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Dynamics of Helicopter Ground Motion

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Unsteady curvilinear motion of a helicopter on the ground is nothing similar to the motion of a car or the ground motion of a plane. Calculations carried out have allowed us to determine conditions of the helicopter running takeoff and its tipping over when making turns at taxiing.

1. Formulation of the problem

The conventional dynamics theorems were employed to solve the problem of helicopter ground unsteady curvilinear motion, yet supplemented with three ground reactions at the points where the helicopter wheels touch the runway. Such a methodic is relevant to both aircraft and vehicles ground motion analysis. However the nose landing gears of the nowadays planes prevent them from tipping over at taxiing, while only loss of the lateral stability makes vehicles tip over. It is all the way about with the helicopters as the pilot can always counteract banking in progress (which leads to tipping the helicopter over) by deflecting the swashplate.

In addition, the helicopter ground motion differs from that of the plane or the car for they apply the nose landing gears to make turns, as well as differential braking of the main landing gears and changing the engine power. The single-rotor castoring helicopter makes turns by changing the tail rotor thrust, while the helicopter with running engines suffers the torque reaction in the plane of motion.

2. Equations of motion

The helicopter motion is analysed in the c.g.-centered body axes (fig.1). The underlying surface restricts the helicopter DOF in the vertical direction, pitching-up, and rolling; so the conventional system of the motion differential equations is as follows:

$$m\dot{V}_x = T\sin\varepsilon - H - X_f - G\sin\vartheta_0 - F_u,$$

$$m\dot{V}_z = sign_1(Z_a + Z_u),$$

$$J_y\dot{\omega}_y = sign_2[M_{y_a} + (F_l - F_r)\frac{b}{2} + Z_u c]$$

$$M_{y_a} = M_e - T_{tr}L_{tr} + M_{y_f.}$$

$$Z_a = T\sin\gamma + S - T_{tr} + Z_{f,}$$

$$sign_1 = \begin{cases} 1 & \text{if} \quad |Z_a| \geq |Z_u| \\ 0 & \text{if} \quad |Z_a| < |Z_a| \end{cases},$$

$$sign_2 = \begin{cases} 1 & \text{if} \quad |M_{y_a}| \geq \left|(F_l - F_r)\dfrac{b}{2} + Z_u c\right| \\ 0 & \text{if} \quad |M_{y_a}| < \left|(F_l - F_r)\dfrac{b}{2} + Z_u c\right| \end{cases}.$$

Where

m, G, J_y - the helicopter mass, gravity and yawing moment of inertia respectively;

V_x, V_y - the forward speed components;

T, H, S - the thrust, longitudinal and lateral forces of the rotor;

T_{tr}, L_{tr} - the tail rotor thrust and the helicopter c.g. – tail rotor distance;

X_f, Z_f, M_y - the aerodynamic forces and yaw moment applied to the fuselage;

F_u, Z_u - the tangential and lateral forces of reaction applied to the landing gears;

F_l, F_r - the tangential forces applied to the left and right main landing gears respectively;

b, c - the track and distance between the landing gear axis and helicopter c.g.;

ε, ϑ_0 - the angle of the rotor axis setting and helicopter static ground angle;

γ - the helicopter angle of roll.

At a low speed of the helicopter ground motion *(V<50 km/h)* the tilt of the rotor cone, lateral force and fuselage aerodynamic moments can be well neglected:

$$\tau_H \dot{H} + H \approx TD\chi,$$
$$\tau_S \dot{S} + S \approx TD\eta.$$

Where

χ, η are the swashplate deflections in the longitudinal and lateral planes accordingly;

D is the kinematics coefficient;

τ_H, τ_S - time constants responsible for the rotor dynamic properties.

The rotor and tail rotor thrust, fuselage drag are determined by the conventional aerodynamic analysis with regard to the underlying surface being extremely close to the helicopter.

3. Forces applied to the landing gears

Normal reactions acting on the nose, left and right landing gears (P_n, P_l, P_r) we find from the moment equations obtained for all the forces applied to the landing gears at the point where the wheels touch the ground. After some obvious transformation [3] we have the following set of equations:

$$P_n = \frac{1}{a}[(G-T)c + Tx_m - M_z],$$

$$P_l = \frac{1}{2a}A - \frac{1}{b}B,\ \ P_r = \frac{1}{2a}A + \frac{1}{b}B,$$

$$A = (G-T)d - Tx_m + M_z,\quad B = M_x + 2\frac{h_m}{b}\Delta eG.$$

Where

$a = c + d$ - the wheelbase;

Δe - the main landing gears deformation difference;

x_m - the longitudinal center of gravity.

The longitudinal moment M_z and lateral one M_x the helicopter is exposed to are as follows:

$$M_z = Hy_m + m\dot{V}_x h_m$$

Where

y_m, y_{tr}, h_m - the distances between the helicopter center of gravity and the rotor plane of rotation, the tail rotor axis and ground surface accordingly;

ω_y - the helicopter yaw rate.

Having summed up all the three equations for the landing gears reactions we obtain the following:

$$P_n + P_l + P_r = G - T.$$

Thus generally in case of unsteady ground motion the sum of the landing gears normal reactions keeps constant, while the normal reactions get re-distributed among the landing gears. In particular, if $P_l = 0$ the left landing gear totally relieves the load. When $\frac{1}{2a}A - \frac{1}{b}B < 0$, the left landing gear raises off the ground and the helicopter banks forward and to the right about the *q-q* axis (which is the tipping over axis, refer to fig. 1), $P_l = 0$ till the mentioned condition is valid.

The tangential and lateral forces of the ground reaction applied to an *i*-th landing gear are determined from the corresponding normal reactions P_i and coefficients of friction f_j:

$$F_i = f_x P_i,\ \ Z_i = f_z P_i.$$

Here the following condition is valid for the nose castoring landing gear: $Z_n = 0$, while for the rest of them $F_0 = F_l + F_r,\ Z_0 = Z_l + Z_r$.

In general, the following expressions are valid for the unsteady ground motion of the helicopter (taking into account the main landing gears veering and braking):

$$f_x \approx f_f + f_z|\beta| + f_x(\lambda)f_c^{(\beta)},$$
$$f_z \approx f_z(\beta, P_i)\bar{f}_z^{(\lambda)},$$
$$f_z \leq \sqrt{f_c^2 - f_x^2}$$

Where

f_f - the coefficient of rolling friction;

f_z - the coefficient of the veer drag;

f_c - the coefficient of friction;

$\lambda = \frac{n_0 - n_b}{n_0}$ - the relative wheel skidding from the rotational speed of n_0 to n_b;

$f_x(\lambda), \bar{f}_z^{(\lambda)}, f_z(\beta, P_i), \bar{f}_c^{(\beta)}$ are experimental data [1] shown in fig.2.

Note should be taken that

- $f_z = f_x(\lambda) = 0$ at free rolling that lacks wheel veering and braking;
- $f_x(\lambda) = 0, \bar{f}_z^{(\lambda)} = 1$ at stringent rolling with wheel veering under the lateral force;
- $f_z = 0$ at rectilinear wheels motion with account of friction.

The maximum values of the fuselage tilt due to the difference in the shock struts and tires compression while the helicopter banks and tends to tip over equal $3°...5°$, whereas the tipping over angle reaches $30°...40°$. Further we assume that

- helicopter tipping over and preceding banking has non-periodic nature, which allows us to consider only static properties of the landing gear shock struts and tires;
- changing of the aerodynamic and inertia forces arms about the tipping axis due to the difference in the shock struts and tires compression becomes significant after one landing gear has raised off the ground;
- the main landing gears compression does not impact the track, and turning of the nose castoring landing gear does not influence the wheelbase, thus keeping the tipping axis motionless.

The shock strut and tire compressions (e_a and e_t accordingly) comprise the landing gear deformation:

$$e_i = e_a + e_t$$

Since the helicopter main landing gear shock strut is placed at the angles of ξ_1 and ξ_2 about the vertical reference planes (figure 3), then

$$e_a = e_S \varphi_S.$$

Where e_s is the shock strut compression in the direction of its own longitudinal axis;

$\varphi_s = \cos\xi_1 \cos\xi_2$ is the shock strut gain.

The shock strut work

$$A_S = P_S e_S = P_i e_a$$

where we find the shock strut axial loading:

$$P_S = P_i$$

here P_i is the main landing gear radial loading.

The conventional curves for the tires and shock struts are used to determine the tire compression under the wheel radial loading P_i and shock strut compression under the axial loading P_s (the shock strut charging is assigned).

4. Helicopter banking dynamics

A tendency to tip over is typical of the helicopter (equally it is fair for any vehicle), and can come true under some crucial conditions about the *q-q* tipping axis, which comes through the points where the nose landing gear and one of the main landing gears touch the ground. The following differential equation describes helicopter banking (ω_q is the banking rate) under the tipping moment M_q :

$$J_q \dot{\omega}_q$$

The rigid body moment of inertia J_q about the intersected and parallel axes is

$$J_q = J_x \cos^2 \chi + J_z \sin^2 \chi + m(h_m^2 + d^2 \sin^2 \chi).$$

The banking angle γ_q made with the horizon determines angular position of the line l (refer to fig. 1,3), and can be found from the following differential equation:

$$\dot{\gamma}_q = \omega_q,$$

at the same time till the helicopter starts banking

$$\gamma_{q_o} = \arcsin \frac{h_m}{l}.$$

This banking angle γ_q supplements the traditional landing gear anti-nosing over angle γ_{nv}: $\gamma_{q_o} = \frac{\pi}{2} - \gamma_{nv}$. This banking angle γ_q enables us to identify the very event of tipping over (when the resultant vector F_{nv} of the forces applied to a vehicle crosses the ground outside the triangle formed by the points where the vehicle wheels touch the ground [2]):

$$\gamma_{q_{nv}} = \frac{\pi}{2} - arctg \frac{F_{nv}}{G - T}.$$

When $\gamma_q = \frac{\pi}{2}$, tipping over is inevitable.

The banking moment M_q influencing the helicopter after a landing gear has raised off the ground, is determined with the use of the d'Alamber principle and the one of the connection release:

$$M_q = M_z \sin\chi + M_x \cos\chi + M_q^{\omega_q}\omega_q - Gl\cos\gamma_q .$$

The rotor damping moment is assumed equal to the lateral damping moment $M_q^{\omega_q} \approx M_x^{\omega_x}$.

Let us assume that helicopter starts banking at a moment t_0 when the normal reaction on the wheel internal in turn equals zero, while $\gamma_q = \gamma_{q_0}$. The banking leads to either side-forward tipping over ($|\gamma_q| \geq \frac{\pi}{2}$) or on reaching some banking angle $|\gamma_q| < \frac{\pi}{2}$ the helicopter tends to come back on three wheels ($|\gamma_q| > \gamma_{q_0}$). At the same time while in banking it moves on the ground unsteadily along a curvilinear path on two landing gears (the nose landing gear and a main one).

5. Characteristic results obtained from modelling

All the results adduced below have been obtained for the Mi-8 production-line helicopter thorough studied in various flight tests and long-lasting operation. The latter was especially useful for verification of the developed math model.

Figure 4 presents comparison of the data obtained from flight tests (solid lines) with the ones obtained from the math modelling of the helicopter regular running takeoff on the concrete runway (dashed lines). The piloting technique and main kinematic parameters at takeoff were maintained following the Flight Manual for the mentioned helicopter.

One can easily see that on the whole experimental data agree well with the ones obtained from modelling. A similar pattern is shown in fig.5, where the comparison is drawn for an overloaded helicopter takeoff on the nose landing gear while the main landing gears raise off the ground (the nose-down pitching $\vartheta = -(8^\circ ... 12^\circ)$). This considerably improves the rotor propulsive force and takeoff acceleration. The takeoff time and ground run get twice as less in comparison with the regular running takeoff on three landing gears. Russian pilots of the Mi-8 and Mi-24 military helicopters fully took advantage of this very effective takeoff pattern in Afghanistan [4].

Now in conclusion I'd like to draw your attention to the most complicated and dangerous though design helicopter motion – abrupt turns at taxiing, which have often entailed tipping over and damage to the helicopters.

Let us consider a right turn at a constant speed of taxiing. The helicopter enters the turn by a sharp deflection of the right control pedal, which increases the tail rotor setting by $\Delta\varphi_{tr}$ following a linear law from its balancing value to nearly critical one, which implies the right landing gear load relief and helicopter left-forward banking followed by an equally sharp linear deflection of the left control pedal to counteract the banking (fig.6).

This banking is mainly due to the lateral component of the centrifugal force and lateral moment of the tail rotor thrust that appear after the right pedal has been deflected to enter turn. The other things being equal, the outcome depends on both duration of the exposure and amount of the disturbance $\Delta\varphi_{tr}$, i.e. the result depends on the disturbance impulse. The tipping over however takes no longer than 3 s after the right landing gear has raised off the ground (the value of γ_q comes from its initial value γ_{q0} to the limiting value $\gamma_q = 90^\circ$).

An excessive collective pitch of the rotor at taxiing (e.g. $\varphi_0 = 4^\circ$ vs. regular $\varphi_0 = 2^\circ$) makes the helicopter bank faster, all the other things being equal, including equal disturbance from the tail rotor. This phenomenon is due to the destabilizing effect of the rotor, which promotes unsteadiness of the helicopter ground component of the centrifugal force at turns. Tipping over has never happened to the helicopters moving at a speed under 10 km/h, no matter how abrupt were the turns they were making. Finally, slimy ground worsens the helicopter motion. A gain of the speed is one more crucial factor making taxiing turns unsteady for it increases the lateral dynamic response at taxiing turns (larger coefficients of friction and sliding) for both the longitudinal and lateral braking becomes much more significant.

Generally pilots can employ the directional control pedal, cyclic pitch control stick and collective pitch control lever (or combine the controls) to counteract banking after a main landing gear has raised off the ground by proportional deflections of various magnitude and time lag.

Note should taken that sharp displacement of the pedals may hold up banking of the helicopter yet does not avert its tipping over (refer to fig.6, dashed curves).

References

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3. A. M. Volodko. Helicopter overturning dynamics in taxiing. *TsAGI's Papers, vol.XXI, N2, 1990.*
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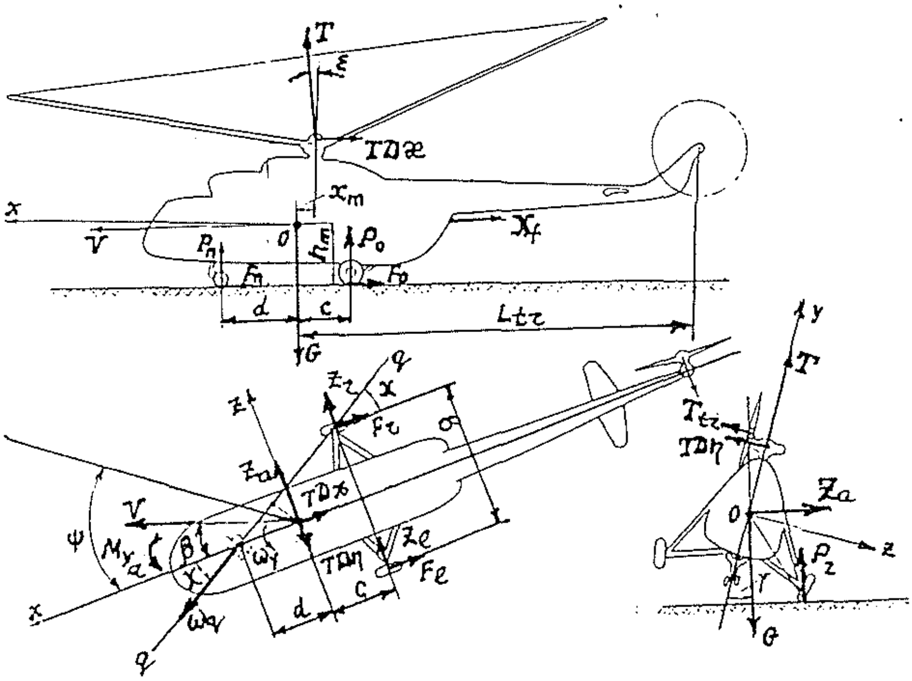

Fig. 1. Calculating scheme

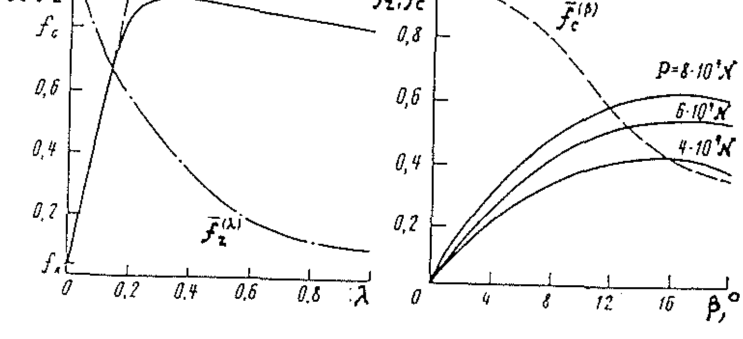

Fig.2. The influence of helicopter movement parameters on coefficients of friction

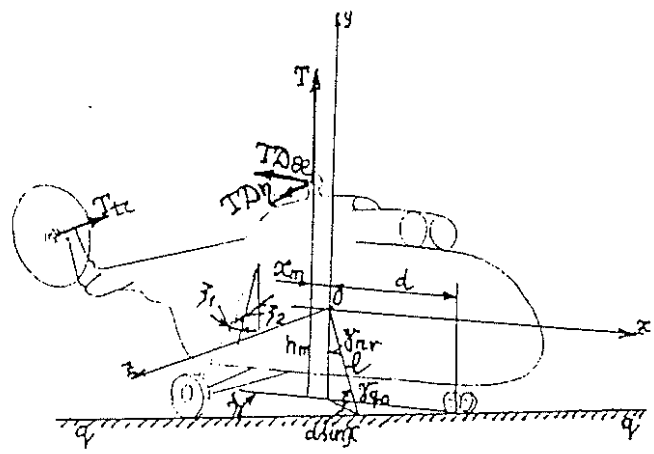

Fig.3. Calculating scheme

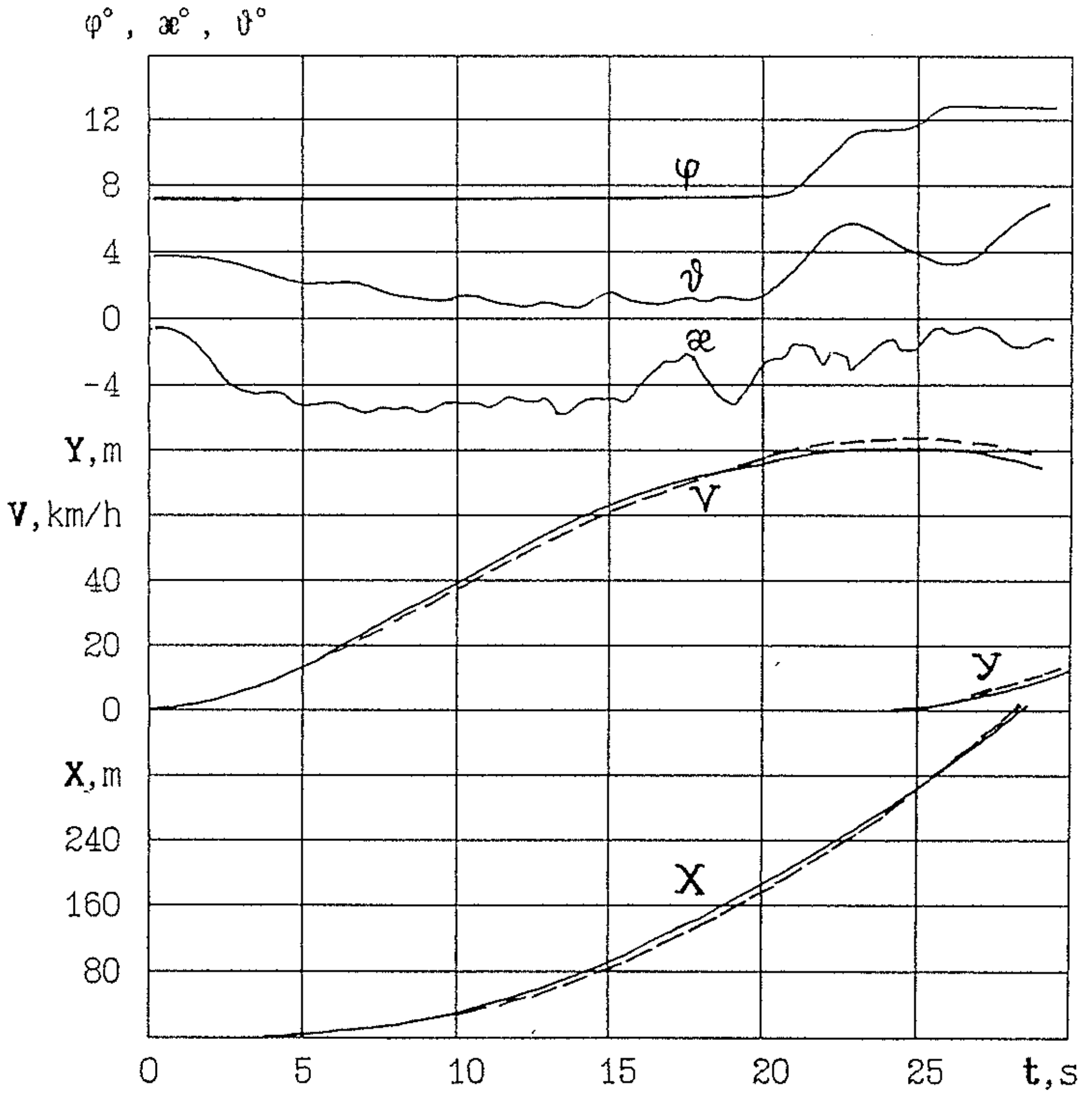

Fig.4. The main parameters of helicopter regular running takeoff on three landing gears

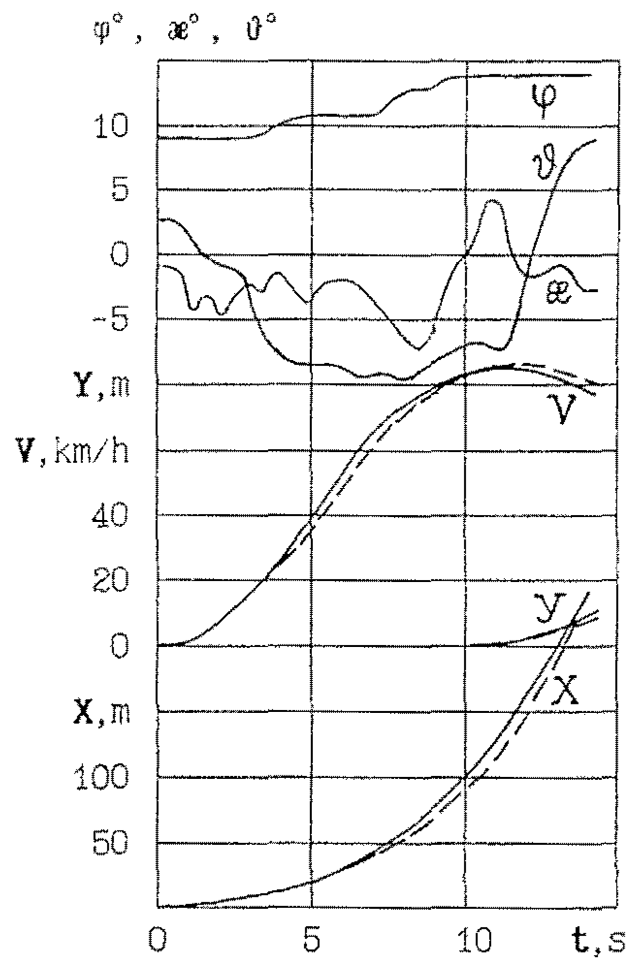

Fig.5. The main parameters of an overloaded helicopter running takeoff on the nose landing gear

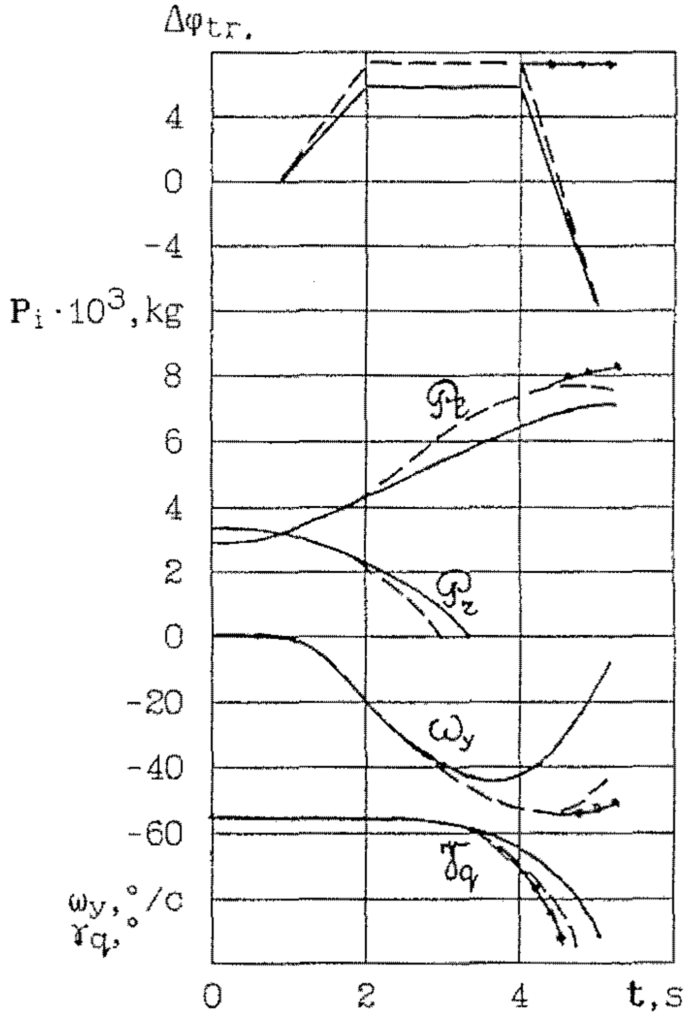

Fig.6. The response to a sharp deflection of the right control pedal