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FLIGHT INVESTIGATIONS IN THE FIELD HELICOPTER MOTION UNDER VARIABLE EXTERNAL MOUNT EFFECTS

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Abstract

Various application tasks require installation of specialized rotating external mounts on helicopters that result in periodically changing aerodynamic forces and moments affecting the aircraft (ref. fig.1). In this connection investigations in the field of helicopter flight dynamics, stability and controllability become very important.

The helicopter flight dynamics under an effect of periodically changing external aerodynamic forces and moments has not yet been well treated in literature. The most closely related with problem is that of helicopter dynamics with an underslung cargo. As a rule, external cargo hooking systems are so designed that no considerable disturbing moments can be created on the helicopter at oscillations. In this case only periodically changing by value and direction external mass and inertia forces are transmitted to the helicopter.

The paper presents the results of investigations undertaken jointly by Kamov Company and LEE in the field of mathematical modeling and in-flight imitation on a flying test-bed of the helicopter flight dynamics under an effect of periodically changing forces and moments. The test flight results with external mounts installed are also presented.

1 Evaluation of the helicopter motion dynamics under the influence of periodically changing external effects

A mathematical model representing coaxial helicopter dynamics was used in this evaluation. The model included the following nonlinear dependencies: motion equation coefficients versus flying speed; main rotor thrust and torque versus its speed; gravity projections to coordinate axes. Limitations of engine power, main rotor lifting ability, available control travels and hydraulic control actuator rod displacement rates were also included.

Static and rotational derivatives of the forces/moments coefficients were defined by computational techniques developed for a coaxial design and the airframe aerodynamic characteristics definition was based on the results of wind tunnel tests of a helicopter model without main rotor at a quasy steady mode of rotating external mount operation. The following system of equations describing the helicopter motion in the right handed coordinate system was obtained with consideration of the above force/moment coefficient variation peculiarities and respective restrictions:

$$dV_x / dt = V_y * \omega_z + V_z * \omega_y + \Delta\overline{X}^* -$$
$$-g * \left[\sin(\vartheta - \varphi_c) - \sin(\vartheta_0 - \varphi_c)\right] + \Delta X/m \ ;$$

$$dV_y / dt = -V_x * \omega_z + V_z * \omega_x + \Delta\overline{Y}^* -$$
$$-g * \left[\cos(\vartheta - \varphi_c) * \cos\gamma - \cos(\vartheta_0 - \varphi_c)\right] + \Delta Y/m \ ;$$

$$d\omega_z / dt = \Delta\overline{M}_z^* + \Delta M_z/J_z \ ;$$

$$d\vartheta / dt = \omega_z * \cos\gamma + \omega_y * \sin\gamma \ ;$$

$$dH / dt = V_x * \sin(\vartheta - \varphi_c) + V_y * \cos(\vartheta - \varphi_c) * \cos\gamma -$$
$$- V_z * \cos(\vartheta - \varphi_c) * \sin\gamma \ ;$$

$$d\omega / dt = (\Delta M_{keng} - \Delta\overline{M}_k^* * J_p) \ / \ J_p \ ;$$

$$d\Delta M_{keng} / dt = (-k_\omega * \Delta\omega - \Delta M_{keng}) \ / \ T_{eng} \ ;$$

$$d\Delta V_z / dt = - V_y * \omega_x + V_x * \omega_y + \Delta\overline{Z}^* +$$
$$+ g * \cos(\vartheta - \varphi_c) * \sin\gamma + \Delta Z / m \ ;$$

$$d\omega_x / dt = \Delta\overline{M}_x^* + \Delta M_x / J_x \ ;$$

$$d\omega_y / dt = \Delta\overline{M}_y^* + \Delta M_y / J_y \ ;$$

$$d\gamma /dt = \omega_x - (\omega_y * \cos\gamma - \omega_z * \sin\gamma) * tg(\vartheta - \varphi_c) \ ;$$

$$d\Psi /dt = (\omega_y * \cos\gamma - \omega_z * \sin\gamma) / \cos(\vartheta - \varphi_c) \ ;$$

$$dX_g / dt = V_x * \cos\left(\vartheta - \varphi_c\right) * \cos\psi - V_y * [\sin\psi * \\ * \sin\gamma - \sin\left(\vartheta - \varphi_c\right) * \cos\gamma * \cos\psi] + \\ + V_z * [\sin\left(\vartheta - \varphi_c\right) * \cos\psi * \sin\gamma + \\ + \sin\psi * \cos\gamma] \ ;$$

$$dZ_g / dt = -V_x * \cos\left(\vartheta - \varphi_c\right) * \sin\psi + V_y * [\cos\psi * \\ * \sin\gamma - \sin\left(\vartheta - \varphi_c\right) * \sin\psi * \cos\gamma] + \\ + V_z * [\cos\psi * \cos\gamma - \sin\left(\vartheta - \varphi_c\right) * \\ * \sin\psi * \sin\gamma] \ ;$$

$\overline{X}^* \ldots\ldots\ldots \overline{M}_y^*$ - ref. table 1

The results of helicopter model wind tunnel tests were used to define the vector of periodically changing external effects. Fig.1 illustrates time variations of aerodynamic forces/moments coefficients versus attack and slip angles.

The external effect vector components look as follows:

$$\Delta X = \Delta * V^2 * S_m * \Delta C_x(\alpha) / 16;$$

$$\Delta Y = \Delta * V^2 * S_m * \Delta C_y(\alpha) / 16;$$

$$\Delta M_x = \Delta * V^2 * S_m * L_f * \Delta m_x(\alpha, \beta) / 16;$$

$$\Delta M_y = \Delta * V^2 * S_m * L_f * \Delta m_y(\alpha, \beta) / 16;$$

$$\Delta M_z = \Delta * V^2 * S_m * L_f * \Delta m_z(\alpha) / 16,$$

where $\Delta C_x(\alpha) = C_x(\alpha) - C_{x_{av}}$;

$C_{x_{av}}$ - average value of C_x.

Fig. 2 illustrates the changes of forces/moments affecting the helicopter in flight at a certain speed with the external mount rotating.

As may be seen from the materials presented the presence of an external rotating mount raises a demand for changing the helicopter longitudinal balance due to the fact that the aerodynamic forces and moments contain constant components $X_{av} \ldots\ldots\ldots Mz_{av}$ (fig.2) (average values of $\Delta X \ldots\ldots\ldots \Delta Mz$). The forces/moments variable components cause periodic changes of the helicopter motion parameters.

Calculations show that the control travels required to change the balancing are insignificant so the main attention in the course of investigations was paid to evaluation of a variable components influence upon the helicopter motion dynamics.

Free and controlled helicopter motions are modeled both with the autopilot off and with the autopilot stabilizing roll, pitch and heading angles.

The autopilot operation equations for aircraft attitude stabilization conditions look as follows:

$$d\delta_z / dt = \left(I_\vartheta \Delta\vartheta + I_{\omega_z} \omega_z - \Delta\delta_z \right) / T_{ap};$$

$$d\delta_x / dt = \left(I_\gamma \Delta\gamma + I_{\omega_x} \omega_x - \Delta\delta_x \right) / T_{ap};$$

$$d\delta_y / dt = \left(I_\psi \Delta\psi + I_{\omega y} \omega_y - \Delta\delta_y \right) / T_{ap};$$

where T_{ap} - autopilot time constant.

The results of the study are presented in the form of dependencies of two types, i.e. helicopter attitude versus time (fig.3) and roll/pitch/heading angle oscillation amplitudes versus flying speed (fig.4).

The presented materials demonstrate that availability of an automatic attitude stabilization function considerably reduces the oscillation amplitude however it still remains considerable and may cause the crew fatigue.

With the aim of reducing the helicopter angular oscillation amplitude it is proposed to introduce into the autopilot law certain corrective signals the change of which is nearing the external effect character.

table 1

$$\begin{vmatrix} \Delta\bar{X}^* \\ \Delta\bar{Y}^* \\ \Delta\bar{M}_z^* \\ \Delta\bar{M}_k^* \\ \Delta\bar{Z}^* \\ \Delta\bar{M}_x^* \\ \Delta\bar{M}_y^* \end{vmatrix} = \begin{vmatrix} \bar{X}^{V_x} & \bar{X}^{V_y} & \bar{X}^{\omega_z} & \bar{X}^{\omega} & \bar{X}^{V_z} & \bar{X}^{\omega_x} & \bar{X}^{\omega_y} & \bar{X}^{\delta_z} & \bar{X}^{\varphi} & \bar{X}^{\delta_x} & \bar{X}^{\delta_y} \\ \bar{Y}^{V_x} & \bar{Y}^{V_y} & \bar{Y}^{\omega_z} & \bar{Y}^{\omega} & \bar{Y}^{V_z} & \bar{Y}^{\omega_x} & \bar{Y}^{\omega_y} & \bar{Y}^{\delta_z} & \bar{Y}^{\varphi} & \bar{Y}^{\delta_x} & \bar{Y}^{\delta_y} \\ \bar{M}_z^{V_x} & \bar{M}_z^{V_y} & \bar{M}_z^{\omega_z} & \bar{M}_z^{\omega} & \bar{M}_z^{V_z} & \bar{M}_z^{\omega_x} & \bar{M}_z^{\omega_y} & \bar{M}_z^{\delta_z} & \bar{M}_z^{\varphi} & \bar{M}_z^{\delta_x} & \bar{M}_z^{\delta_y} \\ \bar{M}_k^{V_x} & \bar{M}_k^{V_y} & \bar{M}_k^{\omega_z} & \bar{M}_k^{\omega} & \bar{M}_k^{V_z} & \bar{M}_k^{\omega_x} & \bar{M}_k^{\omega_y} & \bar{M}_k^{\delta_z} & \bar{M}_k^{\varphi} & \bar{M}_k^{\delta_x} & \bar{M}_k^{\delta_y} \\ \bar{Z}^{V_x} & \bar{Z}^{V_y} & \bar{Z}^{\omega_z} & \bar{Z}^{\omega} & \bar{Z}^{V_z} & \bar{Z}^{\omega_x} & \bar{Z}^{\omega_y} & \bar{Z}^{\delta_z} & \bar{Z}^{\varphi} & \bar{Z}^{\delta_x} & \bar{Z}^{\delta_y} \\ \bar{M}_x^{V_x} & \bar{M}_x^{V_y} & \bar{M}_x^{\omega_z} & \bar{M}_x^{\omega} & \bar{M}_x^{V_z} & \bar{M}_x^{\omega_x} & \bar{M}_x^{\omega_y} & \bar{M}_x^{\delta_z} & \bar{M}_x^{\varphi} & \bar{M}_x^{\delta_x} & \bar{M}_x^{\delta_y} \\ \bar{M}_y^{V_x} & \bar{M}_y^{V_y} & \bar{M}_y^{\omega_z} & \bar{M}_y^{\omega} & \bar{M}_y^{V_z} & \bar{M}_y^{\omega_x} & \bar{M}_y^{\omega_y} & \bar{M}_y^{\delta_z} & \bar{M}_y^{\varphi} & \bar{M}_y^{\delta_x} & \bar{M}_y^{\delta_y} \end{vmatrix} * \begin{vmatrix} \Delta V_x \\ \Delta V_y \\ \omega_z \\ \omega \\ V_z \\ \omega_x \\ \omega_y \\ \Delta\delta_z \\ \Delta\varphi \\ \Delta\delta_x \\ \Delta\delta_y \end{vmatrix}$$

2 In-flight modeling techniques for the controlled helicopter motion dynamics

In order to increase the safety of any helicopter flight tests with a rotating external mount and to evaluate its controllability and piloting peculiarities it is desirable to perform special tests that envisage in-flight modeling of a helicopter controlled motion in the presence of external disturbance effects. The modeling technique for the above on the flying test-bed is as follows.

With those aerodynamic characteristics of an external mount that can be actually obtained, the helicopter linear accelerations under the rotating external mount forces effect are moderate so the helicopter speed longitudinal and lateral components do not change much.

However, as shown by the mathematical modeling results the helicopter angular oscillations may be rather considerable and the pilot would naturally try to compensate for them. So to evaluate the dynamics, controllability and piloting techniques peculiarities of a helicopter with an external mount it is just enough to model moments acting along three axes in a test-bed flight. The forces created here on the main rotor may be neglected since the evaluation results prove their role to be insignificant.

The modeling may be done on a helicopter with an autopilot connected differentially. For that purpose signals creating variable moments equal to those caused by an external mount should be issued to the autopilot along three control channels. From the equilibrium condition of the moments created by a external mount and corresponding control it is possible to find the values of control surface deflection i.e. longitudinal and lateral deflections values of the swashplate and a rotor differential pitch value for a coaxial helicopter (or a tail rotor pitch value for a single rotor helicopter):

$$\Delta\delta_z^{dis} = \frac{\Delta M_z(t)}{\bar{M}_z^{\delta_z}} I_z \qquad \Delta\delta_x^{dis} = \frac{\Delta M_x(t)}{\bar{M}_x^{\delta_x}} I_x$$

$$\Delta\delta_y^{dis} = \frac{\Delta M_y(t)}{\bar{M}^{\delta_y}} I_y \quad \left(\text{or: } \Delta\varphi_{tr}^{dis} = \frac{\Delta M_y(t)}{\bar{M}_y^{\varphi_{tr}}} I_y\right)$$

where: $\Delta M_Z(t)$, $\Delta M_X(t)$, $\Delta M_Y(t)$, -time variation amplitudes of the moments created by an external mount;

$\bar{M}_z^{\delta_z}, \bar{M}_x^{\delta_x}, \bar{M}_y^{\delta_y}, \bar{M}_y^{\varphi_{tr}}$ - helicopter control system efficiency ratios for a corresponding channel;

I_x, I_y, I_z - helicopter inertial moments in respect to coupled **XYZ** axes.

In this case the autopilot operation equations take the following look:

$$d\delta_z / dt = \left(I_\vartheta \Delta\vartheta + I_{\omega_z} \omega_z - \Delta\delta_z + \Delta\delta_z^{dis} \right) / T_{ap};$$

$$d\delta_x / dt = \left(I_\gamma \Delta\gamma + I_{\omega_x} \omega_x - \Delta\delta_x + \Delta\delta_x^{dis} \right) / T_{ap};$$

$$d\delta_y / dt = \left(I_\psi \Delta\psi + I_{\omega y} \omega_y - \Delta\delta_y + \Delta\delta_y^{dis} \right) / T_{ap};$$

The competence of the described imitation method is illustrated at fig. 5 presenting the values of the helicopter attitude change in flight at a specified speed under the influence of external forces and moments while creating these moments by deflecting the rotor resultant at various values of the autopilot actuator rod displacement (50%, 100% of the total stroke available).

The control travels most closely approaching the real effect of the rotating external mount have been deffined through comparision of these values with the flight test results.

The longitudinal control channel functional diagram in the presence of such external effect imitation system is shown at fig. 6. The imitation system is similarily built for the lateral and heading channels.

The imitation system includes a measuring tape recording equipment and a computer. The recording equipement is used for a simultaneous onboard reproduction of not less than three signals recorded earlier on a magnetic tape in the course of preparation for tests. The application of a tape recorder permits to perform investigations using not only harmonic signals but also signals of an arbitrary form or phase, for example signals that are proporional to the values of the moments created by the rotating external mount (ref. figs. 1,2).

The computer ensures the in-flight control over the imitation system and amplification of the signals, reproduced by the tape recorder, up to the required level. Adjustment of the imitation signal amplitudes envisaged in the computer permits to gradually, from mode to mode, amplify the signals issued to the autopilot pitch, roll and heading channels and, consequently, to increase the moments affecting the aircraft.

3 Flight investigations

The above discribed techniques were applied to model the angular motion dynamics of a helicopter with a rotating external mount in flight. The main purpose of those investigations was a pilot evaluation of peculiar piloting techniques and helicopter controllability with the autopilot on and off. Besides, angular motion stabilization effectiveness was evaluated with an autopilot on, and the main rotor system and control system loadings were evaluated while imitating oscillations by an actuator rod displacement.

The calculations show that to obtain disturbing variable moments ΔM_X, ΔM_Y, ΔM_Z, it is required to ensure oscillations of a definite actuator rod amplitude in roll, pitch and heading channels. The flight tests were performed at various signal amplitudes at the computer output (ref. fig.6) when disturbing moments changed from 50% to 170 % of their nominal values.

The flight tests envisaged flying conditions most typical for the aircraft with a rotating external mount i.e. horizontal flight at various instrumental speeds ranging from 50 to 120 km/h and coordinated turns at a specified speed at roll angles up to 15°. The helicopter was piloted by several pilotes during the tests.

Peculiarities of piloting techniques and helicopter controllability with the autopilot on and off.

To evaluate the helicopter piloting and controllability, disturbing moments were excited in three channels, i.e. roll, pitch and heading. The autopilot gain values were very near to those adjusted by the manufacturer. The pilot aimed at maintaining the specified flying conditions and counteracting the arising helicopter oscillations.

Average angle oscillation amplitudes and control travels depended rather little upon the flying conditions and increased considerably when the exitation level increased.

In case of an autopilot failure imitation the helicopter pitch and especially roll angle oscillations increased quickly and so after 5-6 seconds the pilot was compelled to intervene.

The results obtained when modeling in flight the helicopter motion under the influence of disturbing moments (fig.7) correlate well with the analytical results illustrated at figs.3 and 4.

According to the test pilot evaluations the helicopter piloting under the disturbing moments effect with the autopilot on and off is possible both visually and instrumentally that is also confirmed by the character of the controls motion and the helicopter attitude change. However, with the autopilot off and especially in case of its failure the load upon the pilot increases considerably. So the pilots think that duration of flight when the modeled disturbing moments really affect the helicopter must be limited.

Considerable decrease of the pilot load and improvement of the aircraft stabilization quality in flight with a rotating external mount may be achieved by application of an additional loop in the helicopter stabilization automatic system where, as mentioned above, it is required to generate a program signals connected with the azimuthal position of the mount in respect to the helicopter.

Results of flight tests with a real external mount installed

The values of corrective signals to reduce the angular oscillation amplitudes are based on the test-bed flight results while imitating the moments caused by external rotating mount and the results of mathematical modeling. The character of those corrective signals is near to the character of the effects that in case of an external rotating mount have a harmonic form, i.e:

$$d\delta_z / dt = (I_\vartheta * \Delta\vartheta + I_{\omega_z} * \omega_z - \Delta\delta_z + \\ + \Delta\delta_{z_o} * \sin(2\omega_{ex} t + \psi_1)) / T_{ap};$$

$$d\delta_x / dt = (I_\gamma * \Delta\gamma + I_{\omega_x} * \omega_x - \Delta\delta_x + \\ + \Delta\delta_{x_o} * \sin(2\omega_{ex} t + \psi_2)) / T_{ap};$$

$$d\delta_y / dt = (I_\psi * \Delta\psi + I_{\omega y} * \omega_y - \Delta\delta_y + \\ + \Delta\delta_{y_o} * \sin(2\omega_{ex} t + \psi_3)) / T_{ap};$$

where: ω_{ex} - external exciting mount speed;

ψ_1, ψ_2, ψ_3 - signal phase shifts required to compensate for the control system phase lag;

$\Delta\delta_{z_0}, \Delta\delta_{x_0}, \Delta\delta_{y_0}$ -corrective signal amplitudes in the corresponding autopilot channels.

Corrective signal amplitudes and phaze lead values have been specified in the process of mathematical modeling with the amplitude being the flight speed function.

As shown by the results of mathematical modeling, introduction of such harmonic signals to the corresponding autopilot channels permit, at a specified flying speed, to decrease the change of the helicopter attitude (in comparision to the application of a standard autopilot) to the following amplitude values (ref. fig. 8):

- up to 0.5 degree in pitch (instead of 1-2 degrees);
- up to 1.5 degree in roll (instead of 4 degrees);
- up to 1.5 degree in heading (instead of 4 degrees).

Statistical processing of the flight test results permitted to obtain the mean square values of pitch, roll and heading angle deviations illustrated at fig. 9. As may be seen from the graphs shown, introduction of corrective signals considerably decreases the attitude change values of the helicopter with a rotating external mount bringing them near to those values that were typical in flight without such mount.

Conclusions

1 The technique to model the helicopter controlled motion under periodically changing external effects when flying a test-bed equipped with a differential autopilot was developed. It is shown that for real external mounts rotating in the air stream it is enough to model the helicopter angular motion in respect to the centre of mass.

2 The technique permits to increase the helicopter test flight safety when flying with an external rotating mount since it permits to evalute its controllability before starting the flight tests with a gradual increase of exciting moments.

3 Dynamics and controllability evaluations of the helicopter with an external mount were performed on the flying test-bed. When modeling exciting moments created by the external mount in the range from 50% to 170 % of their nominal values, visual and instrumental helicopter piloting with the autopilot on and in case of its failure is possible.

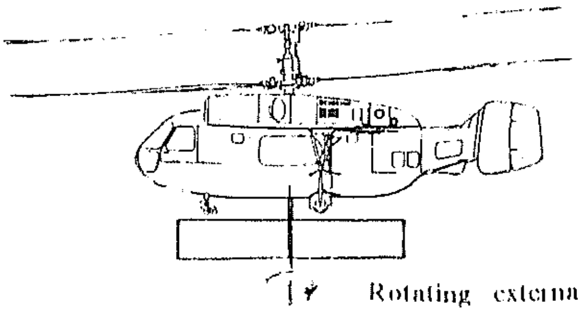
4 A long flight on a helicopter with a standard autopilot in the presence of disturbing moments increases the load upon the crew and the duration of such flight is deemed to be rather limited by the pilots. The autopilot failure should be considered a special flight case.

5 The helicopter attitude stabilization quality is improved by an introduction of corrective signals into the autopilot longitudional, lateral and heading channels the value of the signals being defined by the character of an external effect. In case of external effects caused by a rotating mount corrective signals have a harmonic nature.

6 Introduction of corrective signals into the corresponding autopilot channels permits to reduce, when flying with rotating external mount, the angular oscillation amplitudes to the level typical for the helicopter flight without any rotating mount with a standard autopilot in conditions of a moderate turbulence.

Reference:

L.N.Nikiforova, E.A.Petrosian "Compensation Techniques for Considerable Helicopter External Effects." Russian Helicopter Society Forum II, Moscow, 1996



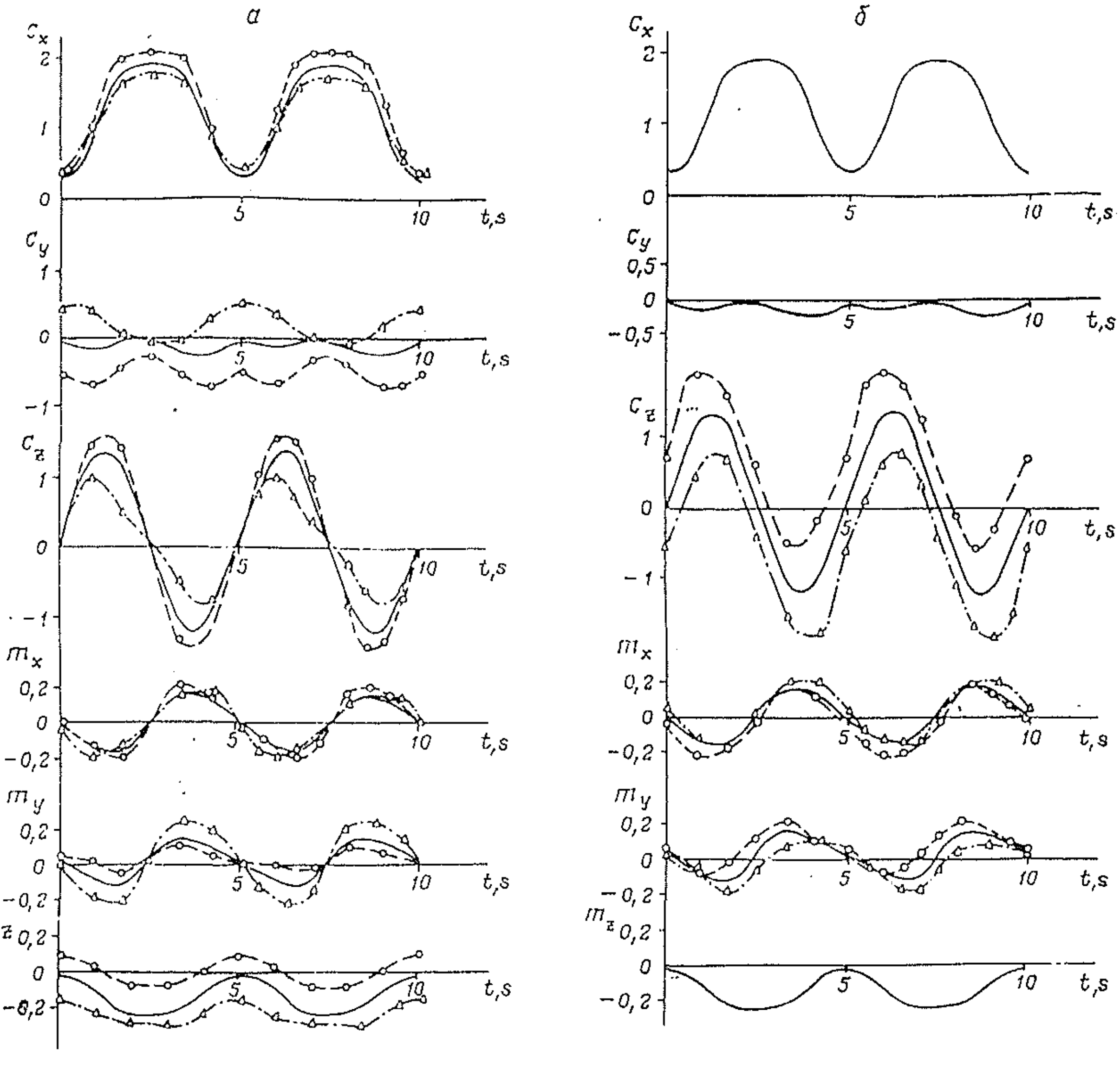


Fig.1 Time variations of force/moment coefficients for a helicopter model with an installed rotating external mount creating external disturbances at variuos angles of attack (a) and slip angles (b)

$a)$ – – – – – – $\alpha = 0$; –o–o–o– $\alpha = -10°$; –Δ–Δ–Δ– $\alpha = 10°$ } $\beta = 0$;

$б)$ – – – – – – $\beta = 0$; –o–o–o– $\beta = -5$; –Δ–Δ–Δ– $\beta = 5$ } $\alpha = 0$

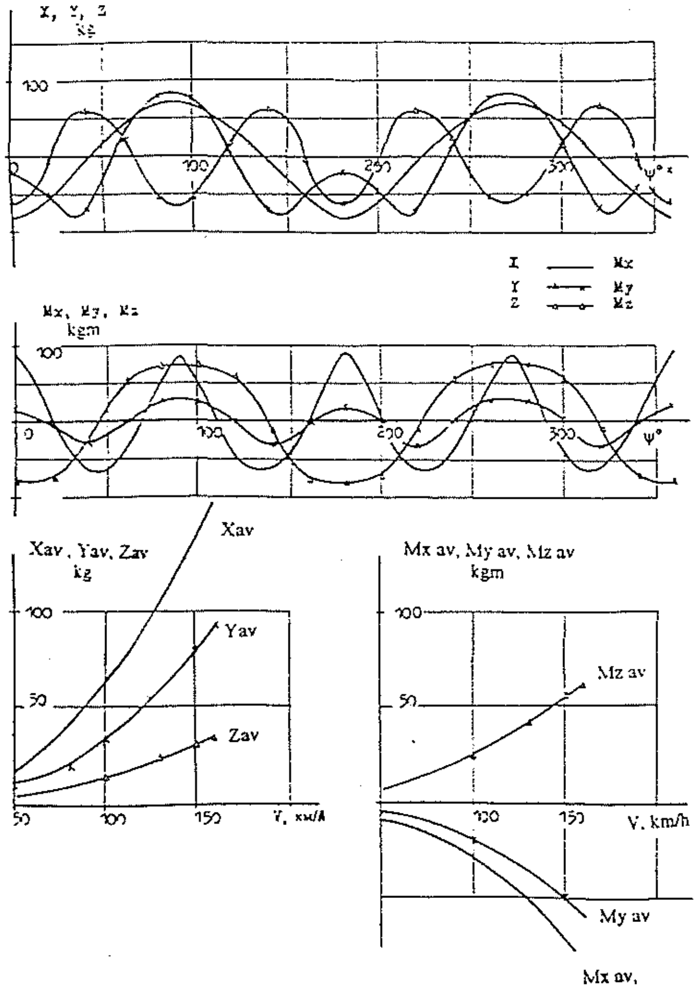


Fig.2 Forces/moments affecting the helicopter caused by external rotating mount versus flying speed

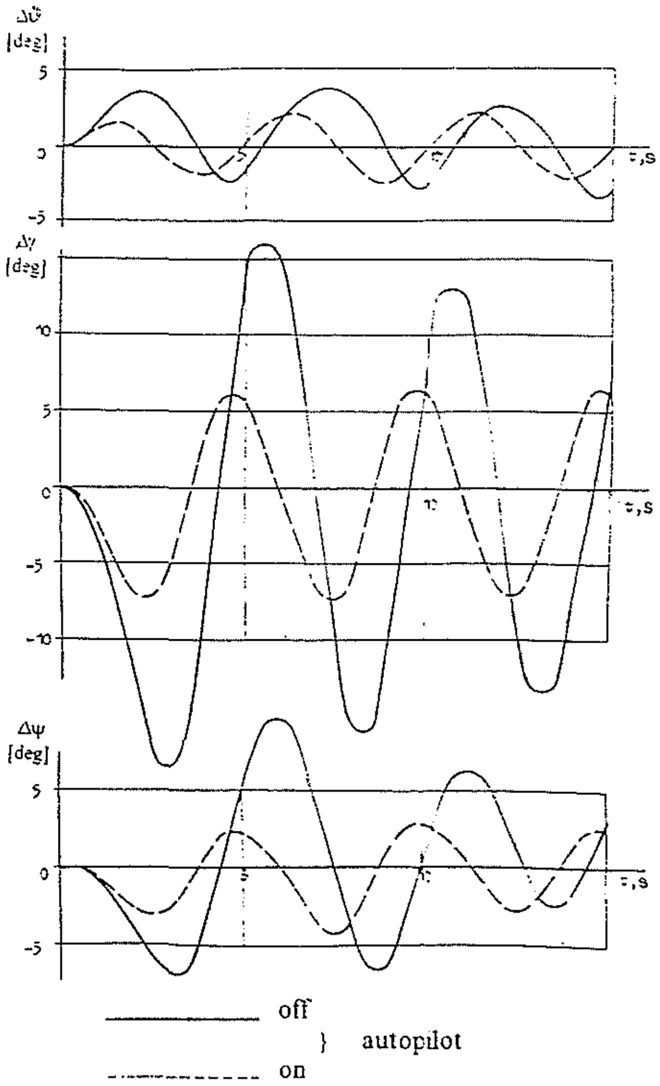


Fig.3 Time variations of helicopter attitude in the presence of an external rotating mount

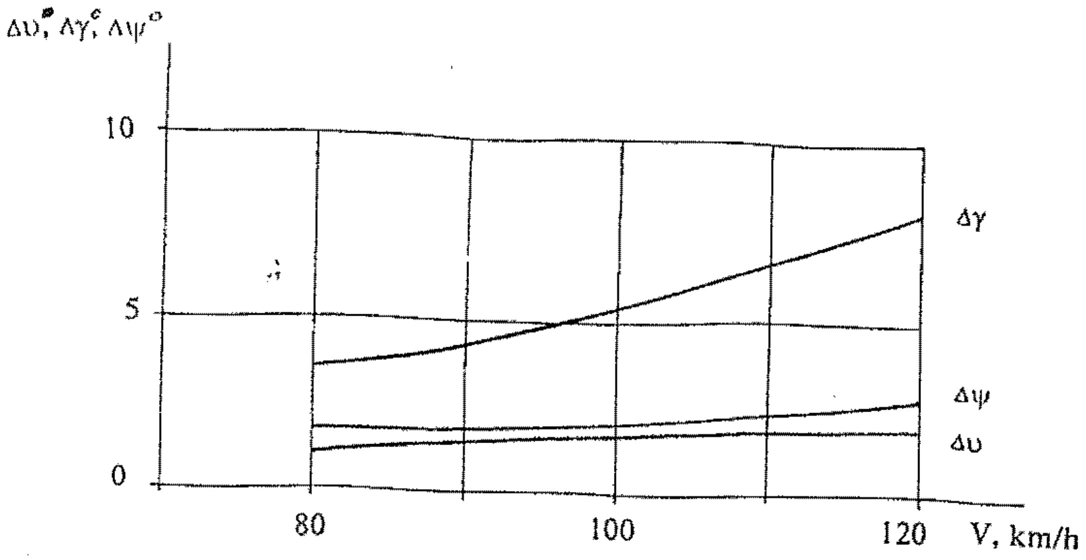


Fig.4 Helicopter attitude change amplitude values under the influence of an external rotating mount versus flying speed

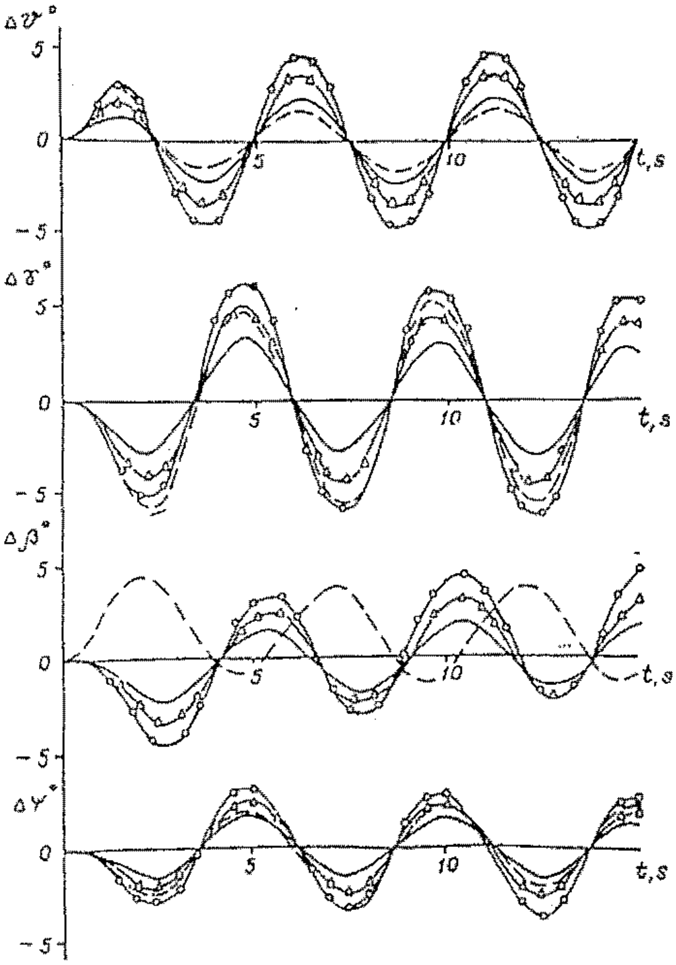


Fig.5 Helicopter motion parameters time variation under the effect of an external disturbance source while imitating this effect by creation of certain moments through a differential autopilot

- - - - external disturbance;

----------- 50 % imitation of moments by introduction of signals

-Δ-Δ-Δ- 66 % causing the corresponding motion of control actuators

-o-o-o- 100 % into the autopilot

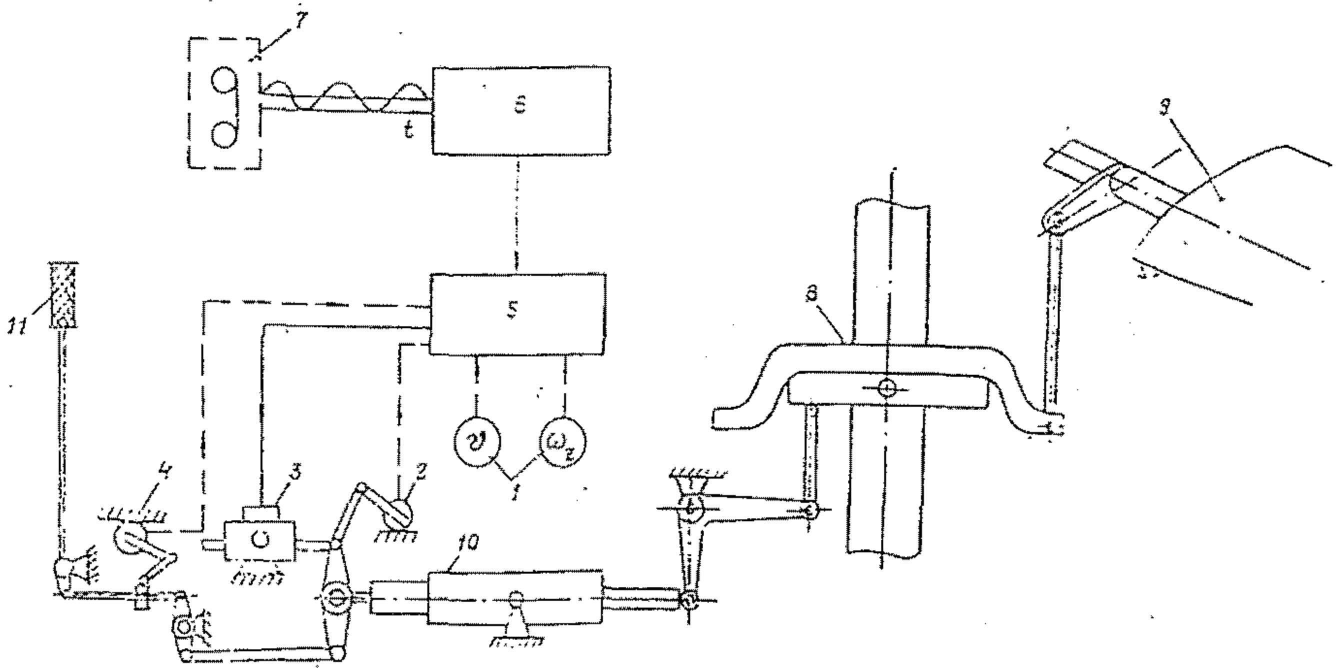


Fig.6 Signal excitation in the helicopter longitudinal control channel.
1- pitch angle and angular rate detectors; 2- feedback detector; 3- autopilot control actuator;
4- compensation detector; 5- autopilot; 6- computer; 7- tape recorder; 8- swash-plate; 9- blade;
10- hydraulic actuator; 11- cockpit control.

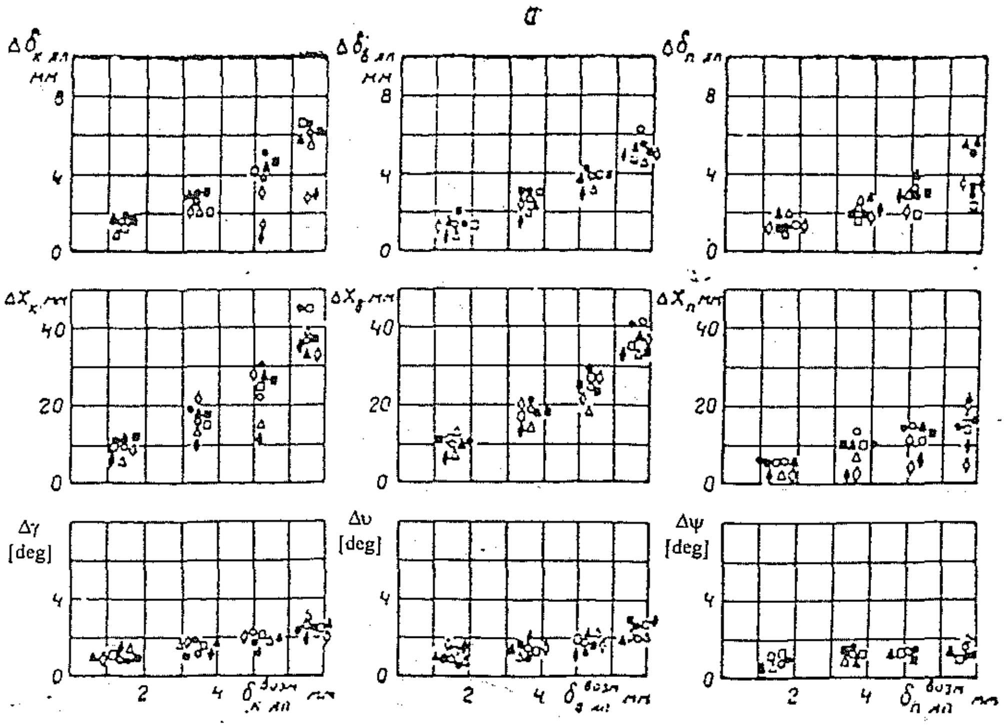


Fig.7 Semiranges of the parameters describing the helicopter oscillations under the influence of combined excitation in roll, pitch and heading channels with an autopilot as set by the manufacturer;
the pilot maintains the flying conditions and counteracts the oscillations.
V=50...100 km/h

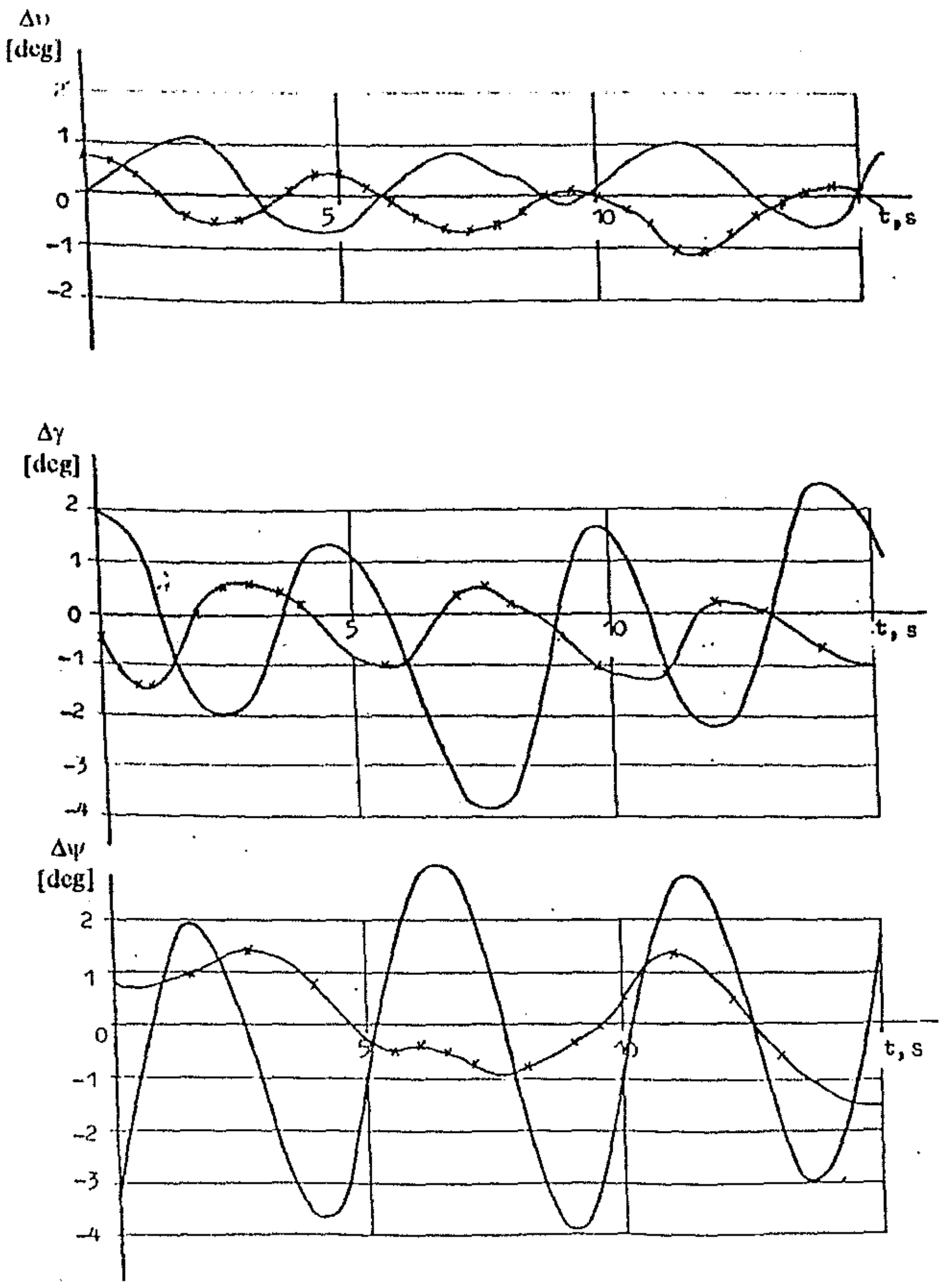


Fig.8 Influence of the corrective,signals introduction upon the helicopter attitude change under the effect of a rotating external mount

--------- standard autopilot;
-x--x--x- standard autopilot with a corrective signal

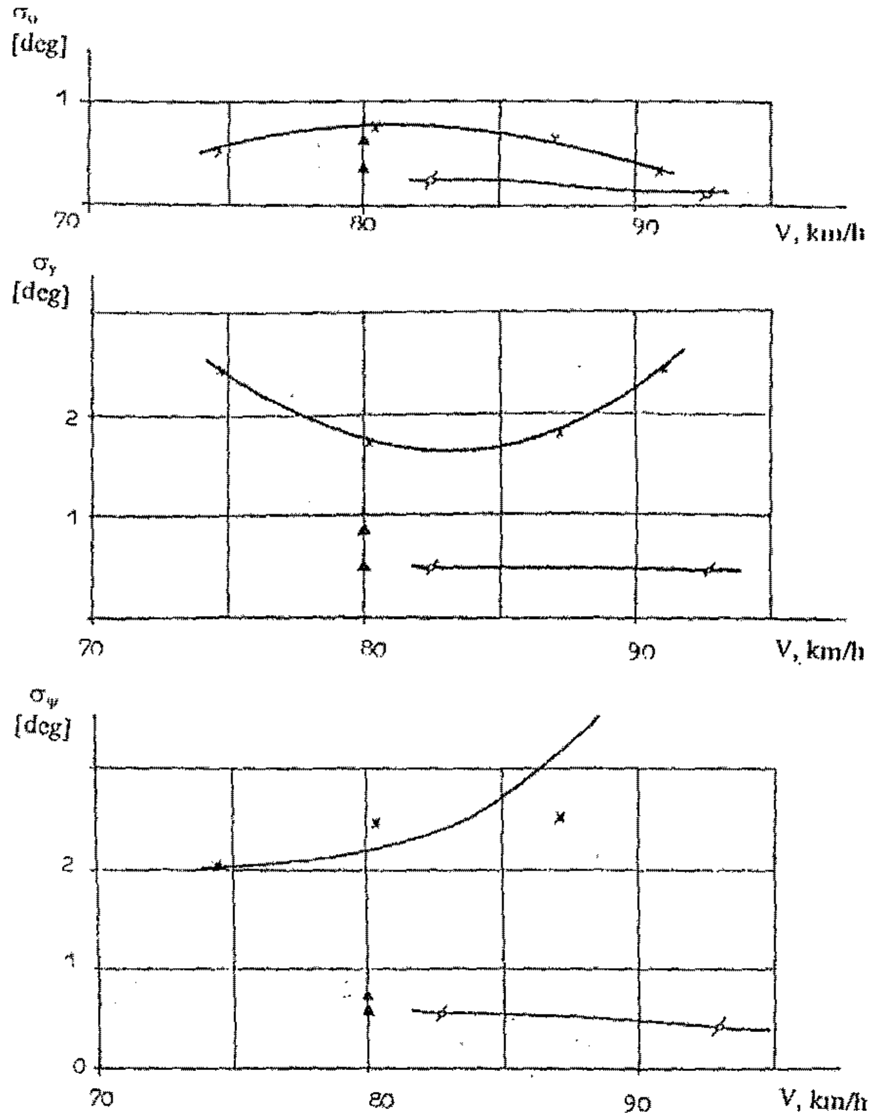


Fig.9 Mean square values of the helicopter attitude changes σ_υ for pitch; σ_γ for roll; σ_ψ for heading under the influence of a rotating mount;

⌀ ⌀ ⌀ standard autopilot (without an external mount)

× × × × standard autopilot

Δ Δ Δ standard autopilot with corrective signals

with an external rotating mount