FOR THE ROTOR VORTEX STRUCTURE ANALYSIS

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Abstract

Vortex wake is being simulated within the framework on non-linear transit rotor vortex theory. Rotor blades are being substituted for thin airfoil with lateral/trailing edge vortices. Vortices are running on motion lines of liquid particies.

Time and space dependent solution is being made by using discrete vortex method.

This paper presents results of comparison between calculation and experimentation of vortex structure as well as analysis of flow and explanation of a number of phenomena already intimated earlier in experiments provided for vortex structure visualization of the coaxial/single rotor helicopters.

1.Formulation of problem

Numeric modeling [1] offers large potential in detailed investigation of rotorcraft aerodynamics specific nature.

In a general case a rotorcraft performing unrestricted motions is examined. The rotorcraft has rotors that can turn with respect to its body, wing and horizontal tail. However, the mathematic formulation of the problem can be examined with an example of a propeller/lifting surface combination arbitrarily oriented with respect to the mainstream.

The blades of rotating lift/thrust rotor turn around axis $O_H Y_H$ that, in its turn, rotate with respect to longitudinal axis *OX* connected with the lifting surface by $\alpha_?$ angle and the whole combination translates at an average speed of $\vec{V}$ and rotates with respect to all axis's of the body-axis coordinate system *OXYZ* at a rate of $\vec{\Omega}$. The main rotor radius R is taken as the typical linear dimension and the main rotor square $F_? = \pi R^2$ is taken as a typical square area. No limitations are posed on the rotor blade configuration, lifting surface and the character of their motion.

The rotor blades and other lifting surfaces are replaced with infinitely thin basic surfaces S_i, (*i* – number of basic surface). The flow behind the combination demonstrates a developed wake in form of free vortex sheets σ_j (*j* – number of free vortex sheet)(fig.1).

An ideal incompressible medium is assumed. Everywhere beyond the rotor blades, other lifting surfaces S_i and their wakes σ_j the flow is consi dered to be nonvortex, i.e. for disturbance velocity potential ? (*x,y,z,t*) Laplace equation is true:

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0\,,\ (x,y,z) \notin (S_i \cup \sigma_j) \quad (1)$$

If $\overline{W}^*$ is lifting surface point velocity caused by translational, rotational and flapping motion and deformation, no-penetration boundary condition is observed in these points:

$$(\nabla\Phi - \overline{W}^*)\overline{n} = 0\,,\ (x,y,z) \in S_i \quad (2)$$

At transfer through the vortex trail surface σ_j pressure continuity and normal velocity component conditions are observed:

$$p_- = p_+\,;\ (\nabla\Phi\overline{n})_- = (\nabla\Phi\overline{n})_+\,,\ (x,y,z) \in \sigma_j\,. \quad (3)$$

Here indexes "–" and "+" refer to different sides of surface σ_j.

For those lifting surface edges from which vortex sheets σ_j flow, Chaplygin-Zhoukovsky hypothesis of finite velocities is true:

$$p_- = p_+\,; (\nabla\Phi\overline{n})_- = (\nabla\Phi\overline{n})_+\,, (x,y,z) \in L_j \quad (4)$$

Here L_j - line of velocity tangential jump surface flow off.

At an infinite distance from rotor/lifting surface combination and its wake disturbances attenuate, hence

$$\lim_{R\to\infty} \nabla\Phi = 0\,,\quad R = \sqrt{x^2 + y^2 + z^2}\,. \quad (5)$$

Now the problem is to find potential $\Phi(x,y,z,t)$ of distributed velocities on blades and lifting surfaces and in the whole space.

In the examined model the lines of vortex sheet flow-off are always postulated on sharp trailing edges of rotor blades and other lifting surfaces. Root and leading blade edges are considered to be rounded. So the position of a flow separation zone is determined in the process of calculating the flow around the combination.

Time deformation of the vortex sheet modeling the wake can be defined by the following equality:

$$(\xi,\eta,\varsigma)=(\xi_1,\eta_1,\varsigma_1)+\int_{\tau_1}^{\tau} w_0(\xi,\eta,\varsigma)d\tau \qquad (6)$$

where ξ,η,ς – sheet point coordinates at time moment τ; $(\xi_1,\eta_1,\varsigma_1)$ – at time moment τ_1; $w_0(\xi,\eta,\varsigma)$ – components of non-dimensional relative velocity of the medium.

Mathematical setting of the problem for rotating rotor/lifting surface combination is common for all elements of a multilevel MM.

To define the loads affecting lifting surfaces S_i, Cauchy-Lagrange integral is used.

2. Numerical method

Numerical method of the main rotor problem solution in nonlinear nonstationary setting using discrete vortices method involves space and time discretization. Continuous vortex layers, used to model basic surfaces of the rotorcraft, other lifting surfaces and their vortex sheets, are replaced with discrete vortex systems and time continuous process of boundary conditions/flow parameters changing, that is continuous in time, is replaced with a step process.

Sheet vortex model proves to be functionally connected with the rotor blade vortex model that demands for elaboration of specific vortex systems for various rotor blade flow conditions. For example, a vortex system based on discrete vortex segments is conceived to be justified for modeling of the main rotor aerodynamic characteristics in blade nonstalling flow conditions. That allows to use available computing power more efficiently. One of plausible blade vortex systems is presented in fig. 2. Lateral vortex filaments are numbered from the leading to trailing edge and longitudinal filaments from root to tip. The system of equations allowing to determine unknown vortex intensities at every specified moment *r* looks like:

$$\sum_{n=1}^{K}\sum_{k=1}^{N+1}\sum_{\mu=1}^{n}\Gamma_{\Sigma n\mu k}^{\mu k-1r}a_{m\mu kv}^{\mu k-1pp-1}+\sum_{n=1}^{K}\sum_{k=1}^{N+1}\delta_{nkk-1}^{(1)r}a_{nn+1kv}^{n+1k-1pp-1}=H_{mv}^{pp-1r} \qquad (7)$$

$$\sum_{\mu=1}^{n}\Gamma_{\Sigma m\mu k}^{\mu k-1r}+\delta_{mkk-1}^{(1)r}=-\sum_{s=1}^{r-1}\delta_{mkk-1}^{(1)s}, \qquad (8)$$

where v=1, 2,...*n*; *p*=1, 2,..., *N*+1; *m*=1, 2,..., ??.

Functions *a* under the sign of sums in equation (7) present known analytical expressions and depend upon the coordinates of vortex segments and points where these functions are calculated. The first equations (7) of the system represent a no-penetration condition (2) in reference points marked in fig. 2 by crosses and equation (8) represents a condition of closed loop circulation constancy. The right parts H_{mv}^{pp-r} of equation (7) are functions of the rotorcraft geometric characteristics and kinematic parameters of its motion, wake shape and motion background.

The values of kinematic parameters remain unchanged within the frame of one time step. At each time step starting from the first one after solution of equation system (7,8) all vortex segment intensities for the system of blades and their wake are determined. Blade loads are obtained using Cauchy-Lagrange integral over defined total vortex intensities. Distributed and total load characteristics are obtained by summing up aerodynamic loads by panels.

The mathematical model was validated in several stages. Analytical results were compared with ADT and flight test results and those obtained by other researches. Analytical results correlate well with the data obtained in physical experiments undertaken to evaluate total and distributed aerodynamic characteristics of blade sections, main rotor blades, rotor/lifting surface and main/tail rotor combinations

3. Results of modeling and their correlation with the experimental data

Vortex structure setting is an essential point of stream modeling in the vicinity of the helicopter rotors. At the same time, vortex structure analysis and its correlation with the experimental data presents difficulties. The most complete investigation results on visualization of rotor vortex system by means of smoke streams exhausting from rear blade edge are presented in V.G. Kolkov papers being made in TSAGI wind tunnel in 1970.

The experiments on test beds of Mi-4, Mi-8 single rotor helicopter configuration and Ka-32 coaxial helicopter rotor configuration test bed being made in FRI named after M.M.Gromov [2,3] are well known also.

Visualization is being realized also by means of smoke. Smoke generators are installed in blade tip fairings.

Smoke stream motions over disc surface were revealed when doing [2,3] experiments. Fig. 3

shows visualization for single-rotor helicopter configuration, figs. 4-5 – for coaxial helicopter rotor configuration. The experiment results 2,3 contradicts to experimental ones obtained in WT.

Created mathematical model allow to simulate rotor vortex sheet motions.

Vortex sheet of side blade edge is used for modeling of smoke streams going from tip fairings.

Figs. 6, 7, 8 show motion trajectories of these edge vortices. As may be seen, these motions are fully complied with the experimental over disc area. Figs. 9, 10, 11 show all rotor vortices subjected to modeling. It is evident that these vortices are going down word from the rotor and complying with the stream of WT experiment. The modeling results presented offer explanations on distinctions between smoke structures obtained in modeling and full-scaled experiments. It is connected with the smoke blowing out direction. In WT experiment the smoke showed rotor vortex structure, and in full-scale experiment – stream beyond the bounds of the vortex column.

Figs. 12, 13 show smoke structures of both full-scaled and modeling experiments in isometry of vortex sheets going from upper coaxial helicopter rotor tips. As may be seen, modeling results describe smoke stream motions in full-scaled experiment positively.

4. Conclusion

This paper presents results of correlation of vortex structures beyond rotors obtained in calculation and flying experiment.

This paper provides an explanation of distinctions in smoke structures obtained in modeling wind tunnel and full scaled flying experiments.

References

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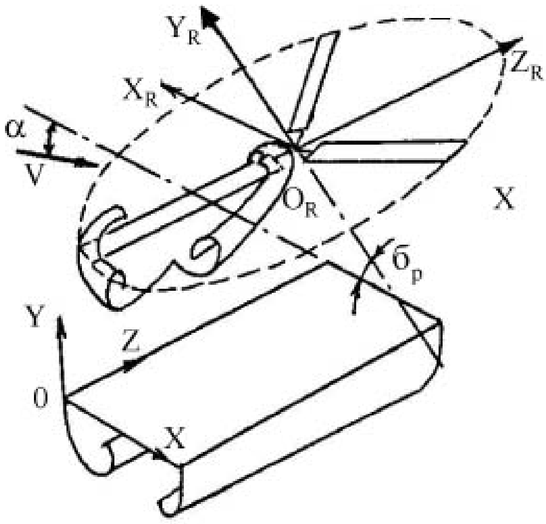

Fig. 1.

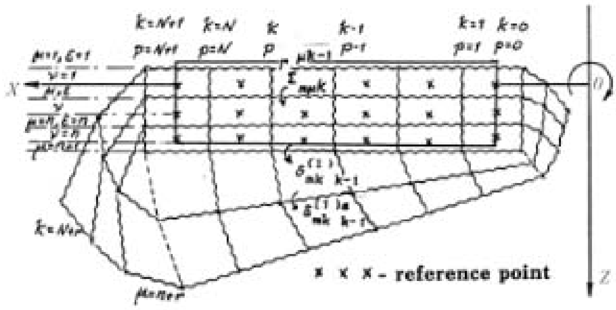

Fig. 2.

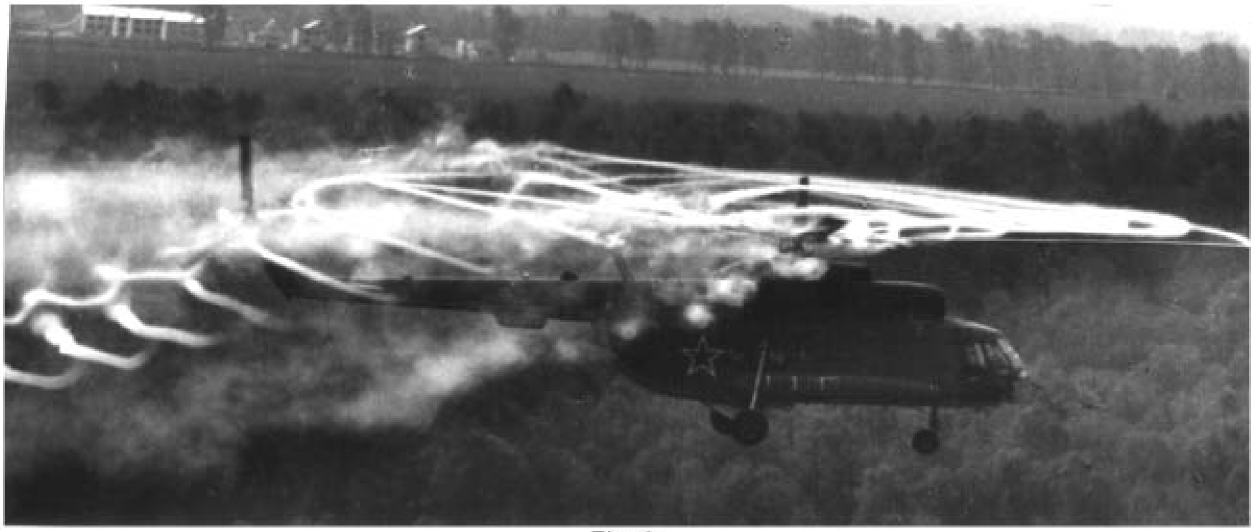

Fig. 3.

Fig. 4.

Fig. 5.

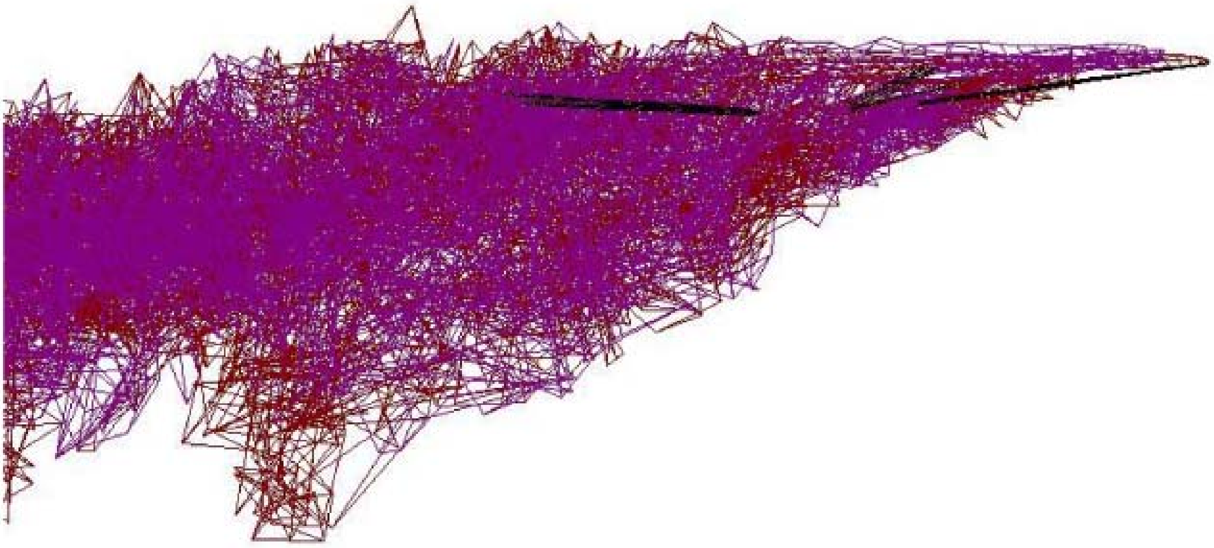

Fig. 6.

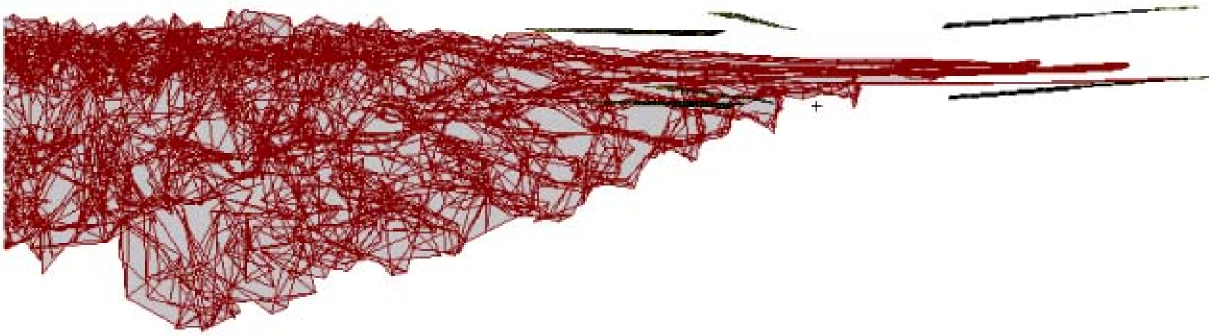

Fig. 7.

Fig. 8.

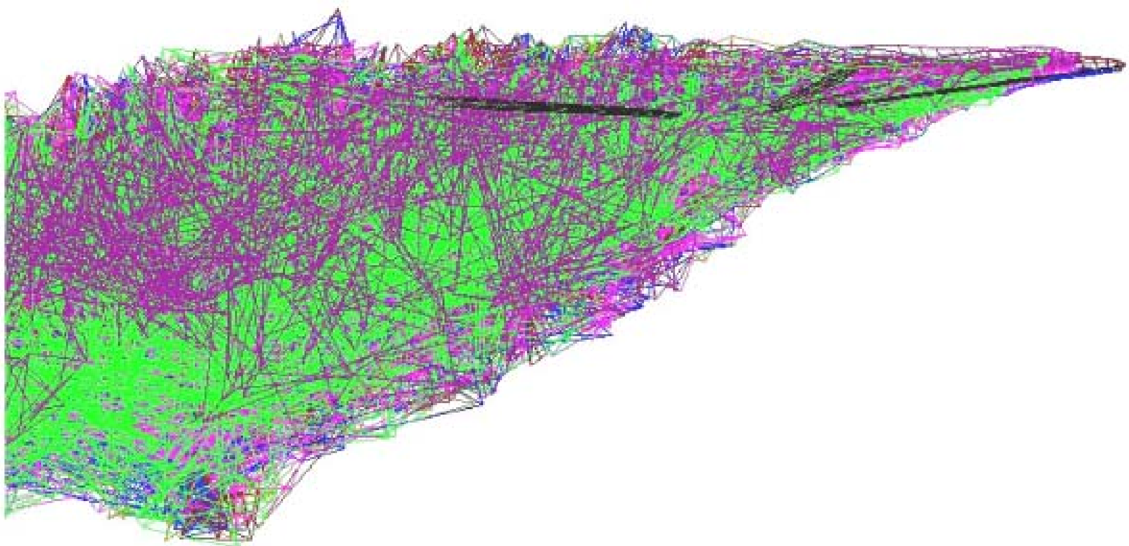

Fig. 9.

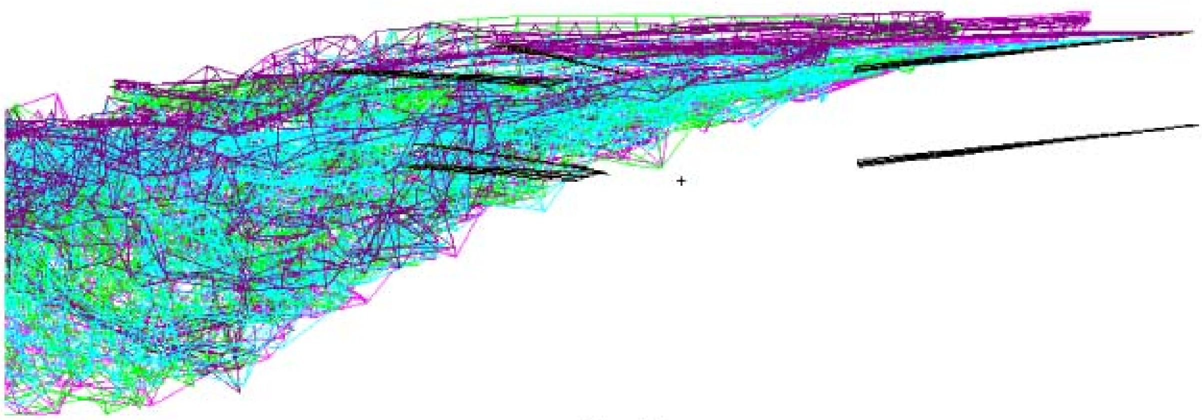

Fig. 10.

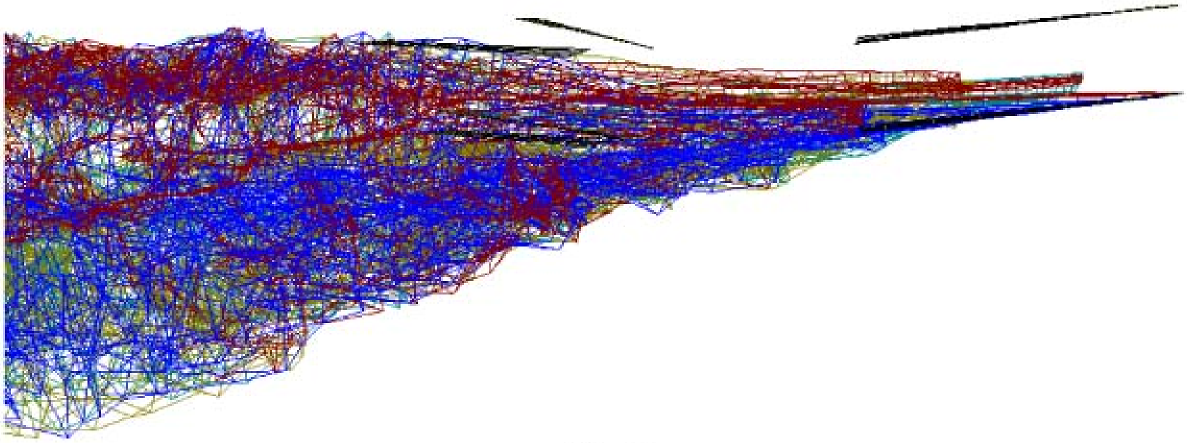

Fig. 11.

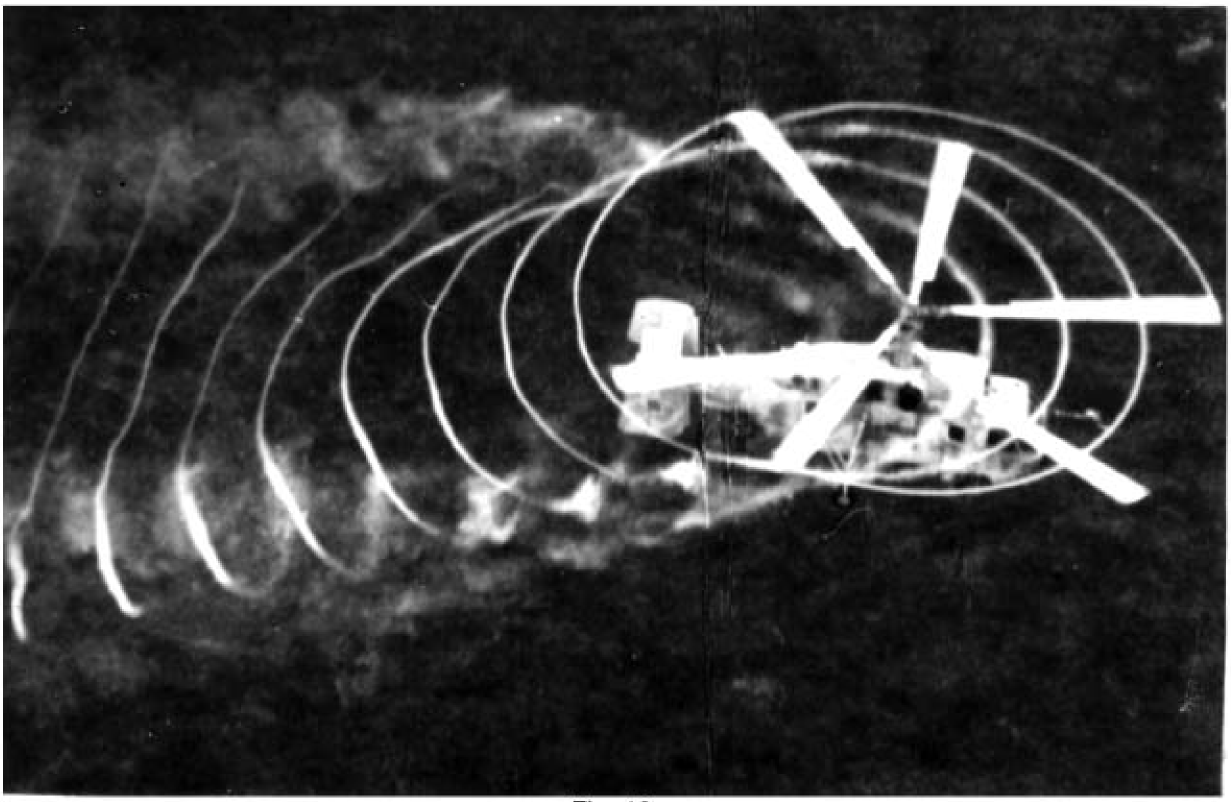

Fig. 12.

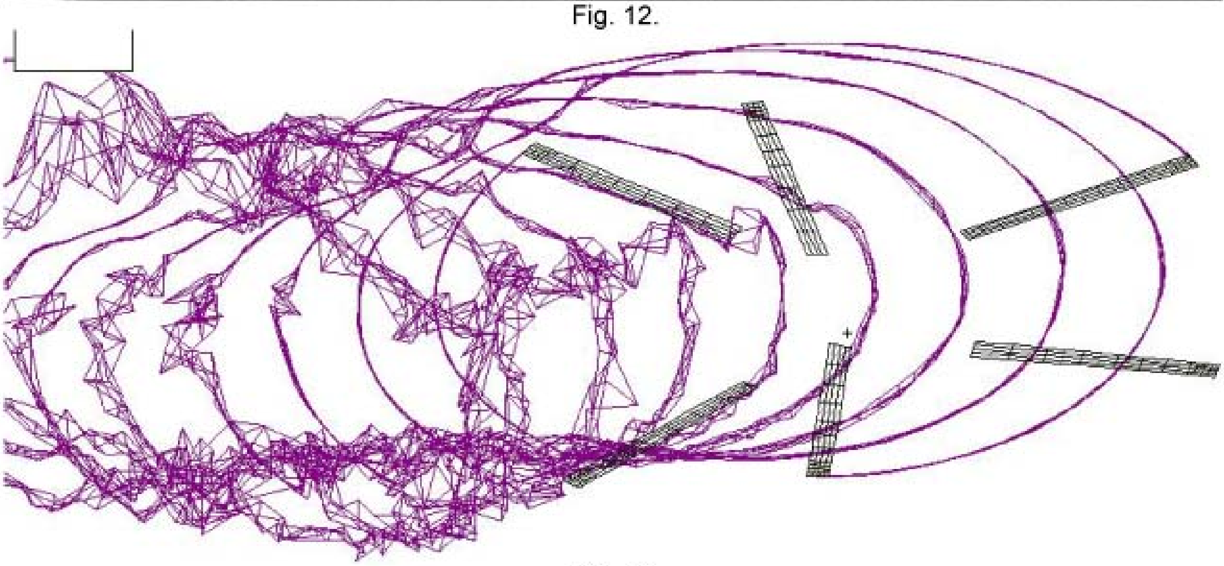

Fig. 13.