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SAFETY PROVISION AGAINST "GROUND RESONANCE"
FREE VIBRATION OF A COAXIAL HELICOPTER.

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Abstract - The paper presents the problem of safety provision against "ground resonance" free vibration of a coaxial helicopter. The following function has been plotted as a result of the carried-out work for safety provision against "ground resonance": relative damping moments in lag hinges of the upper and lower rotors versus helicopter inertia-mass parameter which may be used for a safety evaluation in the process of a helicopter designing.

"Ground resonance" is a kind of helicopter self-induced free vibrations on the ground and in the air, the propogation of which interactively amplifies stator and blade vibrations in the plane of rotation at certain combinations of natural friquency, damping and rotor rotational speed. As a rule, in case of the "ground resonance", variable loads reach thear maximum values and the structure fails. The helicopter parameters are sorted out with due regard for the helicopter safety provisions and tests are initiated with a safety check against free vibrations. A lot of extensive analyses of a "ground resonance" are available including the instability area limits determination , equivalent characteristics of a shock-absorber-type and blade systems;-see, e.g.,[1,2]. Nevertheless, in the process of a helicopter design some problems are springing up, the specific character of which is not fully considered in the analyses. Therefore, discussing the problems of a "ground resonance" on the coaxial helicopter we shall diwell on the questions conserning safety provision against free vibration.

The calculated model, considering vibration in the plane of blades rotation for upper and lower rotors and the stator motion,is employed for the definition of the instability area limits. If blades are without a lag hinge the vibration will be considered by the first note, and if the lag hinge is available the motion relative to that lag hinge will be taken into account. The number of the blades for each rotor is not less than three ($k \geqslant 3$). The stator degree of freedom is the following: for the helicopter on the ground-movements along longitudinal, vertical, lateral axes and rotation round those axes; for the helicopter in flight - movements along longitudinal and lateral axes and rotation round those axes; symmetrical and antisymmetrical bend of the coaxial mast shafts installed on the flexible fuselage [3].Figure 1 schematically shows springs and dampers

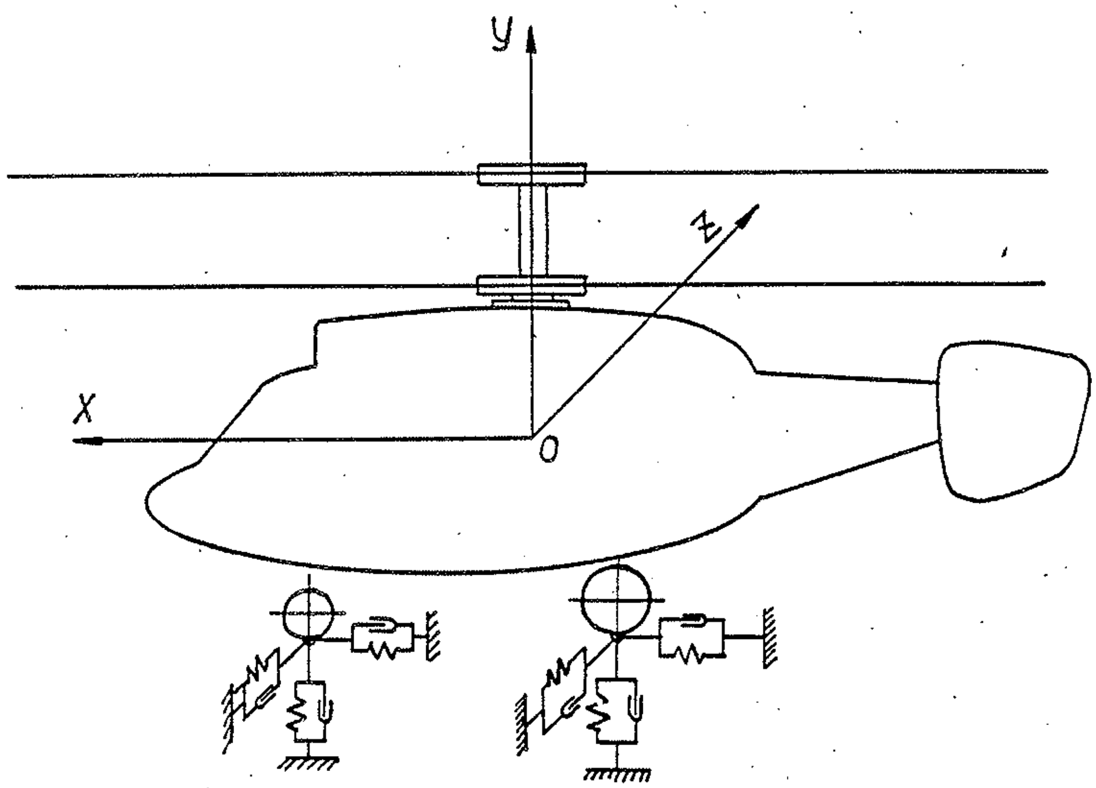

Fig. 1 The coaxial helicopter model at ground vibrations.

with linear characteristics for the landing gear. Damping and flexibility characteristics in the lag hinge of the calculated model are also linear. It should be mentioned that relations found in articles [1,2] are used for the linearization of the structure non-linear characteristics. The character of the helicopter movement is estimated by general differential quadratic equations with constant coefficients using Gerebtsov-Coleman variables [1]. Results of the calculations are usually offered as a plot of rotors r.p.m. at the instability area limits ω^* ($\bar{\omega}^* = \omega^*/\omega$, where ω is a rated rotors r.p.m.) versus helicopter parametres and more often versus the structure damping and rigidity. Figure 2 shows as an example the $\bar{\omega}^*$ versus the blade damping $\bar{n}_{bL}$ for coaxial helicopter on the ground when the rotors mast is not equipped with lag hinges ($\bar{n}_{bL} = \delta_{bL}/2\pi$, where δ_{bL} is a damping factor during vibration of the isolated blade). The helicopter movement is unstable when rotors r.p.m. are as follows: $\bar{\omega} > \bar{\omega}^*$. Safety provision against "ground resonance" for a coaxial helicopter depends to a considerable extent on the flexural rigidity of rotor shafts. With a view to illustrate the above the figure 3 shows the $\bar{\omega}^*$ versus the helicopter shaft rigidity EJ on the ground and in the air when the rotors must is equipped with lag hinges ($\overline{EJ} = EJ/EJ_0$, where EJ_0 is a rigidity of the structure variant under consideration).

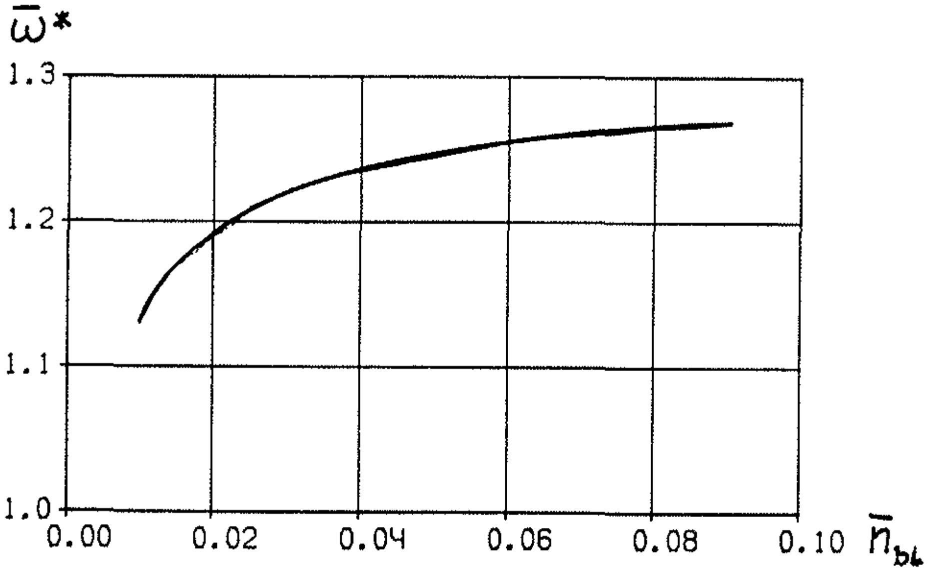

Fig. 2 The $\bar{\omega}^*$ for the helicopter on the ground versus blade damping.

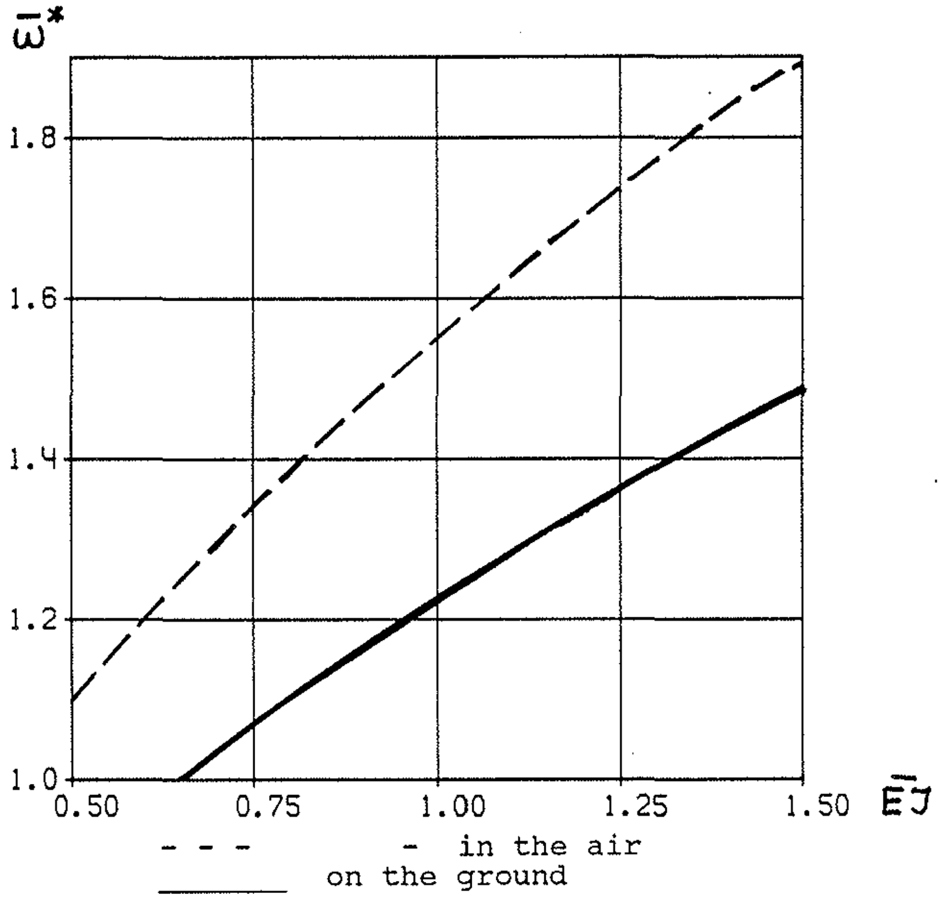

Fig. 3 The $\bar{\omega}^*$ for the helicopter on the ground and in the air versus shafts rigidity.

During the calculation of the coaxial mast natural vibrations its inertia-mass characteristics are schematized by descrete masses, the centres of which are found at the rotor rotational axes and the masses themselves are on the members of the mast multi-supported flexible beam which consists of coaxial shafts for the upper and the lower rotors and the gearbox sleeve. The disposition of discrete masses and shaft supports are shown in fig. 4. The absolutely rigid gearbox body is provided with a lower support 1 for the upper rotor shaft and the sleeve is fixed on the top of the body and serves as flexible base for two supports 4 and 5 of the lower rotor which is also provided with two supports 2 and 3 for the upper rotor shaft. The gearbox body is flexibly secured on the base (bench or fuselage). Natural vibrations

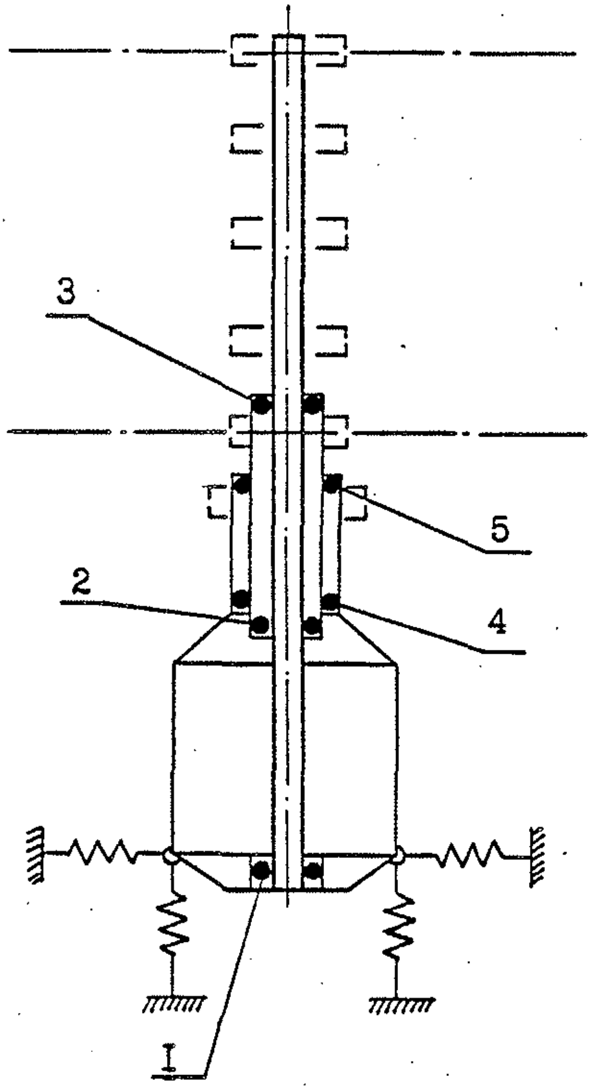

Fig. 4 Disposition on shaft supports and discrete masses for the coaxial mast calculated model: ● - shaft support, ⊏⊐ - descrete masses; 1-5 - numbers of shaft supports.

of the coaxial mast in the helicopter longitudinal plane (symmetrical) and lateral plane (antisymmetrical) are considered with due regard for the linear displacement of the discrete masses, schematizing main rotors, linear and angular displacement of the gearbox body. The mast elastic deformations are determined relatively to the gearbox body by the matrix of influence coefficients, in the process of their computation the static indefinability of the multi-supported beam is evaluated. Following computations of the natural vibrations using linear rigidity EJ_f , defined by geometrical profiles under the drawings, the frequencies p_f appeared to exeed the experimental values p_{ex} . One of the reasons being at the bottom of difference between design and experimental frequencies is caused by the clearences in the shaft supports. The influence of the clearences upon the reduction of frequencies or shafts effective rigidity depends on the arrangement of supports and rigidities EJ_f with respect to each other. The support clearence and shaft diameter relations are specified by the design accuracy ratings approved for shaft bearings and supports of the coaxial helicopter gearboxes. In order to plot effective rigidity as a function of gearbox parametres the coaxial shaft stiffness coefficient K_{sh} is implemented provided the design frequencies p , calculated at shaft linear rigidities $EJ = K_{sh} EJ_f$, coincide with experimental ones, i.e. $p = p_{ex}$. Following the analysis of the frequency test materials, calculation results, arrangement of shaft supports and linear rigidities with respect to each other, the the ralative elastic deformation $\bar{\delta}$ of the upper rotor shaft is considered as a gearbox generalized characteristic. The relative elastic deformation is calculated by plotting elastic deformations in the upper rotor rotational plane versus the force effecting in this plane at the gearbox body still position when the

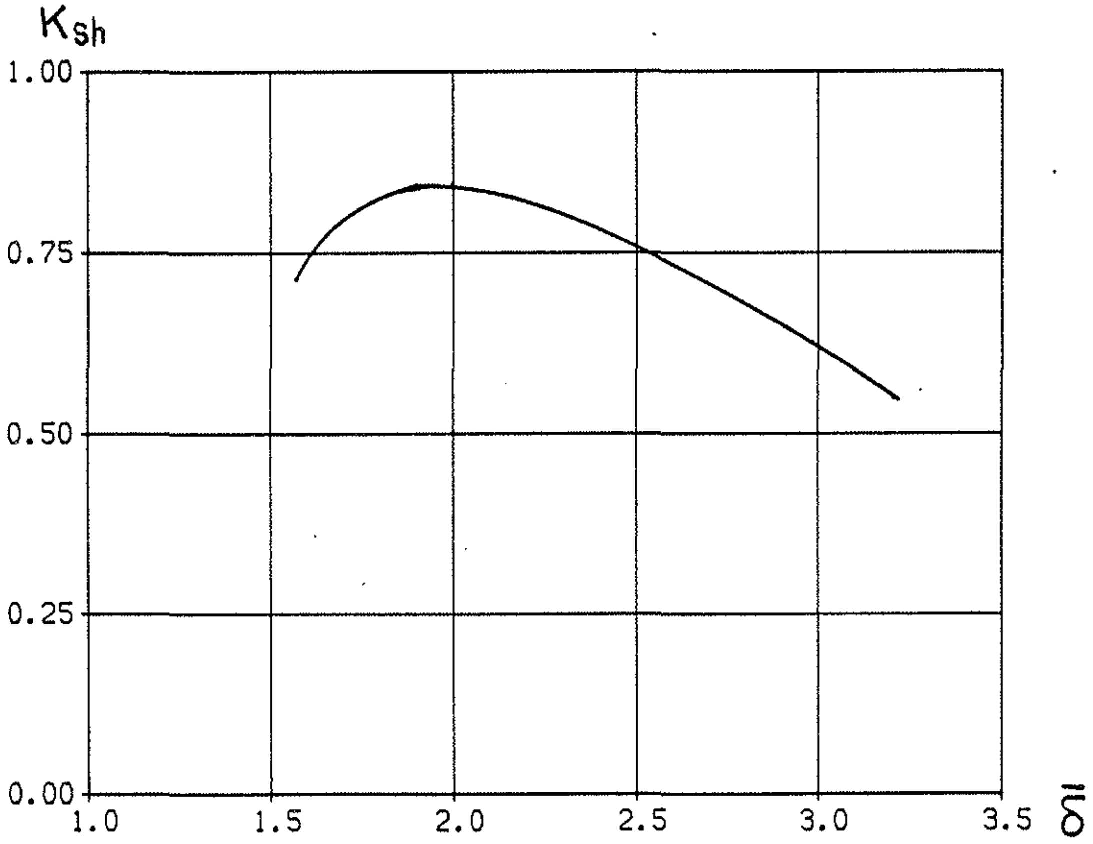

fig. 5 Coaxial shaft stiffness coefficients versus relative elastic deformation on the upper rotor shaft.

upper rotor shaft is installed in the gearbox on two supports 1 and 2 only (deformation δ_{st}) and in case of its regular installation in the gearbox (δ), and thus $\bar{\delta} = \delta_{st} / \delta$. Frequency test materials for coaxial masts, installed on the benches , are used for determination of the shaft stiffness coefficients. The required natural vibration calculations are made with a due respect for rigidity characteristics of the gearbox mounting on the benches. It should be mentioned that the natural frequencies experimental values of the symmetrical and antisymmetrical mast vibrations obtained on the bench and on the helicopter are within the range of the following values $(1.3 \div 2.3)\, \omega$. Figure 5 shows K_{sh} versus δ . Application of the obtained function allows to define the natural frequencies design values of the flexural vibrations for the coaxial mast installed on the fuselage to an accuracy of~5%.

The following experimental values of the wheel tyre rigidities are used during the calculation of the stator natural vibrations for the coaxial helicopter on the ground: vertical - C_y , lateral - C_z , longitudinal - C_x . In case if the experimental values and are not available at the first design stages, the required characteristics may be obtained with the help of functions made on the basis of tests results of other tyres [4]. For that purpose the experimental results at a single-contact loading are offered in the form of relative values: $\bar{C}_z = C_z / C_{y_0}$; $\bar{C}_x = C_x / C_{y_0}$; $\bar{y} = y / D$, where:

y - is the vertical tyre deflection;
D - is the tyre diameter;
C_{y_0} - is the vertical tyre rigidity at the relative deflection of $\bar{y} = 0.055$.

Tests are carried out at different air pressure values P_0 of wheel tyres. The relative rigidities $\bar{C}_z$ of the high pressure tyres practically do not depend on the deflection and they are as follows: $\bar{C}_z = 0.42$ at $P_0 = 1.0$ Mpa; $\bar{C}_z = 0.3 \div 0.34$ at $P_0 = 0.4 \div 0.8$ Mpa. The relative rigidity $\bar{C}_x$ function is given in figure 6. Practical rigidity coefficients of the undercarriage leg structure in the longitudinal and lateral directions are usually obtained by frequency test results for undercarriage legs. Natural frequency experimental values applied for coaxial helicopter undercarriage leg structure present the generelized characteristics and they are used to determine the undercarriage rigidity at the design stage.

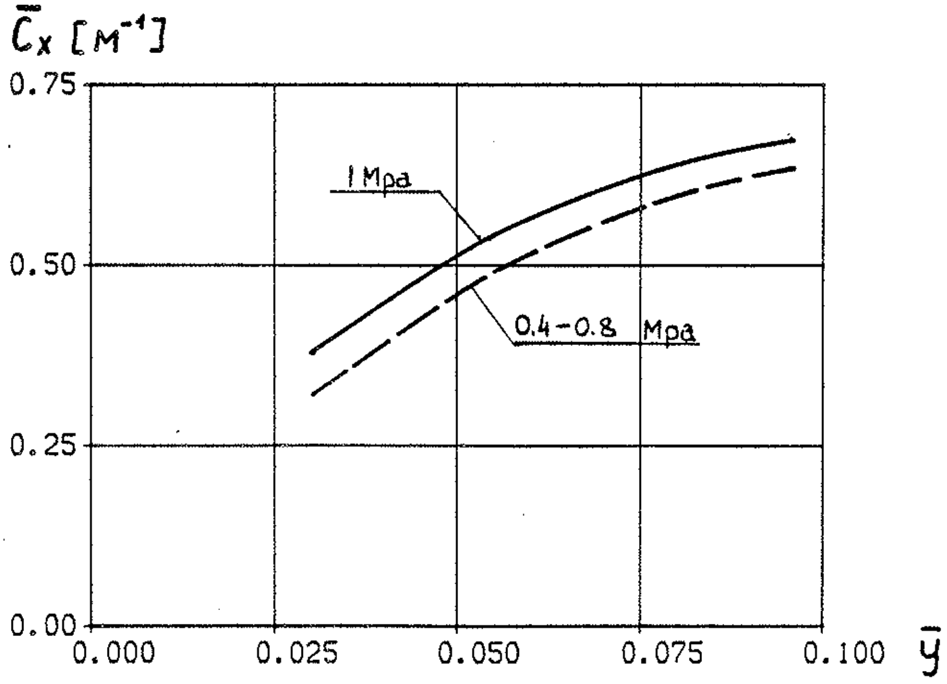

Fig. 6 Longitudinal tyre rigidity versus deflection

During frequency tests, when coaxial helicopter exciting is observed on the ground along axis OX; OY; OZ and around them, the undercarriage shock-absorber rods do not move and therefore the shock-absorbers do not operate. This circumstance allows to compare design natural frequencies P , obtained by characteristics of tyres and undercarriage leg rigidities in longitudinal and lateral directions, with the experimental one P_{ex} . Table 1 shows natural frequency values for the structure variant.

Table 1

Helicopter vibrations	P [Hz]	Pex [Hz]
along axis OX	1.3	1.48
along axis OY	2.16	2.39
along axis OZ	0.8	1.11
around axis OX	2.25	2.31
around axis OY	1.51	1.81
around axis OZ	4.02	3.62

Satisfactory correspondence between analysis and experiment has been obtained for such a system as helicopter on the ground.

Damping characteristics of wheel tyres are defined experimentaly on the special benches. Before test conducting the longitudinal K_x , vertical K_y and K_z lateral for tyres damping may be defined by the following formulas: $K_x = \bar{K}_x C_x$; $K_y = \bar{K}_y C_y$; $K_z = \bar{K}_z C_z$, where $\bar{K}_x$, $\bar{K}_y$, $\bar{K}_z$ are coefficients obtained on the basis of test results of other tyres. For the high pressure tyres, at $_{-3}$ $P_o = 0.8 \div 1.0$ Mpa, their values may be considered as follows: $\bar{K}_x = 2.5 \cdot 10^{-3} s$; $\bar{K}_y = (5 \div \div 10) \cdot 10^{-3} s$; $\bar{K}_z = 2.5 \cdot 10^{-3} s$. Damping of the undercarriage leg structure in longitudinal and lateral directions is calculated by relative damping coefficients $\bar{n}$,obtaining at frecquency tests for existing undercarriage leg structure, usually their values are as follows: $\bar{n} = 0.035$. The relative damping coefficient of symmetrical and antisymmetrical flexural vibration notes for coaxial mast shaft is less as compared to undercarriage leg and for the structures under design it may be assumed to be as follows: $\bar{n} = 0.025$. Such damping characteristics were used in the process of damping determination for the structure veriant. Table 2 shows design $\bar{n}$ and experimental $\bar{n}_{ex}$ values for relative damping coefficients of natural vibration notes.

Table 2.

Helicopter vibrations	$\bar{n}$	$\bar{n}_{ex}$
along axis OX	0.0674	
along axis OY	0.0343	0.0302
along axis OZ	0.0052	0.033
around axis OX	0.0248	0.022
around axis OY	0.0355	0.0353
around axis OZ	0.0531	0.0573

Thus, the application of the obtained damping characteristics allows to get acceptable (with the exception of vibration along axis OZ) correspondence between design and experimental values for relative damping coefficients of natural vibration main notes when the coaxial helicopter is on the ground.

Coaxial helicopter safety against "ground resonance" is controlled during the full-scale test at the following conditions: running-up on the platform, landing from hover mode, taxiing on the airfield, running take-off and landing . The running-up on the platform are performed within the whole range of the rotor operating relational speed and undercarriage shock-absorber rod deflection, from the static attitude to the full extended position with the provocation of a "ground resonance" effect. The provocation is maintained by the vibration of the cyclic-pitch control stick equal to a stator vibration frequency at "ground resonance". For the first time those tests have been carried out by pilots E.I. Larushin and N.P. Bezdetnov. As is generally known, during the "ground resonance" free vibration the stator vibration frequency ρ_s and blades vibration frequency ρ_{bl} in a rotational plane are in the following relation: $\rho_s = \omega - \rho_{bl}$. The running-up on the platform, provoking the stator and blades vibration amplitude in the rotational plane, shows the highest ρ_s and ρ_{bl} values with the helicopter vibrating on tyres, fully-extended rods and disabled shock-absorbers. The full-scale test showed that the least "ground resonance" margins at all tested conditions are found during the running-up on the platform provoking vibration by a control stick and extending completely the shock-absorbers. Therefore at the design stage the coaxial helicopter parametres are selected in the way that the safety against "ground resonance" is also sure to be provided at the above condition.

The following factors should be considered during the "ground resonance" test: firstly, the "ground resonance" test is a risky business for a crew; secondary, this test may entail serious helicopter damage due to loads occured at "ground resonance"; thirdly, the pilot has to engage a great number of modes varying the rotor rotational speed, amplitude, frequency and trajectory form of the cyclic-pitch control stick . Those tests require high servise life level of the prototype. Since the "ground resonance" tests are labour-intensive and risky business the planning of experiments presents the urgent problem. The planning presupposed the analysis actively varying the helicopter parametres and vibration excitation parametres. Further,on the basis of the analysis results the most unstable condition and the most effective regime for the "ground resonance" provocation are to be selected. The obtained condition is tested on the helicopter. Besides, by analysing results of the calculation you may leave or remove limitations for the cyclic-pitch control stick motion. Thus the calculated model is required to be made which allows to show the helicopter behaviour at "ground resonance" excitation. For all this the cyclic-pitch control stick motion should be simulated. The calculated model will present the model of the helicopter forced vibrations. The above calculated model considers the helicopter movements decomposed as a series of vibration notes. The following stator vibration notes are taken into account: travels along longitudinal, vertical and lateral axes, round those axes and rotor shafts bending in longitudinal and lateral planes. In this case the generalized characteristics of vibration notes are used. Such approach has the following advantages. First of all that provides an apportunity to use more effectively the results of the helicopter test for the model calculation. The equation includes frequency values, damping relative coefficients, centre of masses vibration amplitudes for the fuselage and the upper and lower rotor hubs which are found by vibration note forms and used to define the generalized masses. The application of the generalized characteristics and the above initial data allows the complete consideration of the helicopter fuselage flexibility. All this provides for the accuracy improvement of the calculated model. The given calculated model considers all possible variations of the cyclic-pitch control stick motion ,i.e. the stick linear travel in any direction, clockwise and counter clockwise circular motion, travel along the elliptical trajectory; in this case the ellipse axis may be oriented in any direction. The cyclic-pitch control stick motion causes the swashplate rings deflection on the upper and lower rotors. The Coriolis forse acts due to the blade flapping in the rotatinal plane. Aerodynamic forces acting at the rotor blades are considered in accordance with the rotor cone angle value. Besides it is implied that the "ground resonance" tests are carried out at relatively calm surrounding flow, i.e. the gust is not observed and the flow level surrounding the helicopter does not change with the cyclic-pitch control stick motion. In this case the forces equal to Coriolis forces sum at the upper and lower rotor will act on the helicopter stator. The rotor thrust projection appeared due to swashplate rings deflection from the neutral position, will also act on the stator. The solution of the obtained set of differential equations consists of general and particular ones. The general solution corresponds to the set of equation with the zero right side i.e. the set of homogeneous equations. The solution is obtained by determination of the helicopter stability against "ground resonance" vibrations. The particular solution to the set of equations proceeds from the unknown parametres expansion into a Fourier series. After such substitution the equation set becomes the set of linear algebraic equation. Amplitude values of the helicopter stator and blades forced vibrations are obtained by solving the equation set employing the Gayss method. The effectiveness of this or that vibration excitation condition is clearly shown in fig 7 and 8 by the centre of masses mechanical trajectories for upper and lower rotor blades. It is seen from the above graphs that the lower rotor reacts more readily on the circular counter clockwise excitation by the cyclic pitch control stick and the upper rotor is more sensitive to the circular clockwise excitation. The lag hinge characteristics at free vibrations may be determined by clockwise and counter clockwise circular excitations.

The discribed calculated model is a part of programs intended to define the "ground resonance" characteristics for a coaxial helicopter which are entered into computer, that allows to obtain all required information for the experiment planning quikly, handy and clearly.

Disk and hydraulic friction dampers, metal-polymeric sliding bearings requiring no lubrication are applied for coaxial helicopters in order to damp the rotor blades vibration in lag hinges [5,6,7]. Due to different location of the coaxial rotors with respect to the helicopter height the values of permissible damping moments in the lag hinge of the lower rotor blade Mli, may be less as compared to the moments of the upper rotor Mupi ("i" is a rotor blade number). This facts allows to reduse loads in rotational plane of the lower rotor. Hydraulic dampers of the KA-26 helicopterare installed on the upper rotor only. The blade damping moment on the lower rotor is stipulated by friction in the lag hinge structure component loaded by the blade centrifugal force, cutting-off forces and bending moments in the flapping plane. Friction disk dampers are installed on the upper and lower rotors of the KA-25K helicopter. Since the play of friction disk dampers may mount to 40′ the metal-polymeric sliding bearings were installed in addition to friction dampers in lag hinges, and the lower rotor dampers were disregarded. Based on the experience obtained by KA-26 and KA-25K helicopters with different damping moments on upper and lower rotors lag hinges the KA-32 helicopter was equipped with the lag hinges metal-polimeric sliding bearings showing different moment values on rotors. During the Ka-32 helicopter "ground resonance" test the upper rotor damping moment $M_{up} = \frac{1}{k} \sum_{i=1}^{k} M_{upi}$ was plotted as a function of the lower rotor damping moment $M_L = \frac{1}{k} \sum_{i=1}^{k} M_{Li}$ ("k" is a number of rotor blades), at the maximum moment domain boundaries in lag hinge, which $M_{up} = f(M_L)$ (see fig. 9). The helicopter, the damping moments of which are less than the permissible ones, is unstable against this "ground resonance". It should be mentioned that the KA-32 blades relative vibration frequency in the rotational plane in the lag hinge is characterised by the following value: $\bar{P}_{bL} = 0.34$ ($\bar{P}_{bL} = P_{bL}/\omega$). This figure also shows the KA-25K, KA-26 and KA-126 moments with $\bar{P}bl = 0.3$. Metal-polimeric sliding bearings and hydraulic dampers for the upper rotor are installed in rotor lag hinges of the KA-126 helicopter.

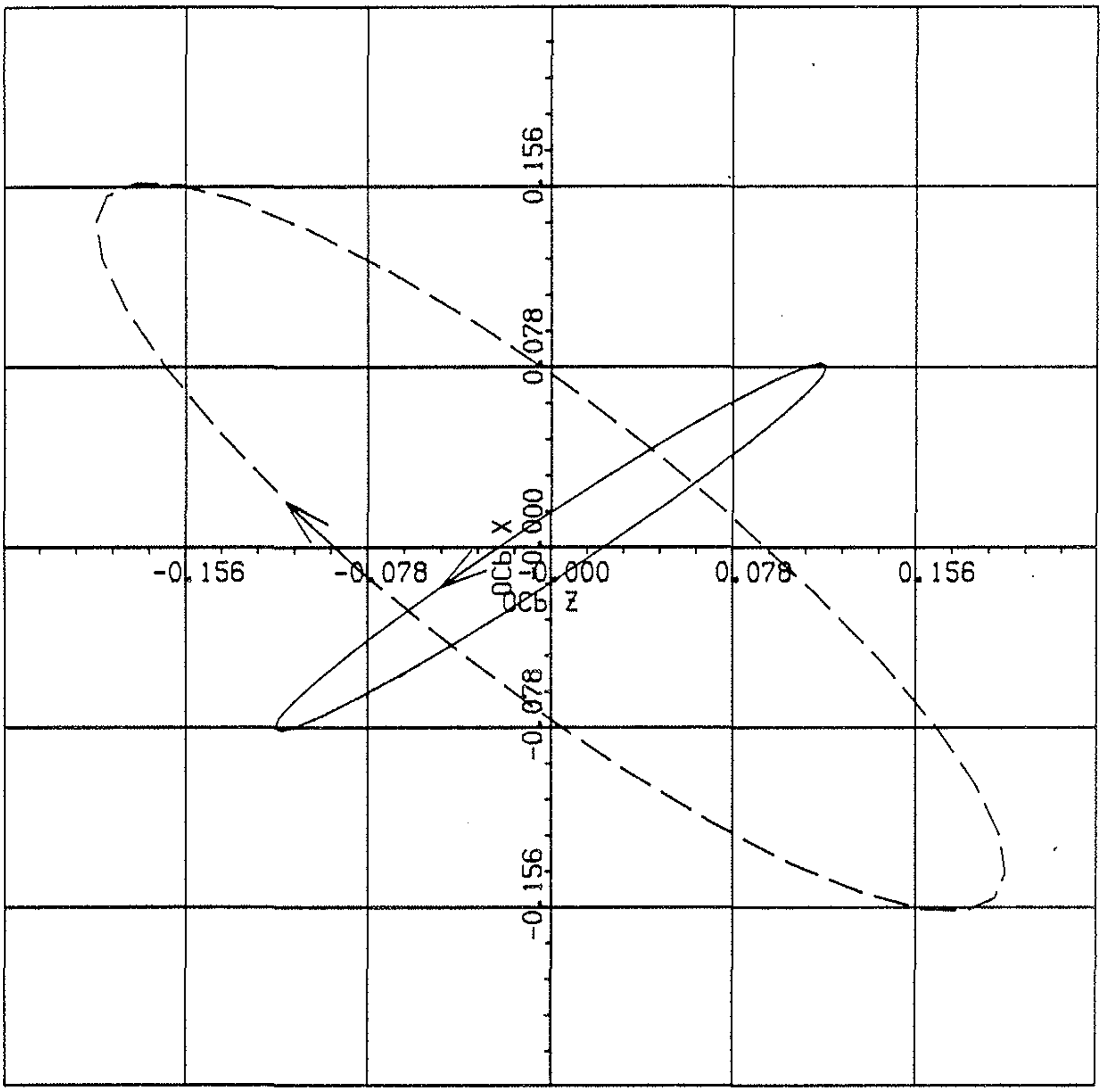

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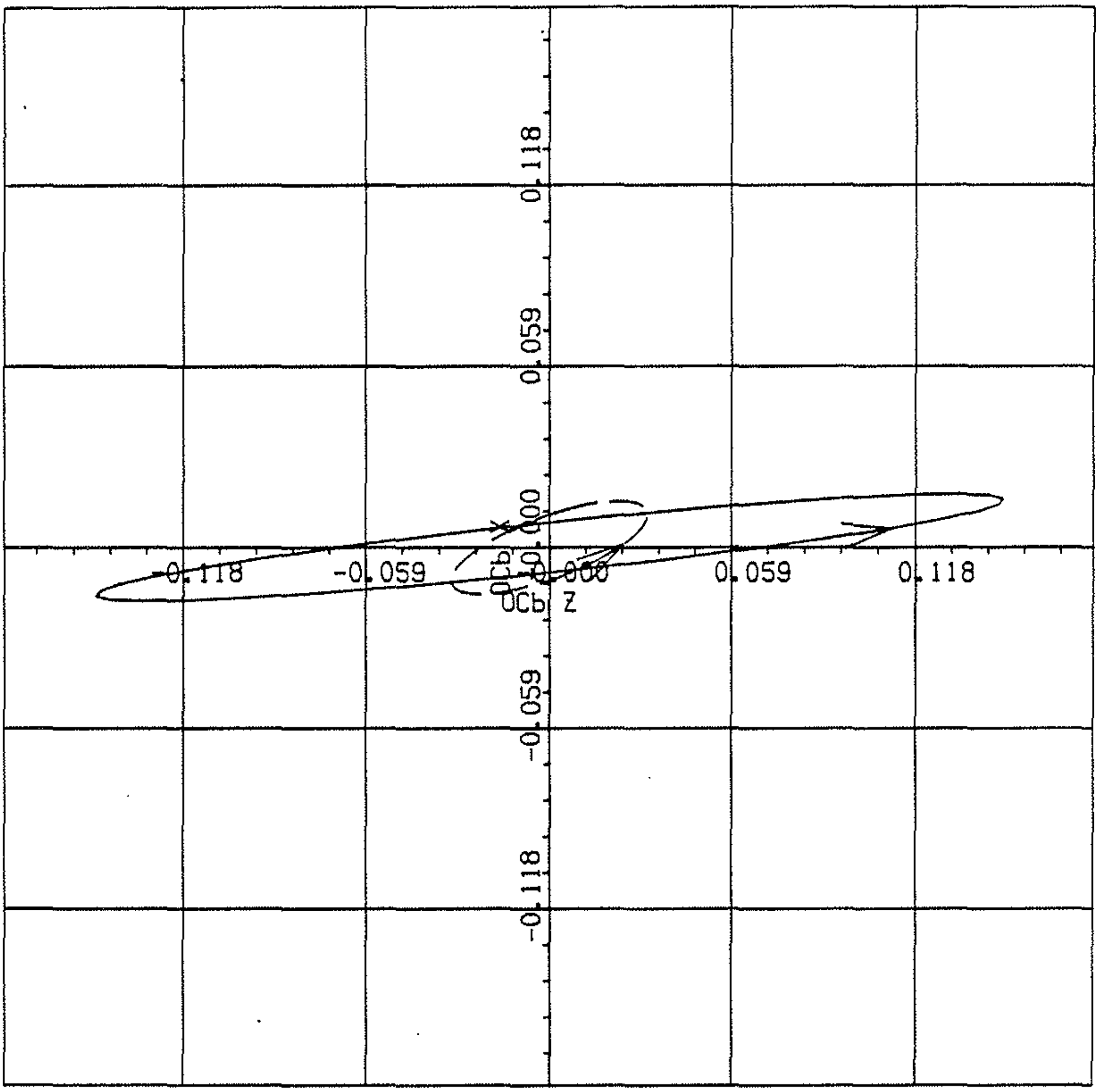
Fig. 7 Centre of masses mechanical trajectories of the rotor blades at clockwise circular provocation by a cyclic-pitch control stick.



_______ centre of masses of the lower rotor blades.

------- centre of masses of the upper rotor blades.

Fig. 8 Centre of masses mechanical trajectories of the rotor blades at the counterclockwise circular provocation by a cyclic-pitch control stick.

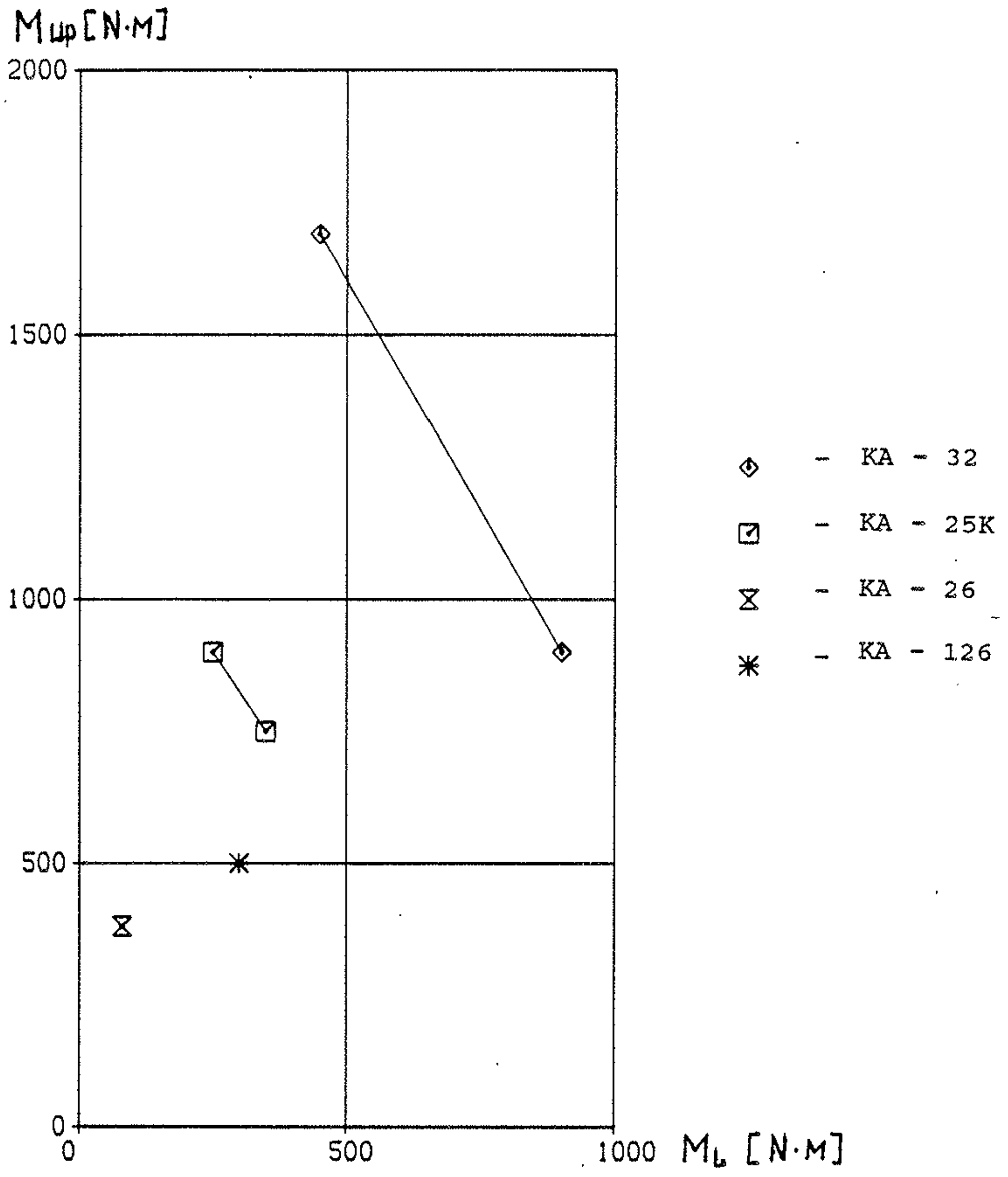


Fig. 9 Blades lag hinge moments at the maximum values domain boundaries.

Assume that the rotor permissible moments are $M_{\Sigma} = M_{up} + M_{L}$, then the relative characteristics are as follows: $\bar{M}_{\Sigma} = M_{\Sigma} / G$, $\bar{M}_{up} = M_{up}/G$, $d = Mh^{2}/J$, where:

G, M - helicopter weight and mass,
J - the helicopter inertia moment relative to the longitudinal axis,
h - distance from the helicopter center of mass to the upper rotor hub center.

Fig. 10 shows the $\bar{M}_{\Sigma}$ value for coaxial helicopters and fig. 11 shows the $\bar{M}_{up}$ value; the average $\bar{M}_{up}$ values are given for KA-25K and KA-32 helicopters.

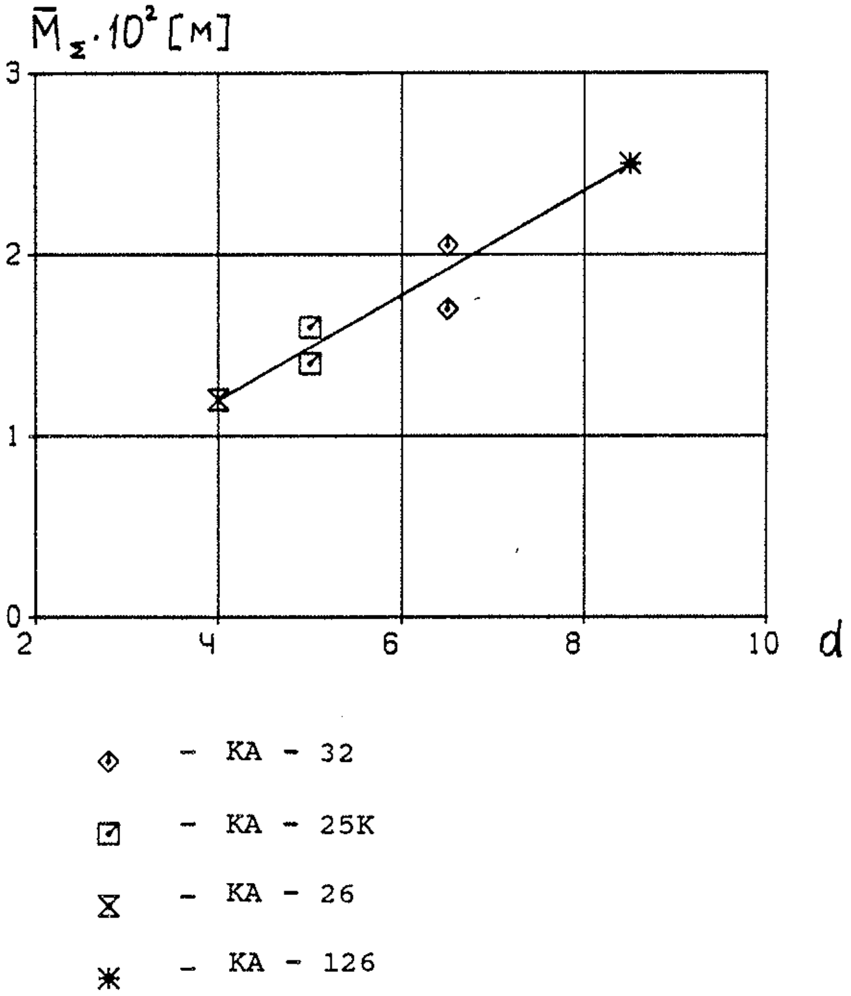


Fig. 10 Permissible moments in lag hinges versus the helicopter inertia-mass parameter.

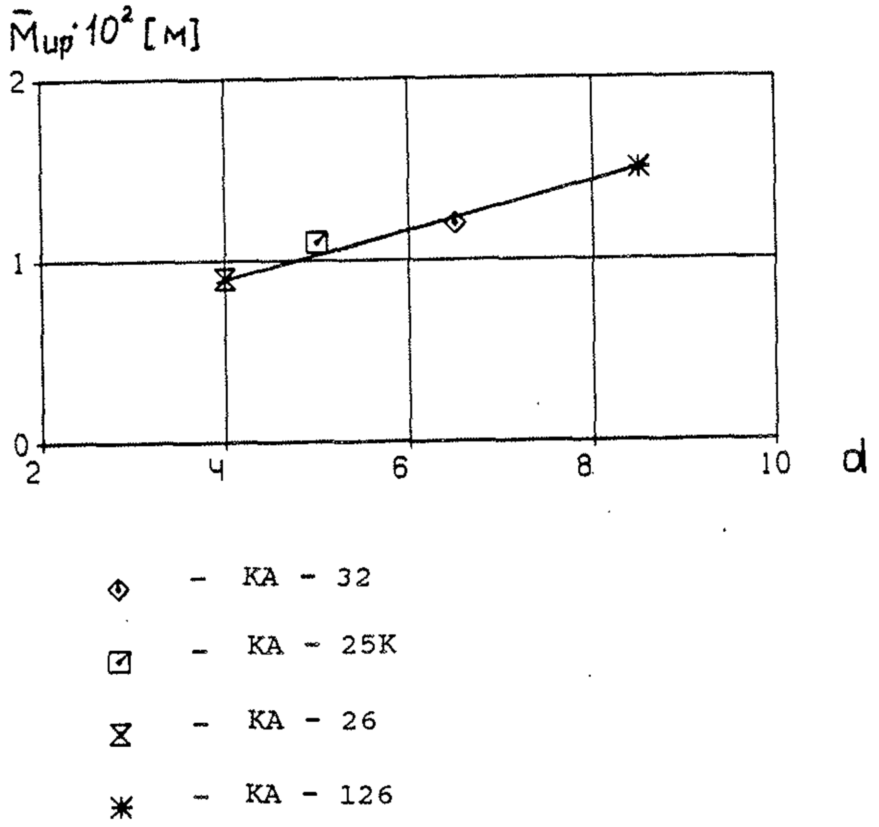


Fig. 11 Permissible moments in the upper rotor lag hinges versus the helicopter inertia-mass parameter.

Relative damping moments in rotor blades lag hinges versus the helicopter inertia-mass parameter were obtained following a number of experiments aiming at the safety provision against "ground resonance", that may be used for safety evaluation in the process of a helicopter desigining.

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