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VIBRATIONS OF HELICOPTERS OF "MI" FAMILY. INVESTIGATION, VIBRATION ABSORBERS APPLICATION, BUFFET

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ABSTRACT

Physical and mathematical models used to resolve the problem of rotor-and-support system coupled oscillations are considered in this paper. These models take into account the variety of blade-to-hub attachment conditions and blades natural twist.

The results of research of vibro--condition and vibration absorbers application are analised. Special attention was given to analysis of non-linear effects and pendulum swing friction minimization. Now is the time for mass scale use of vibro-absorbers both on the Mi-8 basic model and on prototypes. "Mi" family helicopters have found their second spring 25 years after the first prototype maiden flight.

Also presented are the results of flight helicopter vibro- condition analysis at high flight speeds including those for A-10 helicopter in its record flight with the use of vibro- absorbers at the airspeed of 368.4 kmph. The study and the identification of unsteady lateral vibrations which mostly occur on Mi-8 helicopter family have brought us to the understanding of helicopter buffet.

ROTOR AND FUSELAGE COUPLED OSCILLATIONS.

VIBRATIONS.

Helicopter dynamics investigation calls for examination of the coupled oscillations of the rotor and fuselage as elastic support. This paper shows the application of dynamic stiffness method to the calculation of rotor-and-support system coupled oscillations.

A rotor has three or more identical blades evenly positioned over the rotor disc, each has the same type of attachment to the hub. The method enables to examine any combination of articulated or stiff blade-to-hub attachment, conditions in thrust and rotation planes (the flapwise and chording directions) as well as the use of so-called lag dampers and other damping devices [Ref.4].

The rotor blades are being deformed in the sections main stiffness axes direction. Due to blade natural twist the main stiffness axes form a spiral surfaces. The axis of an undeformed blade is a straight line. For such a model flapwise and chordwise blade oscillations are coupled owing to the blade twist and non-zero pitch angle even when there is no oscillation coupling through the support (the fuselage).

The schematic beam consisting of the weightless sections of constant profile with discrete weights on their bounds is used as computation model. Sections lengths, stiffness values in the direction of main rigidity axes and sections pitch angles to the axes of the hub are chosen as an approximation of corresponding values of the real blade.

Within the limits of dynamic stiffness method we represent the system as two parts – one as rotating rotor and the other as stationary elastic support (fuselage). Small displacement of the system at the place of its joint (at the rotor shaft) are defined by the following expression:

$$\vec{\delta}(t) = \vec{\delta}_0 e^{ipt} \qquad (1)$$

where $\vec{\delta}_0\{ X, Y, Z, x, y, z \}$ is a deformation amplitude vector. Its components are the complex values of displacements and angles.

Natural oscillations are defined by equilibrium conditions for non--rotating coordinate system:

$$(C + D) = 0 \qquad (2)$$

Natural oscillations frequencies are found from the following equation:

$$\det (C + D) = 0 \qquad (3)$$

where C and D are the matrixes of dynamic stiffness coefficients of the fuselage (support) and the rotor correspondingly.

The coefficients of C matrix are defined by finite element method on beam or combined model using shell, beam, frame or rod elements. An extrapolation of the results of the measurements on prototypes is also applied. The rotor dynamic stiffness coefficients of D matrix are defined in accordance with [Ref.3] by the following expression:

$$D = G_0 Dw(p) G_0 + G' Dw(p_1) G' + G Dw(p_2) G$$

$$. \; . \; . \qquad (4)$$

where $Dw(p) = \sum_{K=1}^{n} \Delta_K^{-1} D_b(p) \Delta_K$

and similar expressions for the arguments

$$p_1 = p - w \quad ; \quad p_2 = p + w$$

where w – rotor angular velocity;
n – number of blades;
Δ_K – matrix of coordinate transformation to the axes system connected with the blade number "k".

Db = blade dynamic stiffness matrix with pitch angle and angular velocity "w"

and the special matrixes G_0 and G for linear displacements of the rotor center have a form

$$G_0 = \begin{Vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{Vmatrix} \qquad G = \begin{Vmatrix} 1/2 & -1/2i & 0 \\ 1/2i & 1/2 & 0 \\ 0 & 0 & 0 \end{Vmatrix}$$

(G' – transpositioned)

As one can see from the expression (4) D matrix consists of three items each being a similarity transformation from rotating to non-rotating coordinate system of the corresponding component of rotor dynamic response vector, depending on one of two combination frequencies " p ± w " or of frequency "p".

Fig. 1 shows the solution of equation (3) for the most typical case when the hub is moving along the rotation plane only. The results are presented as a function of natural oscillations frequency versus mean value of support stiffness. The parameter is the support anisotropy coefficient (Cx/Cz ratio).

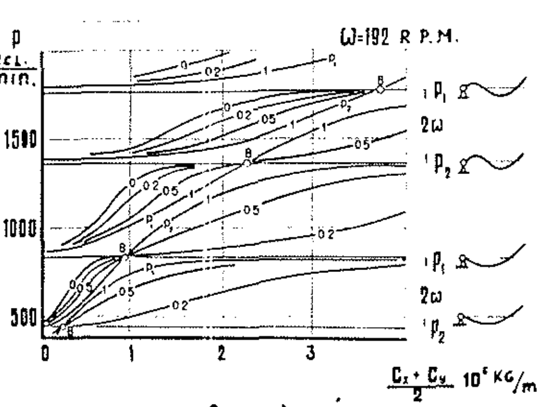

fig. 1

In some cases the influence of anisotropy is significant, particularly when there is the greatest influence of support stiffness on the whole. The asymptotes on the picture are defined by antiresonances when the blade dynamic stiffness becomes infinite. The difference between the two corresponding asymptotes is 2w. Singular points B on the picture correspond to such an oscillation mode when the rotor center is moving in a circle due to antiresonance at one of the combination frequencies. This type of motion belongs to the whole family of the curves crossing the B points irrespective of anisotropy level. In the general case when oscillations of any natural mode occur the rotor center is moving along the ellipse and the blades are oscillating with two frequencies (p ± w) at once.

A characteristic feature of the oscillations of interest is their dependence on the blade pitch angle as shown on fig. 2.

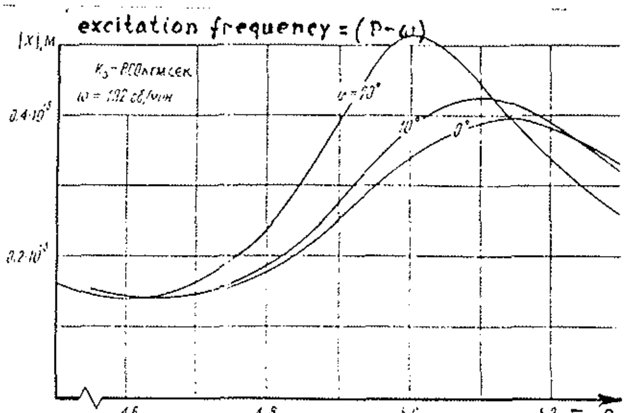

fig. 2

This is explained by the fact that the share of the blade oscillations in the least stiffness plane changes with the pitch angle increase.

The present results were obtained under normalized values of external loading which vector corresponds to the oscillations with (p - w) combination frequency. The diagram on fig. 3 shows the influence of rotor angular velocity on its resonance characteristics in the vicinity of vibration harmonic frequency.

p = p/w = 5

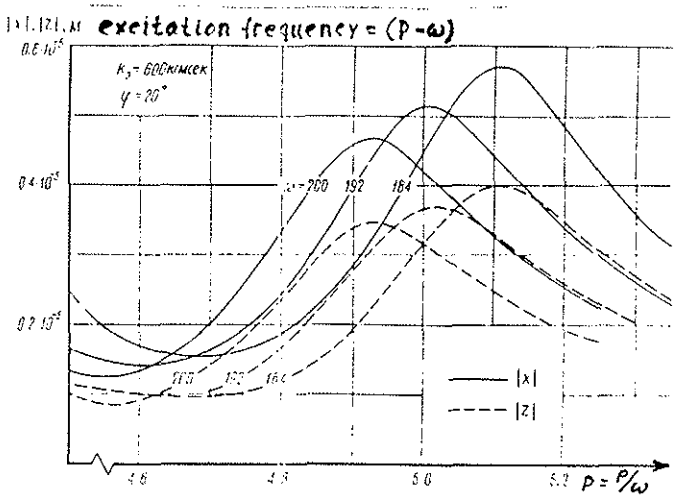

fig. 3

These circumstances specified vibration level in the cockpit at 16 Hz frequency for the Mi-8 helicopter family to be never more than 0.3 g at cruise and 0.4 g at maximum airspeed. At the same time this level for the helicopters throughout the fleet might differ by two times. This vibration level was considered satisfactory for the period of 1960 - 1970.

VIBRATION ABSORBERS

A well-known tendency of comfort level improvement and vibration level reduction have brought us to the understanding of the need to develop the vibration absorbers, as it was the case with many other helicopter designers.

The Mi-8 helicopter prevailing load components which cause fuselage oscillations with vibration harmonics are the forces acting in the plane of rotation with 4w frequency. Therefore the application of vibro--absorber tuned to the 4th harmonic solves the problem of vibration reduction for the frequency of the fundamental vibration harmonic and provides the desirable comfort level. Thus, in addition to the well-known filtering properties of the rotor we insulate the fuselage from traditional vibration harmonics of the load - from the fundamental 5th harmonic (16 Hz) in this particular case.

Among various possible design solutions the preference should be given to the pendulum type dynamic vibro-absorbers installed on the main rotor. Pendulum absorbers keep required tuning under any rotor angular velocity due to the linear dependency of pendulum oscillations natural frequencies versus angular velocity and therefore their functional efficiency keeps being rather high. Their installation on the rotor proves to be beneficial in terms of the exciting forces balancing at the place where they are applied.

While developing vibro-absorbers the main attention was given to minimization of friction when the pendulum is swinging which promised the greatest effect in dynamic response with minimal pendulum weight. The positive result was achieved through selection of required surface geometry in bifilar pendulum suspension and by means of proper selection of cone negative angle as shown on fig.4, that removes the lateral loads off the thrust washer.

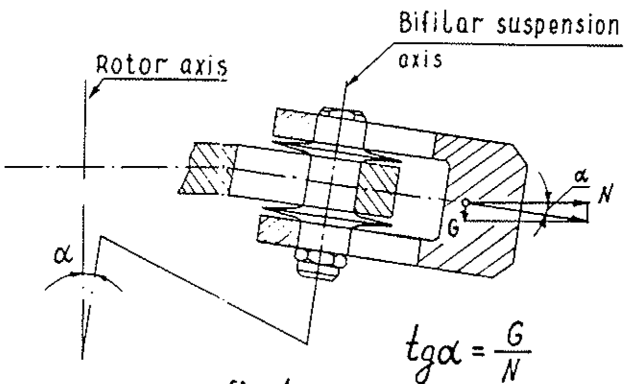

fig.4

For the purpose of proper pendulum weight selection and for fine tuning procedures the analysis of pendulum forced oscillations modes stability with regard for non-linear dependency of righting moments versus deflection angle has been performed. It is known that when the deflection amplitudes are large these moments are proportional to Sinφ. The results of this analysis are presented on fig.5. One can see that the resonance peak shifts towards lower frequencies as amplitude increases. This fact should be taken into account to obtain the large pendulums oscillation amplitudes and the stability of the operation at the same time. When the oscillation amplitudes are higher than 0.8 the operating efficiency starts to drop rapidly because of the mode instability or even circular pendulums motion.

NON-LINEAR OSCILLATIONS OF ABSORBER'S PENDULUM [Sinφ]

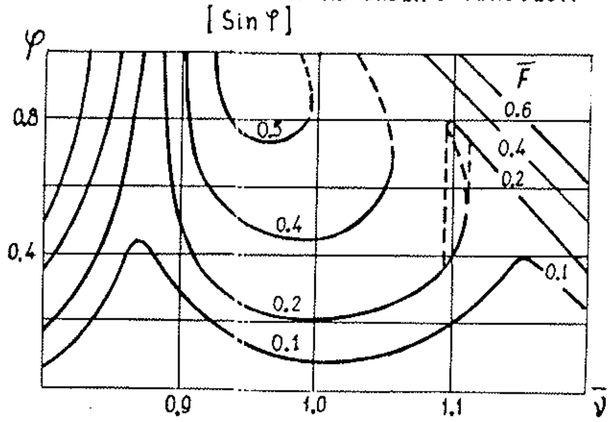

fig.5

Using the results of the above-mentioned investigations a favourable positive effect of up to 10 times reduction of the vibration level has been obtained for the parameters chosen with active mass weight of about 0.4% of TOW. This effect compared with initial level is shown on fig. 6,7 as a function of cockpit vibration level versus helicopter airspeed and spectral density of vibration level around the frequency of 16 Hz (i.e. 5th harmonic). Similar effect has been achieved for practically all the structural elements of the fuselage and equipment. Besides the smoother ride this situation provides a significant effect of structural units life-time increase up to the life-time of the airframe.

Vertical vibrations in the cockpit
f=16 Hz (5ω)

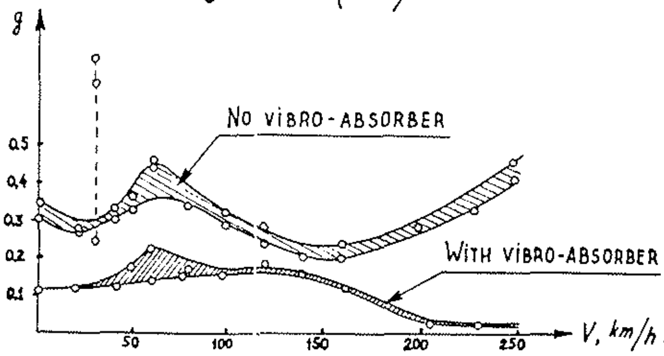

fig. 6

THE SPECTRUM OF VIBRATIONS IN THE COCKPIT AT CRUISING AIRSPEED

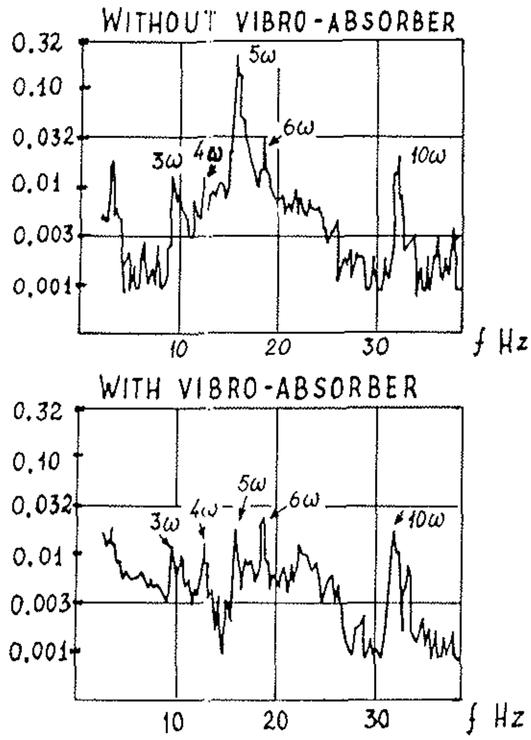

fig. 7

25 years after the maiden flight of the first prototype Mi-8 helicopters nowadays are going through their second youth. At present about a thousand of such a vibration absorbers are being operated on the basic helicopter model as well as on its Mi-8MT, Mi-17 and Mi-14 modifications.

The application of vibro-absorbers is naturally related to achievement of high airspeeds of about 350 - 400 kmph by a helicopter. We came across this problem in 1979 during the preparation of the world speed record flight on the A-10 helicopter. This helicopter unlike its prototype the Mi-24 had to be prepared for this flight in the configuration without a wing for various reasons. This circumstances must have redoubled the problem of the alternative loads and vibration growth with airspeed increase over 340 kmph. The obstacle on the way to further increasing of airspeed in our case was the loss of comfort and piloting conditions as well as rizing in strength. Permissible vibration level and the ability to reach a record for that time airspeed of 368.4 kmph could be only achieved through installation of vibro-absorber on this helicopter. Fig. 8 shows vertical vibro--accelerations in the cockpit compared with initial values.

High flight speed vibrations

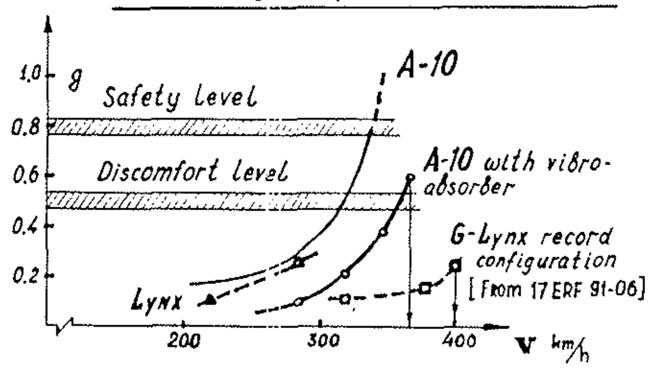

fig. 8

The case is worth emphasizing because the vibro-absorber used was not a specially designed one. It was a modified vibro-absorber from the Mi-8 helicopter. Therefore, the pendulums oscillations didn't coincide with the optimum mode and the critical amplitude values were exceeded so the result obtained was only minimum of required. At the same time the analysis of the conditions to perform speed record flights without the use of propulsive devices shown on fig. 9 indicates that the problem of vibration level has always accompanied this progress or was one of the main obstacles on the way.

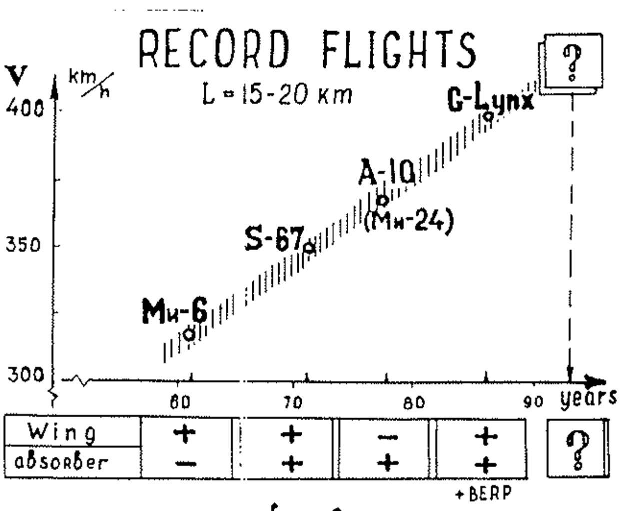

fig. 9

In every example shown one can see a wing and/or vibro-absorber used and in case of G-Lynx record helicopter there are also special aerofoils [Ref.6]. The solution of this problem will become even more topical for the future speed records.

LATERAL VIBRATIONS

The study and identification of unsteady lateral vibrations have been an important area in solution of vibration problems of the helicopter group under consideration.

The specific features of such a vibration type were the following:

1) Casual nature of their appearance. Though some of them have gained a very bad reputation.

2) Their occurrence, in the main, at medium flight speeds with no correlation to atmospheric turbulence along the flight route or aircrew actions.

3) The oscillations occur with the frequencies close to the lowest tone in the lateral plane but with a quite broad spectrum band.

The features mentioned along with specific perception by the crew of the lateral accelerations have been arising a psychological discomfort and expectation of some latent defect.

A numerous investigations and flight experiments with several helicopters have been performed during a considerably long period of time. As a result about a dozen of the versions explaining the origin of the phenomenon has been studied. The basic ones are shown on table 1:

TABLE 1
MODELS AND VERSIONS FOR LATERAL OSCILLATIONS ANALYSIS

	Oscillating loop or name	Feedback. Cause
1	Main Rotor + flexible fuselage	a) Kinematic displacement in (flight) control circuit b) Oscillating loop "autopilot - -servo actuators"
2	Tail Rotor + flexible fuselage	Kinematic displacement in (flight) control circuit
3	M.R. + T.R. + transmission + + engines	Pumps-regulators in fuel-automatics

TABLE 1 (CONTINUATION)
MODELS AND VERSIONS FOR LATERAL OSCILLATIONS ANALYSIS

	Oscillating loop or name	Feedback. Cause
4	M.R. + flight controls + + hydraulic actuators	Hydraulic pumps drive; Interconnections due to actuator's mounts deformability
5	M.R. + T.R. + flight controls	Non-linear self-oscillations with sub-garmonics generation due to Coulomb friction in lag and flap hinges
6	Tail wegging: T.R. + flexible fuselage	Shaft possible travel in angular directions x and z, presence of flap compensator
7	Buffet: Flexible fuselage + + T.R. in the vortices from the hub and cowlings	Influence of hub and cowlings vortex sheet on the tail rotor

The latter version on the list has been accepted as being corroborated by the required evidence. The phenomenon has lost its fearing mysteriousness.

Below are the main findings of the investigation.

Fig. 11-13 presents the level of oscillations versus flight speed, vertical descent velocity or climb rate and slip angle. The spectrum of vibrations measured and of tail boom bending moments as well as their distribution along the fuselage prove the phenomenon to be a form of natural bending-torsional lateral oscillations of the fuselage by its lowest form with a frequency of about 4,5 Hz.

Besides, the evaluation of the decrements of excited oscillations has been performed by two different methods. In the first case the harmonic signal of required frequency and amplitude has been fed by an electric signal generator through an autopilot to the jaw control actuator. Owing to actuator rod travel and corresponding tail rotor thrust variations the oscillations being considered have been excited. The decrement has been determined by the attenuation of the transient after the excitation were switched off.

In the other case the decrements have been determined using vibration spectral density function (the same way as by resonance peak width for one-degree-of-freedom system). To obtain a reliable spectrum when processing the result of vibration measurements the smoothing methods (to obtain smooth functions) were used and averaging time chosen was 40 sec and more.

Both methods used gave practically the identical results, which convinced us additionally that the system (i.e. the helicopter) didn't have any signs of self-oscillations.

The analysis of the result obtained allowed to suggest the availability of turbulent flow kernel passing through in the neighbourhood of tail rotor.

The analysis of the airflow motion

and its pattern in vicinity of the tail rotor has been made using filming by two cameras. One camera was placed on the tail gearbox case showing a panorama of main rotor head, cowlings and engine exhaust pipes from the rear. The other one was on the board of the helicopter flying in parallel to the test machine. A forty-eight shots per second filming frequency proved to be sufficient. Flow visualization was realized by means of remote-controlled smoke generators (smoke pots) as shown on fig. 10.

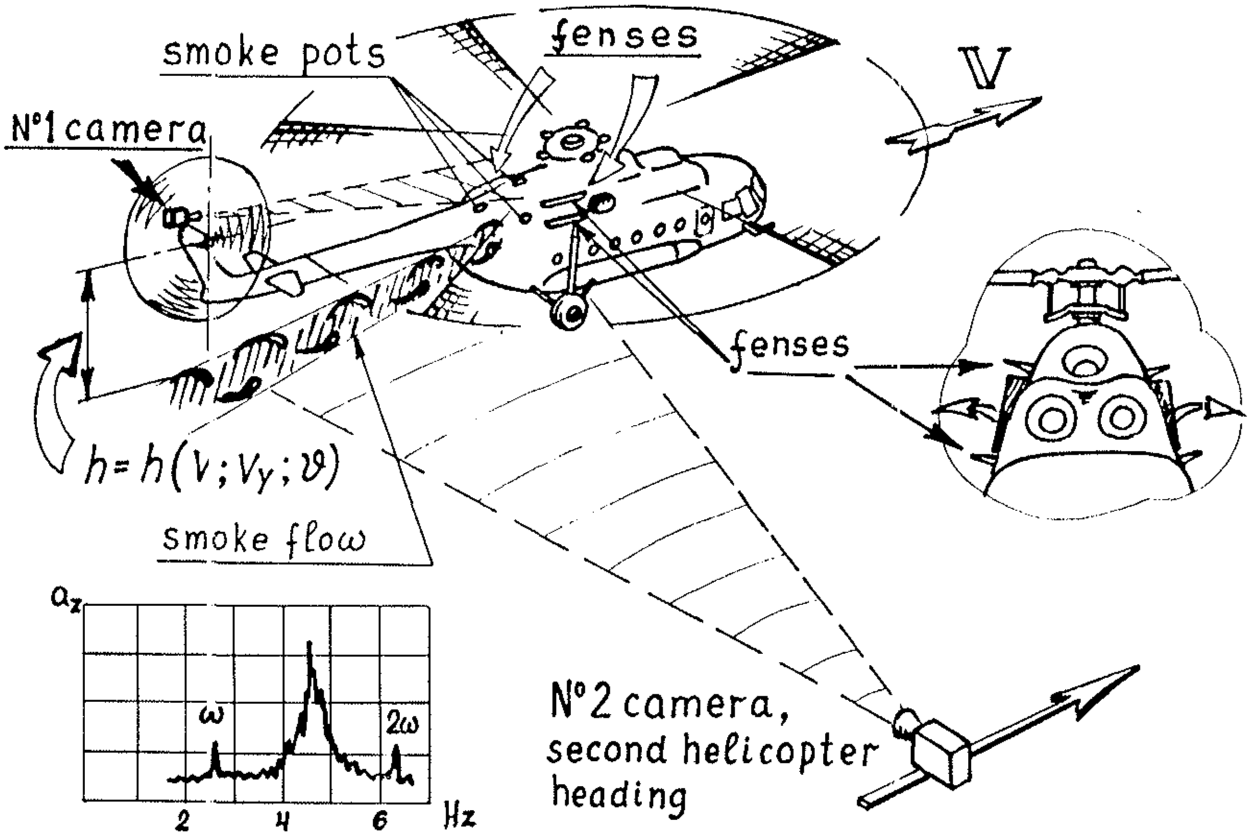

Fig.10 FLIGHT EXPERIMENT FOR BUFFET STUDY

The results of shooting have shown direct correlation between the lateral vibrations level and position of visualized flow against the tail rotor. The correlation gave one of the main evidences in favour of this version. Besides, the film enabled to define the frequency of vortex rotation which was found to be almost the same as the frequency of fuselage lateral oscillations. This fact largely predetermined the appearance of such a vibrations on Mi-8 helicopter.

High accuracy of the results was reached due to control of rotor blade passage on the film sequences. This result gave us a second proof of the version being analyzed.

The third witness we have obtained from the experiment with installation of aerodynamic fences on the cowlings (fig. 10). The purpose of the fences installation was to reduce the intensity of vortex formation and to modify the spectrum of flow velocities. Test results are shown on fig. 12 compared with the initial variant. One can see that the level of lateral oscillations has been reduced by two or three times, no dependence on slip angle can be seen any more. Thus, the vibration level remained can be practically estimated as background one.

At the same time this third feature has shown the approach how to solve similar problems on newly designed helicopters. For example when designing the Mi-26 helicopter a number of wind tunnel experiments has been carried out on a scaled helicopter model to identify the points of vortex formation, to choose the optimum outlines of the cowlings and fuselage tail.

We were much interested to see the paper on similar problems from the other helicopter companies at the 17th European Forum [Ref.5].

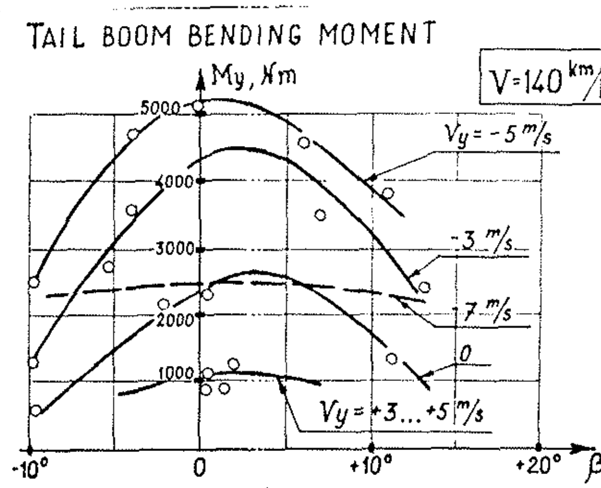

fig. 11

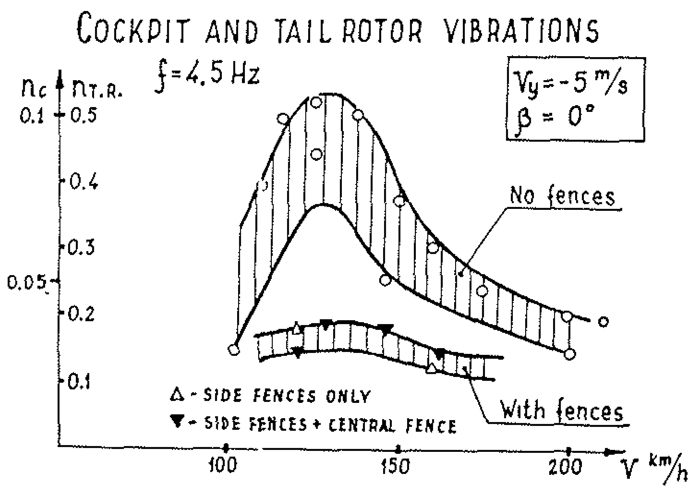

fig. 12

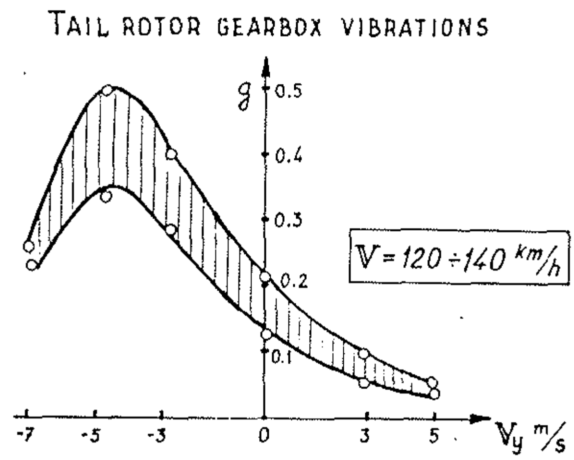

fig. 13

A SYSTEM OF ARGUMENTS AND CONCLUSIONS

1. Lateral oscillation decrement values are large enough (about n = 0,07) and are equal to the damping values defined by a spectral density function of natural oscillations.

2. Maximum oscillations occur under such a combination of horizontal and vertical flight velocities as well as pitch and slip angles, when the flow from helicopter cowlings and rotor head runs into tail rotor disk area.

3. The frequency of vortex rotation and associated velocity pulsations are close enough to fuselage natural frequency.

4. The destruction of the vortex wakes from cowlings and head reduces the lateral oscillations level down to its complete disappearance

REFERENCES

1. Риз П. М., Пожалостин А. И. " Вибрации и динамическая прочность воздушных винтов" Труды ЦАГИ Вып. 609 1947

2. Гродко Л. Н. Вибрации вертолета - в книге " Вертолеты: расчет и проектирование" - т. 2 М. Машиностроение 1967

3. Мягков Ю. А. "О применении метода динамической жесткости к решению задачи о собственных колебаниях винта на упругом анизотропном основании" Прочность и долговечность авиационных конструкций Вып. 6 Киев 1973

4. Myagkov Y. A. " Some comments on tail rotor ground resonance problem" 18 ERF, p. 22

5. C. Mazzuccelli, E. T. Wilson " The achievement of aerodynamic goals on the EH-101 project through the "Single Site" concept" 17 ERF, 91-06

6. D. E. H. Balmford, B. S. Bender "The Compound Helicopter- - a concept revisited" 17 ERF, 91-07