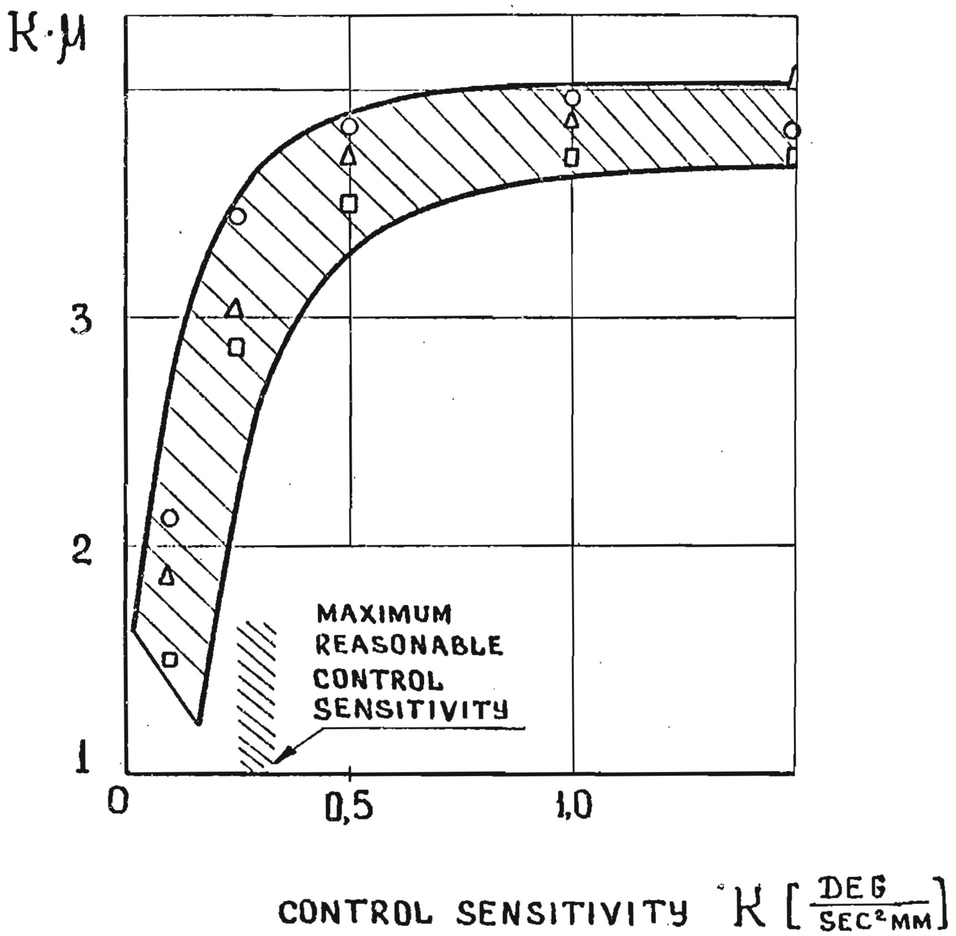

K·μ
3
2
1
0
0,5
1,0
MAXIMUM
REASONABLE
CONTROL
SENSITIVITY
CONTROL SENSITIVITY K [DEG / SEC²MM]

Fig. 4

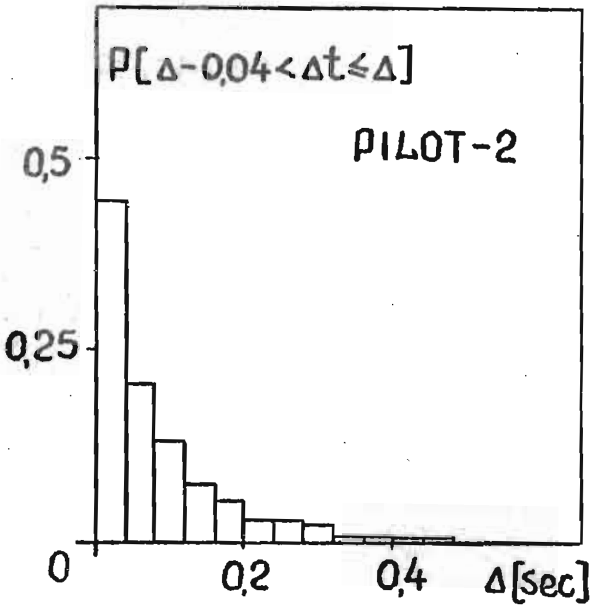


Fig. 5

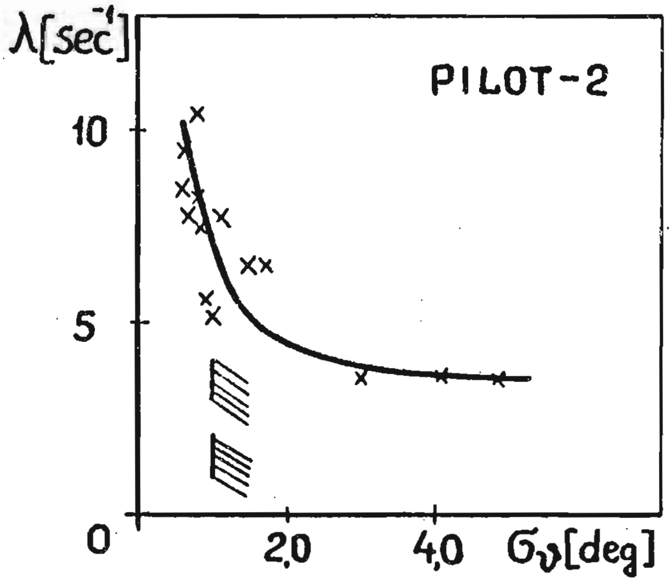


Fig. 6

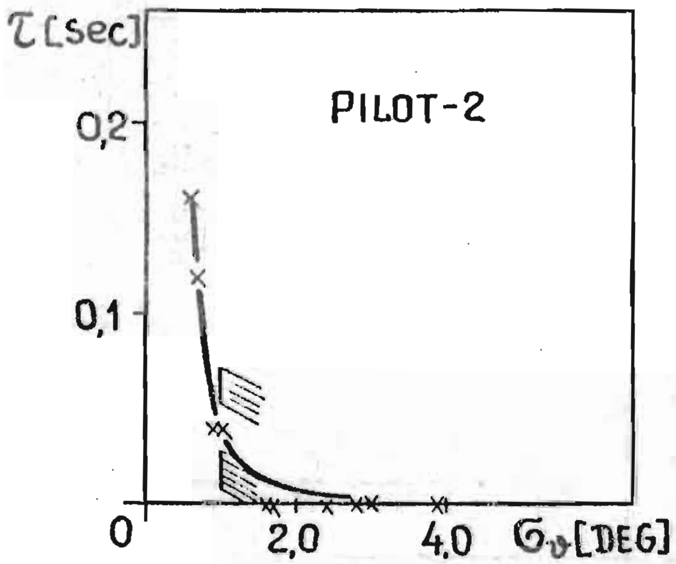
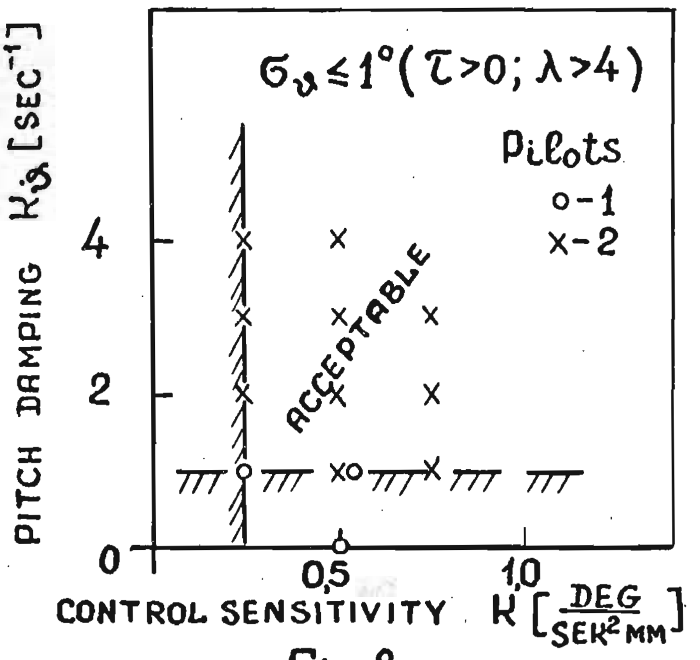


Fig. 7



$\sigma_\vartheta \leq 1^\circ (\tau > 0; \lambda > 4)$
Pilots
o - 1
x - 2
ACCEPTABLE
PITCH DAMPING $K_{\dot{\vartheta}}$ [SEC^{-1}]
4
2
0
0,5
1,0
CONTROL SENSITIVITY K $\left[\frac{DEG}{SEK^2 MM}\right]$

Fig. 8

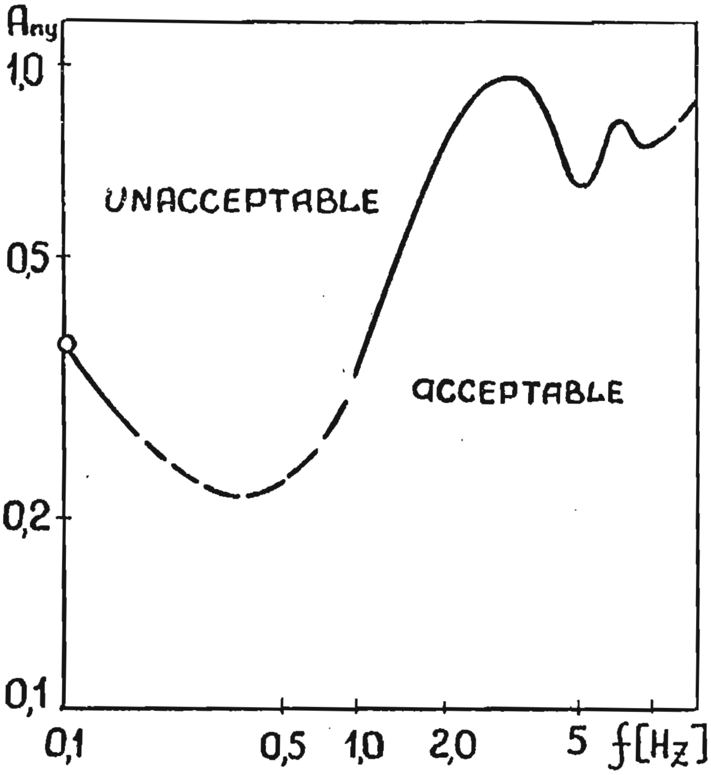


Fig. 9

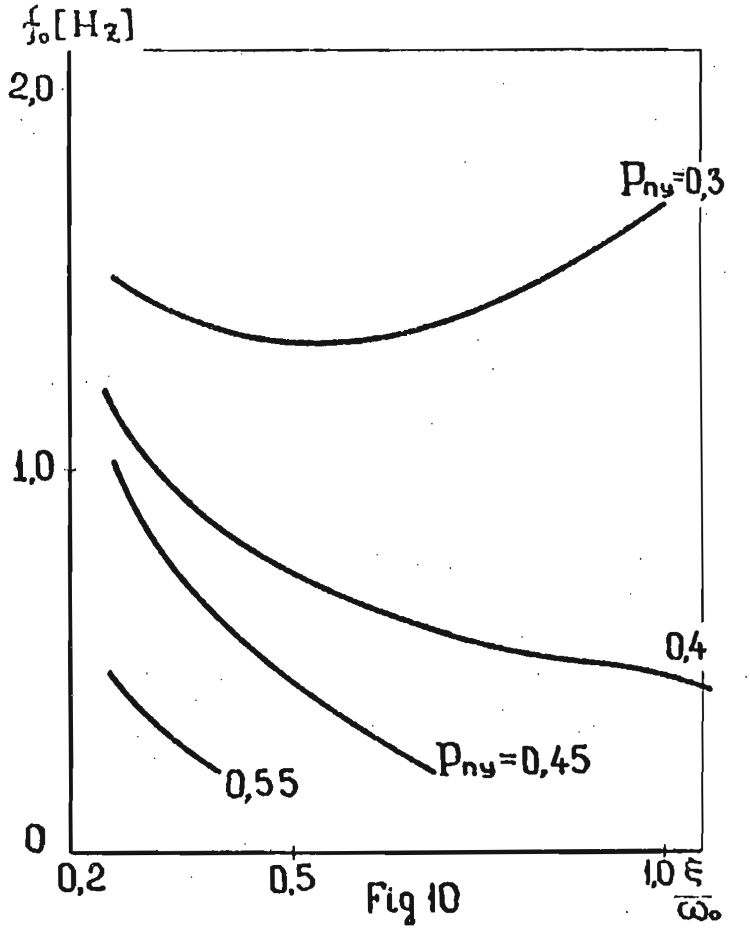


Fig 10

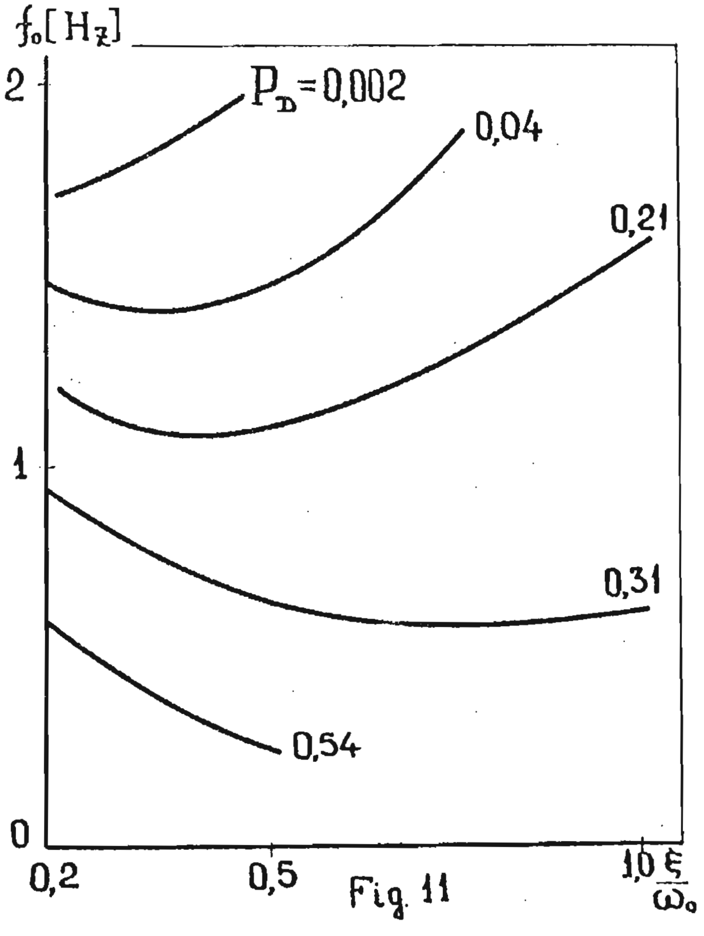


Fig. 11