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COAXIAL HELICOPTER SAFETY FROM GROUND RESONANCE POINT OF VIEW

BY

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ABSTRACT

The paper presents the main activities performance of which ensures coaxial helicopter safety of ground resonance. Generalized characteristics of structures obtained for coaxial helicopters are presented that may be used for evaluation of safety in helicopter design and modification. Selfexcited free oscillations of the helicopter on the landing gear and in the air, i.e. ground resonance, are caused at certain combinations of natural and damping frequences of the blades in the lead-lag plane, landing gear, fuselage, main rotor shaft and main rotor rotational frequences. As a rule, at ground resonance alternating loads reach their altimate values and the structure fails. As is known, certain actions are undertaken to ensure protection against ground resonance i.e. calculation of unstability zone boundaries, tests to define natural frequencies and damping values of structures and full scale tests.

For identification of a coaxial helicopter unstability zone boundaries they use a mathematical model taking account of oscillations in the plane of upper/lower rotor blades rotation, helicopter fuselage displacements along longitudinal, vertical and lateral axises and its turns around them; main rotor shafts bending in longitudinal and lateral planes. The helicopter landing gear is schematically presended by spring with dampers of linear performance. Blade damping in the plane of rotation is also assumed to be linear. A coaxial helicopter model with oscillations on the landing gear is presented in fig. 1. The results of calculations are usually presented as $\bar{\omega}^*$ dependencies upon helicopter structure parameters. Here and below we shall mean the following:
ω_n – main rotor nominal speed;
ω^* - main rotor speed on unstability zone boundary;
relative values $\bar{\omega} = \omega/\omega n$ and $\bar{\omega}^* = \omega^*/\omega n$. As an example fig. 2 shows $\bar{\omega}^*$ dependence upon $\bar{n}b$ blade damping value ($\bar{n}b = \delta b/2\pi$, where δb - is a logarithmic decrement at isolated blade oscillations) for a coaxial helicopter on the landing gear. Helicopter oscillations become unstable at rotor speeds $\bar{\omega} > \bar{\omega}^*$. Unstability zone boundaries are also identified for a coaxial helicopter tied up to a ground running platform and coaxial main rotor test benches in the process of the powerplant transmission ground tests.

In the result of calculations required natural frequences, rigidities and damping values for coaxial designs providing for ground resonance safety were identified. The helicopter components are designed with consideration to these requirements. In the course of structure bench tests and coaxial helicopter frequency tests actual values are identified. Experimental values are used for further calculations of unstability zone boundaries for coaxial helicopters.

When calculating natural oscillations of a coaxial helicopter on the landing gear they use landing gear tyre rigidity and damping experimental values. Tyre experimental values are defined at various Pw air-pressure values inside. In case no experimental values are available at first stages of development, required characheristics may be obtained through dependencies established on the basis of other tyre test results [1].

For that purpose the test results are presented as relative values at single contact loading. Tyre relative values are

$\bar{C}z = Cz/Cyo$; $\bar{C}x = \bar{C}x/CyoD$; $\bar{y} = y/D$

where

y - tyre compression along the vertical;
D - tyre dia;
Cz - tyre lateral rigitity;
Cy - tyre longitudinal rigidity
Cyo - tyre vertical rigidity at relative compression $\bar{y} = 0.055$.

For high pressure tires $\bar{C}z$ relative rigidity practically does not depend upon compression rate and amounts to $\bar{C}z = 0.42$ at Pw =1.0 MP; $\bar{C}z = 0.3...0.34$ at Pw = 0.4...0.8 MP. $\bar{C}x$ relative rigidity increases with compression and in the compression range of $\bar{y} = 0.03...0.097$ it amounts to $\bar{C}x = 0.38...0.67\ m^{-1}$ at Pw = 1.0 MP, $\bar{C}x = 0.33...0.63\ m^{-1}$ at Pw = 0.6...0.8 MP. Tyre relative damping value $\bar{K}x = Kx/Cx$; $\bar{K}y = Ky/Cy$; $\bar{K}z = Kz/Cz$, where

Kx - tyre longitudinal damping;
Ky - tyre vertical damping;
Kz - tyre lateral damping.

With high pressure tyres at $Pw = 0.8 \ldots 1.0$ MP the following relative damping values may be accepted:

$\bar{K}x = 2.5 \cdot 10 -3\ C$; $\bar{K}y = (5 \ldots 10) \cdot 10 -3\ C$; $\bar{K}z = 2.5 \cdot 10 -3\ C$.

Real lateral and longitudinal rigidities and damping values of landing gear struts are usually obtained on the basis of landing gear strut frequency test results. Relative values of these characteristics are also used at first stages of designing.

When exciting coaxial helicopter oscillations with the helicopter positioned on the landing gear, shock absorber rods do not move at frequency testing and, hence, the shock absorbers to do not work. It permits to compare design natural frequencies Pc with experimental P values and to compare design values of natural mode damping relative coefficients $\bar{n}c$ with experimental $\bar{n}$ values. Tyre and strut experimental characteristics in lateral and longitudinal directions were used in analysis. The following values of the coaxial helicopter oscillation main modes were obtained with the helicopter positioned on the landing gear:
around OX axis
  $\bar{P}c = 2.25$ Hz and $P = 2.31$ Hz
  $\bar{n}c = 0.0248$ and $\bar{n} = 0.022$
around OZ axis
  $Pc = 4.02$ Hz and $P = 3.62$ Hz
  $\bar{n}c = 0.0531$ and $\bar{n} = 0.0573$

For such system as a helicopter on landing gear acceptable deviations of approximately ~12% between analytical and experimental values were obtained.

The coaxial helicopter safety of ground resonance is tested in full-scale in the following conditions: ground runs, landing from hover, taxiing along the airfield, fixed wing type take-offs and landings. Ground runs are made in the whole range of main rotor speeds and shock absorber strut compressions from parking position to the fully released position with simullations of ground resonance by the cyclic stick [2; 3]. The pilot rotates the cyclic making circles, and ellipses clockwise (direction of the upper rotor rotation) and counter clockwise (direction of the lower rotor rotation) at a ground resonance frequency. Coaxial helicopter safety of ground resonance with the helicopter tied-up is checked in the following conditions: operation of engines at all ratings; engine acceleration response check from idle to take-off, pulse feeds of the cyclic. Pulse feeds of the cyclic (moving the stick from the neutral and taking it back) are made by the pilot in longitudinal, lateral and diagonal directions. The minimal ground resonance margins of all tested conditions are observed in ground runs with the struts fully released. So when designing a coaxial helicopter its parameters are selected from condition of its safety of ground resonance in these very conditions.

For coaxial helicopters damping moments Mup in the lower rotor blade vertical hinges may be less than those of the upper rotor due to a different position of coaxial rotors in respect to the helicopter height. It permits to reduce loads on the lower rotor in the plane of rotation. So, on a Ka-26 coaxial helicopter with needle roller bearings in vertical hinges hydraulic dampers are installed in the upper rotor. The lower rotor blade damping moment is conditioned only by friction in vertical hinge elements. In Ka-25K helicopter rotors frictional disc dampers are installed. Since with this type of dampers the play may reach 40′ in addition to the friction dampers metal/polymer sliding bearings not requiring lubrication were installed into the vertical hinges and the lower rotor dampers were excluded from operation. The metal/polymer bearings are also installed in the Ka-126 helicopter vertical hinges and hydraulic dampers are additionally installed in the upper rotor. In the Ka-32 helicopter only metal/polymer sliding bearings not requiring lubrication are installed in the vertical hinges that have different damping moments on the rotors. Metal/polymer sliding bearings work in the blade vertical hinge that is loaded by centrifugal and shearing forces and bending moments. In the course of the helicopter bench testing for ground resonance angular displacements of a blade in the vertical hinge take place both at the main rotor frequency and at the ground resonance frequency. Creation of such conditions for the vertical hinge operation in bench testing to define the metal/polymer bearing characteristics is a complex and labour consuming task. A metal/polymer bearing damping moment depend upon the deflection of the blade in the vertical hinge. Starting from some Mo value the metal/polymer bearing moment value reaches Mm maximal value at the maximal γm blade deflection angle. Usually it is connected with "dry" "viscous" friction of the metal/polymer bearing. However, it is also connected with elastic properties of the metal/polymer bearing installed in the vertical hinge. An algorithm developed for identification of metal/polymer bearing rigidity coefficient C and dampling coefficients K in conditions of ground resonance testing was adopted for the Ka-32 helicopter [3]. The results of the tests made are generalized in fig. 3 & 4 where the following generalized parameters are used:

$\bar{M} = Mm / \omega_n^2 Sl$; $\overset{2}{Po} = C/J$; $\bar{K} = K/J$

where J - blade inertial moment in respect to the vertical hinge;
S - blade static moment in respect to the vertical hinge;
l - distance from the rotor rotation axis to the vertical hinge axis.

As the first approximation in designing the following permissible values of the blade vertical hinge moments may be accepted the dependance of which upon helicopter inertial-mass parameter is presented in figs. 5 & 6 [1; 3]. The following relative characteristics are used here:

$\bar{M}_\Sigma = (Mup + ML)/G$; $\bar{M}up = Mup/G$; $d = Qh^2 /Jx$,

where G, Q - helicopter weight and mass;
Jx - helicopter inertial moment in respect to longitudinal axis;
h - distance between the helicopter center of mass and the upper rotor center.

Average values of $\bar{M}up$ for Ka-26K and Ka-32 helicopters are shown in fig. 6.

For coaxial helicopter transmission bench testing a helicopter engine nacelle with the powerplant and main rotor system is placed on a frame that is mounted on the bench girder. The frame is connected to the girder either by hinges or rigidly. In difference to a helicopter the benches envisage only collective and differential pitch control for coaxial rotors.

A sketch of a test bench with hinged frame connection to the girder is shown in fig. 7.

The frame and the girder are interconnected with a two-stage hinge. Coaxial shafts axis is perpendicular to the hinge axises and passes though the hinge center. One axis of the two-stage hinge lies in the engine nacelle longitudinal plane and the second lies in the lateral plane. The hinge reacts the rotor thrust and differential torque. Shock absorbers are mounted between the frame and the girder - two in the longitudinal plane and two in the lateral plane. Air/hydraulic shock absorbers are used here. In identification of unstability zone bounderies of a bench with hinded connection of the frame besides blade oscillations in the plane of rotation they also take into account turns of the engine nacelle with the frame around lateral and longitudinal axises of the two-stage hinge and bending of the main rotor shafts in lateral and longitudinal planes. In frequency testing there is obtained a dependance of $\bar{n}$ relative damping value on p frequency of the bench natural modes around the lateral and longitinal axises of its hinge (ref. fig. 8). This curve was used to calculate the unstability zone boundaries to identify the bench parameters ensuring its safety of grounce resonance. Further tests of the Ka-25 helicopter transmision on a bench with hinged connection of the frame to the girder confirmed the bench safety of ground resonance.

A bench with rigid frame connection to the girder is shown on a sketch in fig. 9. Absence of a two-stage hinge and shock absorbers simplified the bench design. Simultaneously it excludes a possibility of influencing the unstability zones boundary due to the bench mass-inertial characteristics and shock absorber characteristics. When indentifying unstability zone boundaries of a bench with fixed frame connection to the girder, besides blade motion in the plane of rotation, they take into account bending of the main rotor shafts in lateral and longitudinal planes.

Natural frequences and shaft bending damping values in lateral and longitudinal planes are identified in the course of the bench frequency testing. The results of the frequency testing are used to calculate the bench stability. Dependance of $\bar{\omega}^*$ rotors speed at the unstability zone boundary (at $\bar{\omega}$ exceeding $\bar{\omega}^*$ the bench is unstable) on $\bar{n}b$ blade relative damping value in the vertical hinge is shown in fig. 10. Relative damping value at coaxial shafts bending modes obtained at frequency testing is $\bar{n}s = 0.025$. Small rotor speed margins up to the unstability zone boundary are there at relative blade damping values of approximately 0.05 for the blade with $\bar{P}b = 0.34$ and $\bar{P}b = 0.47$ ($\bar{P}b = Pb/\omega n$, where Pb is a natural frequency of a blade in the plane of rotation). For a Ka-32 helicopter blade ($\bar{P}b = 0.34$) with a metal/polymer bearing in the vertical hinge a relative damping value comes to $\bar{n}b \geqslant 0.5$. Rotor speed on the unstability zone boundary does not exceed 1.14. So instead of a metal/polymer bearing they put a needle rolling bearing into the vertical hinge. In this case damping reduces up to $\bar{n}b = 0.06$ and the rotor speed on the unstability zone boundary is $\bar{\omega}^* = 1.38$. In blade with $\bar{P}b = 0.47$ parallel to the blade vertical hinge they install elements that provide an elastic moment in respect to the vertical hinge and relative damping of this structure comes to $\bar{n}b = 0.1$. Testing of Ka-32 and Ka-50 coaxial helicopter transmissions at benches with a rigid frame connection to the girder confirmed the bench safety of ground resonance.

A portion of a diagram depicting frequences of oscillation modes and q increment of bench oscillations build-up ($\lambda = q+i\nu$) - proper values obtained through solution of a bench motion equations system; at $q > 0$ the bench is unstable) is shown in fig. 11 for a bench with a rigid frame connection to the girder. Between rotor speed ω^* on the unstability zone boundary that is located beyond rotor nominal speeds and the rotor ω_n nominal speed there is a resonance frequency ω_I rotor speed value. At this resonance frequency an exitation resonance takes place acting at the 1st hormonic frequency in respect to the rotor speed $P_I = \omega$ with frequency ν of one of the bench modes: common oscillations of the blades rotating in the plane of rotation and bend modes of coaxial shafts. Fig. 12 presents dependences of $\bar{\omega}_1$ and $\bar{\omega}^*$ on $\bar{P}s$ coaxial shaft bending mode proper frequency ($Ps = Ps/Pso$, where Pso is a standard value of coaxial shaft bending mode proper frequency. These dependences are defined in the result of calculating the bench for the Ka-32 helicopter transmisison. As follows from graphs in fig. 9 the curve $\bar{\omega}_1$ ($\bar{\omega}_1 = \omega_1/\omega_n$) lies below the $\bar{\omega}^*$ curve and is practically equisitant to it. So in the course of full scale testing ω_1 value or its rotor speed domain is identified. It permits to define the value of rotor speed margin from nominal speed to rotor resonance speed $\Delta\omega_1 = \omega_1 - \omega_n$ implemented in the bench. Operation practice of such bench designs shows that benches with the required $\Delta\omega_1$ margin value are safe of ground resonance.

It is known that the number of blades and position of the main rotors in respect to the centre of mass influence main rotor speeds on the ground resonance zone boundary. It must be noted that the influence of these helicopter parameters has an opposite nature. So it presents a certain interest to compare the results of analysis for such different configurations as single rotor and coaxial rotor helicopters. Examining this problem we shall use the following designations (fig. 13).

b - distance between the fuselage center of mass and the ground;

hs - distance between the fuselage center of mass and the main rotor hub center of a single rotor helicopter;

hup -distance between the fuselage center of mass and the upper rotor hub center of a coaxial helicopter;

k - number of blades in the main rotor system: in each coaxial main rotor $k/2$ blades are installed.

Design models of single rotor and coaxial helicopters have similar fuselage and landing gear with characteristics of a medium helicopter (mass-inertial, geometric, rigidity, damping). Distance hs as well as b of the design model and a single rotor medium helicopter has the same value.A coaxial rotor of the design model is installed on the fuselage in the same way as it is installed on a real coaxial helicopter.The value of hup/b ratio is same for the model and the coaxial helicopter. For single rotor and coaxial models hup/b ratio is 1.4 Blade characteristics of the two models are same and correspond to those of a five-blade rotor of a medium single rotor helicopter. The blade proper frequency in the plane of rotation and its damping have the following values: $\bar{P}b = 0.57$ and $\bar{n}b = 0.02$. So the same values and the real characteristics of existing structures are used as blade, fuselage and landing gear characteristics for a single rotor and coaxial rotor analytical models. Minimal number of blades for analytical models is four for a single rotor and six for a coaxial rotor (the number of blades in each main rotor is not less than three).The helicopter motion nature is defined by solving a system of ordinary differential equations of the 2nd order with constant coefficients. The results of calculating main rotor speed dependances on the h unstability zone boundary of a helicopter placed on the landing gear upon the number of blades are presented in fig. 14 (at $\bar{\omega}$ exceeding $\bar{\omega}^*$ the helicopter is unstable). A curve of $\bar{\omega}^*$ versus k of a coaxial helicopter passes below that of a single rotor helicopter and is similar to that in its nature. For example, six-blade rotor helicopters have the following rotor speeds on the unstability zone boundary: $\bar{\omega}^* = 1.2$ for single rotor helicopters and $\bar{\omega}^* = 1.18$ for coaxial helicopters. The results obtained for the designs having the parameters of a medium helicopter permit to make the following conclusions. Influence of a coaxial upper rotor placed highly on the fuselage is compensated by the $k/2$ number of blades in this rotor. Rotor speed margines from nominal to the frequency observed on the boundary of the ground resonance zone of a single rotor helicopter are larger (by 10%) than that of a coaxial helicopter. To protect a single rotor helicopter of ground resonance there may be used the structural components having the same relative regidity and dampling values that were used for a coaxial helicopter.

Hence, in the result of performing the following activities:

- theoretical analysis;
- experimental identification of natural oscillation frequences and damping values of the structure;
- definition of generalized structural characteristics;
- full scale tests for ground resonance

a safety of a coaxial helicopter and its transmission ground test benches of ground resonance is ensured.

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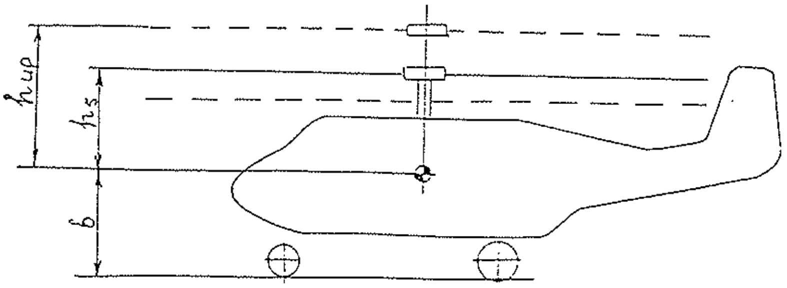

Fig. 13. Positions of a single rotor helicopter main rotor, a coaxial main rotor and a fuselage center of mass in respect to each other

—— single rotor helicopter;

- - - coaxial main rotors;

● fuselage center of mass

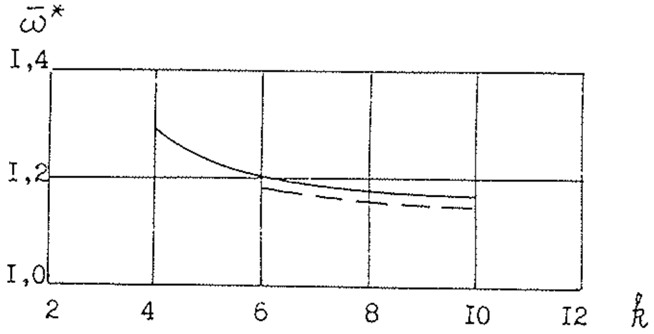

Fig. 14. Main rotor speed on the unstability zone boundary of a helicopter on the landing gear versus the number of blades

—— single rotor helicopter;

- - - coaxial helicopter

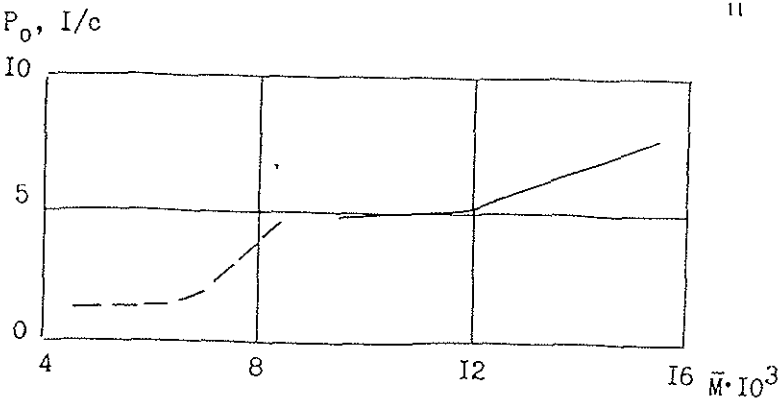

Fig. 3. Po rigidity versus bearing moment value for metal/ polymer bearings of the blade vertical hinge (— upper rotor; - - - lower rotor)

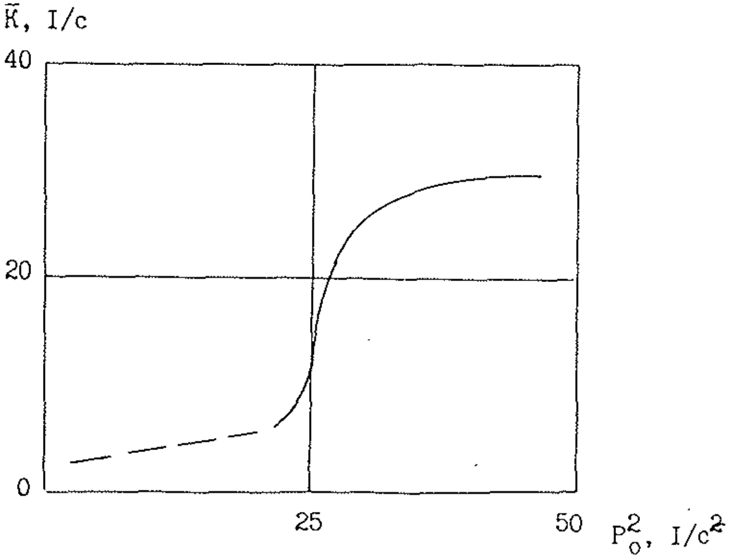

Fig. 4. $\bar{K}$ damping value versus bearing rigidity for metal/ polymer bearings of the blade vertical hinge

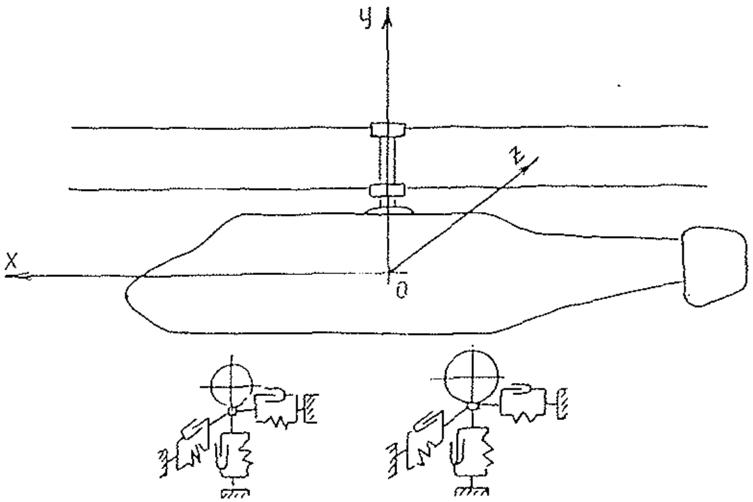

Fig. 1. Coaxial helicopter model oscillating on the landing gear

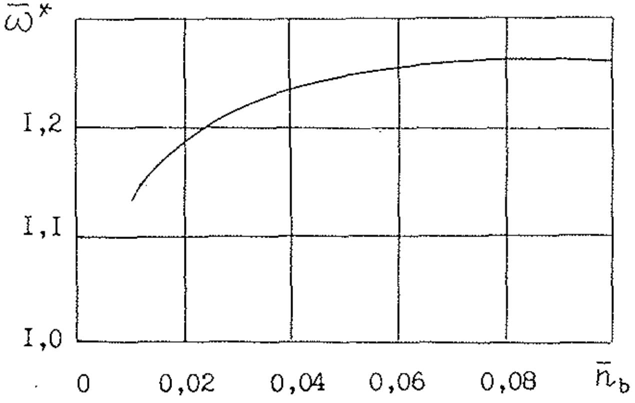

Fig. 2. $\bar{\omega}$ • versus blade damping for a helicopter on the landing gear

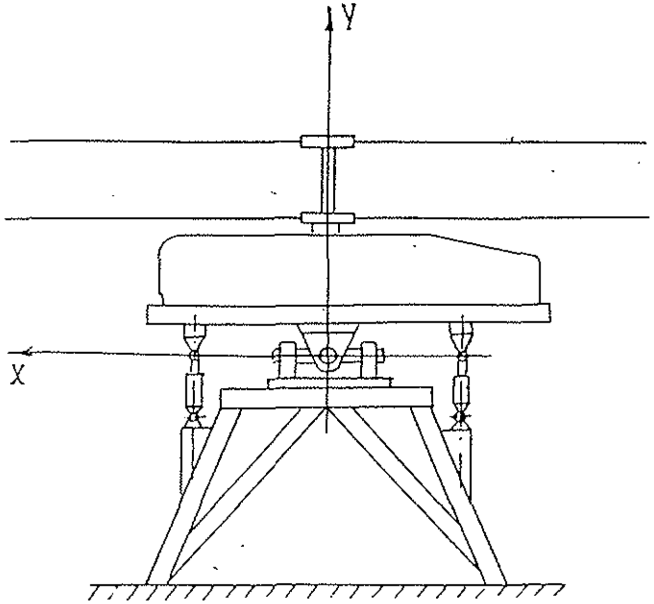

Fig. 7. Test bench with a hinged frame connection to the girder (shock absorbers in the lateral plane are not shown)

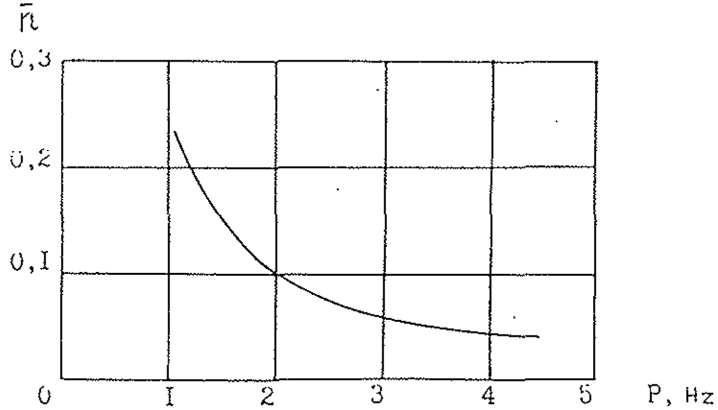

Fig. 8. Relative damping value versus natural frequences for bench oscillations around hinge axises

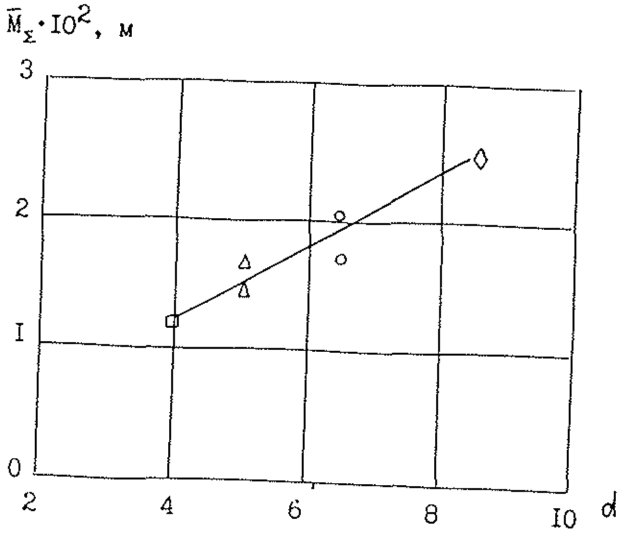

Fig. 5. Allowed vertical hingle moments versus helicopter mass-inertia parameter
(○ – Ka-32; △ – Ka-25K; ◇ – Ka-126; □ – Ka-26)

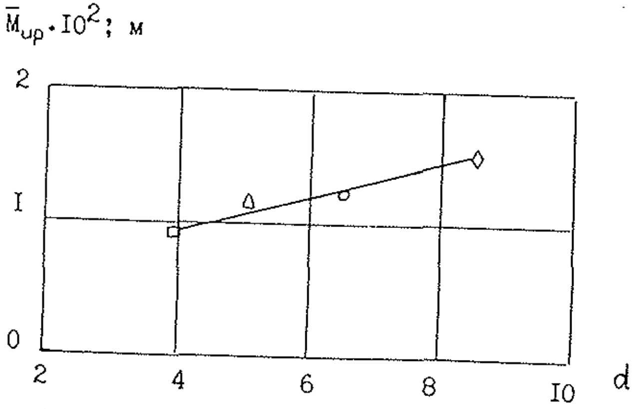

Fig. 6. Upper rotor vertical hinge allowed moments versus mass-inertia helicopter parameter
(○ – Ka-32; △ – Ka-25K; ◇ – Ka-126; □ – Ka-26)

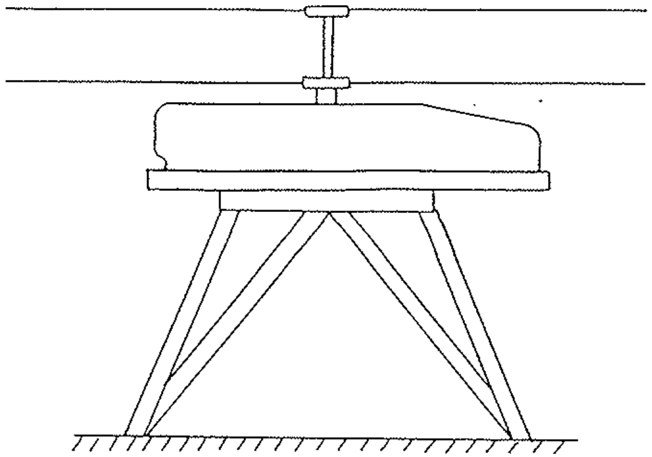

Fig. 9. Test bench with the frame rigid connection to the girder

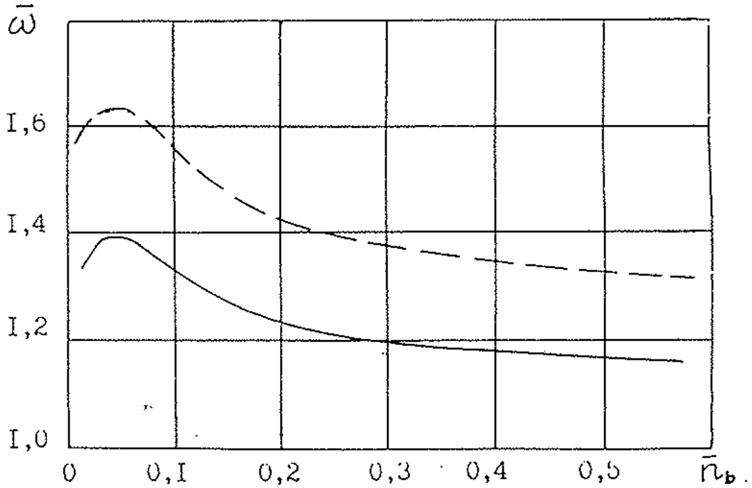

Fig. 10. Rotor speed on the boundary of the Ka-32 transmission test bench unstability zone versus relative blade damping value in the vertical hinge (—— $\bar{P}_B$ = 0.34; - - - $\bar{P}_B$ = 0.47)

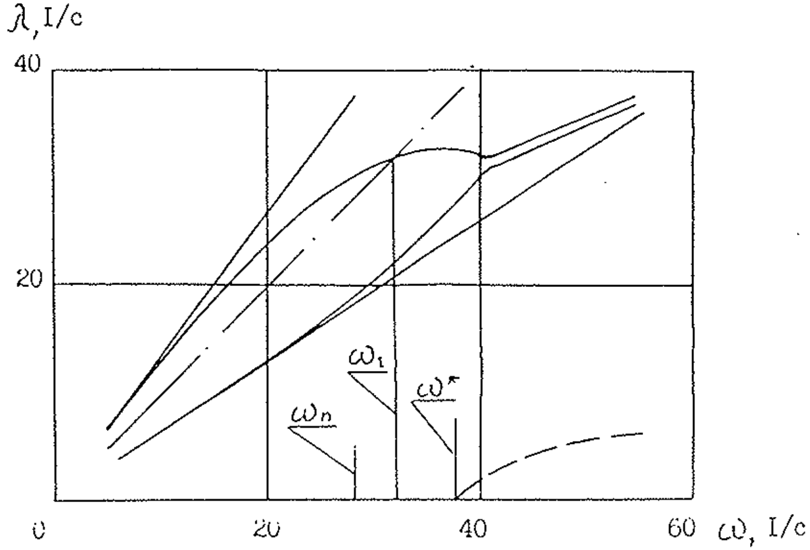

Fig. 11. Part of a diagram depicting proper values of a bench with rigid frame connection to the girder

—— ν frequences of bench oscillation modes;
- - - q increment of bench oscillation build-up;
-·-·- external excitation frequency $P_1 = \omega$

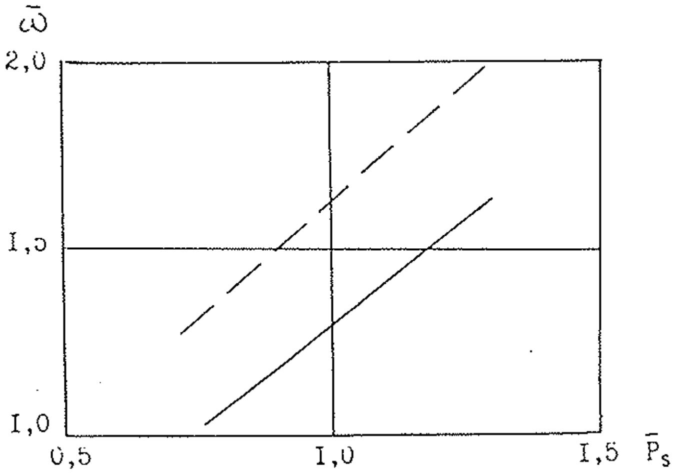

Fig. 12. $\bar{\omega}^*$ and $\bar{\omega}_1$ versus relative frequency of natural bending modes of the Ka-32 helicopter coaxial shafts (- - - $\bar{\omega}^*$; —— $\bar{\omega}_1$)