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PARTICULARITIES OF AERODYNAMICS AND FLIGHT DYNAMICS OF A CONVERTIBLE TILTROTOR AIRCRAFT

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Abstract

A tiltrotor has a set of particularities, which are peculiar neither to a classical helicopter nor to an aeroplane. Studing and analysis of these particularities are necessary when developing such an aircraft. This work is dedicated to research of the particularities as applied to problems of ensuring the air safety in the case of power plant failure near by the earth, in the case of performing a conversion from the aeroplane configuration to the helicopter one under conditions of the total failure of the power plant. Airflow over the airframe and main rotor-airframe interaction are also researched.

There are dangerous areas when the engine fails near by the earth. These areas have forms shown in the fig.1 in the coordinates of " Height-Velocities ". If the failure happens within the shaded areas, the safe landing is not provided. To calculate these areas an approximated quick-acting programme was created; the program allows to calculate motion of the aircraft in accordance with the given control. A technique for determination of a rational piloting procedure was developed [1].

Fig. 1 shows the calculated dangerous areas for a convertible aircraft. The calculations are performed under an assumption that at hovering the thrust losses due to mutual influence of the rotors and the airframe are 8% (K = 0,92). It will be shown below this value was obtained without taking into account of the reverse action of the airframe into the rotors.

The studing of the dangerous areas has shown a high sensibility of their dimensions to difference between available power and required one. When the available power increases, the lower boundary of the dangerous area moves up abruptly. For example, if a relative war-emergency power $\overline{N}$ ($\overline{N}$h.p./kg is a ratio of one engine power at the emergency power condition to the take-off weight) increases from 0.3 to 0.31, that is by 3%, the lower boundary moves up by 16 m at Vx= 30 km/h. When $\overline{N}$=0.3 and 0.31, the left area and right one intetrsect; when $\overline{N}$=0.32, they do not intersect; and when Vx= 40 km/h, the gap between them in the height is 20 m. It allows to set a safety pass of the normal take-off (fig. 1).

The fig.1 shows also the boundaries of the dangerous areas when $\overline{N}$=0.3 with accounting the reverse action of the airframe into the rotors. In this case the total thrust losses at hovering are 6.5% (K =0,935). The drop in the total losses by 1.5% has displaced up the lower boundary of the left dangerous area by 8-9 m in the average. It lends support to necessity of closer determination of the airframe-rotors interaction as against the helicopters with the classical configuration.

When the pass of the normal take-off is specified, the first critical point on this pass can be found. The point is located at a height of h= 35 m (Vx= 48 km/h) and that is much more than for the classical helicopters. The calculations of the required distances for the aborted take-off and for continued one were carried out from this point and had shown larger values of the distances. The fig.2 shows changes of the height h, vertical velocity Vy, and distance L with time when performing the aborted take-off (the solid line) and the continued one (the dotted line). The reguired distance of the aborted take-off having regard to a ground run was 300 m. The required distance of the continued take-off was determinated from an instant at which the climbing rate reached 0.5 m/s and was 560 m. The distance of the continued take-off is deciding.

The particularities mentioned above can be explained by a smaller main rotors moment of inertia about their axes of rotation because of the small radius.That gives abrupt changes of the rate of revolution of the rotors, when available and required power have changed insignificantly. As a whole, the accuracy for determination of the available and required power must be significantly higher for the convertible aircraft, than for the classical helicopters.

Conversion conditions from the helicopter configuration to the aeroplane one and inversely are unique to the convertible aircraft. The special programme allowing to calculate the total motion of the aircraft in the threedimensional space was developed in order of research of such conditions. All the formulae required to calculate velocities, forces and moments were derived in a compact vectorial-matrix form for a general case of an unsteady curvilinear motion. Their deduction is based on step-by-step coordinate transformations [2].

Initially the range of flight velocities in which the convertible aircraft can fly at any configuration was defined and the horizontal velocity of 250 km/h was specified for the conversion (Fig.3). Thereafter the direct calculations of the conversion regimes from one configuration into another were conducted. The longitudinal aircraft motion was considered. Analysis of the calculated dependences has shown that there are no problems from the aerodynamic viewpoint when such conversions are completed at the normal operating power plant.

An other situation arises when conversion from the aeroplane configurations ($\mathcal{E}$ =0 degree) into the helicopter one ($\mathcal{E}$ =90 degree) are completed in the case of the total engine failure. Such a failure is accompanied by some features in work of the main rotors. To gain a better insight of these aerodynamics features the calculations of the longitudinal aircraft motion when conversion regimes were carried out in the cases of the total power plant failure at the horizontal velocities of 250-500 km/h were performed. It was necessary to transform the rotors in the helicopter situation and enter into the autorotation regime.

Fig. 4a,b shows how some motion parameters of the convertible aircraft change with time when the power plant fails at velocity of 500 km/h. The rotors are transfered into the helicopter state. The aircraft retards. The calculations have shown the following features. Even 5 s later after the engine failure before the pilot intervenes in the control a decrease of tip blade speed WR of the main rotors are ceased. The rotors begin to work in the autorotation regime at the negative thrust coefficients (C_t/σ <0). It can be explained by that at the initial regime the rotors work with small attack angles in blade sections. Therefore even small decrease of WR (by 9%) displaces the attack angles in a negative area to the extent that is sufficient for the autorotation regime becomes.

A piece of the flight with the nagative thrust coefficient covers 13 s. Within this piece there is notable sensitivity of the rotor speed to a change of a collective pitch. Therefore the pilot must be especially accurate in the control of the collective pitch.

At the end of the conversion regime (after the rotors have been transfered into the helicopter situation) the rotors have to enter into the autorotation regime with the positive thrust coefficients. The transfer from the autorotation with the negative thrust coefficients to autorotation with the positive ones is required. In the course of such a transfer an area of regimes with positive coefficients of the required power are passed through, where the rotor speed necessarily drops. This is the third qualitative feature inherent only in the convertible aircraft.

To provide the minimum change of rotors speed it is necessary to determine a moment of a transfer from the area of m_k<0 (when C_t<0) to the area where the rotors speed decreases inevitably. To determine the areas of m_k<0 and m_k> 0 when Vx=const and WR=const for different values of φ_0 and α_k (α_k is an attack angle of a main rotor, derived from the constructive plane of rotation) rotor characteristics were calculated.Fig.5 and 6 show the results of such calculations in the axes of $\varphi_0=f(\alpha_k)$ for the horizontal velocities of 500 and 250 km/h. The autorotation regimes are possible in the shaded areas. In the area "2" the autorotation of the aeroplane configuration occurs (C_t/σ<0).In the area "4" the autorotation of helicopter configuration (C_t/σ>0) occurs. When WR decreases at the small flight velocities the area "4" increases.Between α_{k1}= −35 degrees and α_{k2} =10 degrees there is an area " 3 " where

$m_K>0$. The calculations have shown that the value of α_{K1}(Fig.5) is not too dependent on Ux and WR and is within -30...-35. Therefore the moment of penetration into the area " 3 " can be determined by the moment when α_K reaches α_{K1}.

The fig.5 shows a dependence of $\varphi_0(\alpha_K)$, that corresponds to the considered above power plant failure at the velocity of 500 km/h. At the moment of the power plant failure a combination of φ_0, α_K belongs to the area " 1 " with $m_K>0$. Evidently that in the area " 1 " it is necessary to decrease the collective pitch at a maximum pace. When it is reached the area " 2 ", the rotor speed should be increased up to a maximum possible value and then should be kept when we move along the boundary of areas " 1 " and " 2 ". Once the area " 3 " is reached the control of the collective pitch should be changed qualitativaly. Now the pitch should be decreased with a pace of 6-8 degree/s. On falling in the area " 4 " the rotor speed should be increased up to a value corresponding to the rotation speed in the failure instant or up to a maximum possible value for given Vx and should be kept when moving along the boundary of the areas " 4 " and " 5 ".

The analysis of the performed calculations shows that the following piloting technique should be kept to provide the minimum change of the rotor speed and the height drop at the conversion when the power plants falls at the aeroplane flight regime. After the failure the pitch angle should be increased to 15 degrees. Keeping this angle at the given level the rotor should be transfered into the helicopter state and it must be entered into the autorotation regime at velocity of Vx=150km/h. During first 5-8s after the engine failure the rotor speed should be increased to the maximum possible value by the change of the collective pitch. When the horizontal velocity reaches the value of 200km/h a decrease of the collective pitch should begun with a rate of 6-8 degree/s up to an instant of the enter into the rotors autorotation regime. In case of the engine failure at small flight velocities (when a wing operates at regimes closed to a stall) the flaps should be released for decreasing the height drop.

The fig.7a,b show an example of the conversion calculation when the power plants falls at velocity of 250km/h. An algorithm of the optimal piloting technique was introduced. The calculations were performed for two flap position (δ_f =0 degree and 20 degree) and for various laws of pitch angle ϑ(t) change. Rotor speed is not in excess of the limiting tolerable value. After significant decrease the rotor speed is reagained rapidly.

The fig.8 shows the dependence of the height drop ΔH at the instant when the rotors enter into the autorotation regime with maximum speed on the horizontal velocity at the moment of the power plant failure. It is seen that when failures occur at the horizontal velocities more than 400km/h, the transfer to the aotorotation regime comes without the height drop.

One of the features of the tiltrotor lies in the fact that it has a big wing and reasonable small and severely loaded rotors situated at the ends of the outboard wings. Therefore the interaction problems of the airframe, wings and rotors are more essential for it than for a classical helicopter and require fine instruments for studying.

In this work a vortex theory of blades was used for the aerodynamical analysis of the main rotors. A method based on the potential flow theory having regard to thickness chord ratio [3] was applied. A solution is looking for as a distribution of perturbation of a potential in a space of induced velocities. A tail part of the blade is simulated with 220 panels which is to make considered radial flows that is effects related to flow-over from a lower surface to an upper one.

The thickness of a boundary layer on the blade surface is taken into account through building up the airfoil thickness upon the displacement thickness . At first the boundary layer is considered as a laminar one and then it transfers into turbulent layer. To determinate its parameters a two-layered model of turbulence is used.

To provide sufficient quick-action required from a viewpointof engineering practice blade root sections and central ones are calculated using a modified lifting line theory. The modification consists in accounting a spatial orientation of surface elements dividing the blade throughout radius and in arranging a stall of free vortices strictly from the trailing edge of the profile. A form of free vortical surfaces is non-linear.

To calculate the flow around the airframe (the fuselage and wings) the theory of potential flows is also used. In this case the fuselage is simulated with 1200 panels and the wing is simulated with 440 panels. The fig.9 shows a division of the tiltrotor airframe into the panel elements.

On the base of mentioned above techniques an investigation of main rotors-airframe interaction was performed at hovering regime and at small flight velocities in the helicopter configuration. At each step of iterations the mutual effect of the rotors and the airframe has been refined.

At hovering regime the air flow from the main rotor around the airframe creates a negative thrust on the airframe.To determinate thrust losses ΔT_1 induced by the air flow around the airframe the calculations of an isolated rotor at hovering were performed. The induced velocities in an airframe area, defined in these calculations, were averaged over the time. The thrust loss coefficient ΔT_1 through air flow around the airframe was defined using the averaged induced velocities. In this case a deflection downwards of wing flaps for reduction of the losses was taken into account. The coefficient of losses has formed a value of ΔT_1=8% (K =(100-ΔT_1)/100=0.92). The calculations have shown that only the wing is subjected to an active inductive effect of the rotors. The fuselage is out of the rotor wake by geometrical spacing of the rotors on the wing ends and owing to compression of the wake.

Similar calculations were carried out at horizontal velocity of 50km/h. The value of ΔT_1 was 7%. A decrease of losses may be attributed mainly to change of flow direction in the airframe area and a change of parasite drag coefficients Cx. Except that there is an additional drag in a direction of an outer undisturbed flow.

Except for the direct inductive rotor effect on the airframe there is also a reverse effect of the airframe on the rotors. In this case a contribution of the wing is governing. The fig.10 shows level lines of induced velocities V_y and angles of downwash $\Delta \varepsilon$ in a tip-path plane for the hovering regime. The blade parts passing over a middle part of the outboard wing are subjected to the maximum inductive effect. The fig.11 shows the change of angles of downwash $\Delta \varepsilon$ on the rotor along azimuth ψ for different radii r. The downwashes of flow reach 1-1.5 degrees. The fig.12 shows a dependence of $\Delta \varepsilon$=f(ψ ,r) for horizontal flight velocity of 50km/h.

The airframe effect on the rotors involves an increase in the thrust ΔT_2 on the rotors at the same consumed power. The calculations at horizontal flight velocities up to 100km/h have shown that an increase in the rotor thrust looks much the same and is 1.5%. Therefore the total thrust losses $\Delta T = \Delta T_1 - \Delta T_2$ are 6.5% and 5.5% at the hovering regime and the horizontal flight respectively.

Conclusion.

The investigations done in this work have allowed to reveal a set of particularities in the behaviour of the tiltrotor when the power plant falls in the vicinity of the earth or at high velocities in the aeroplane configuration. The data have been received and the recommendations have been worked out for better safety of flights in such situations. Efficiency of the calculation techniques for rotors-airframe interaction has been shown. The loads distributed through the fuselage and the wings as well as the airframe effect on the rotors have been defined. It has been shown that only wing and rotors interact actively in between. The interaction of the fuselage and the rotor is slight.

Literature.

1. V.B. Letnikov. An analytical study of the helicopter flight safety under an engine failure in proximity of ground. The 47th Annual Forum and Technology Display, 1991.

2. V.B.Letnikov. A calculation technique for a general case of the helicopter motion. Proceedings of the All-Union Scientific and Technical Conference. Design Problems of Modern Helicopters. Moscow Aviation Institute, 1979.

3. V.B.Letnikov. Helicopter aerodynamics research techniques and rotor-fuzelage interaction analysys. The 48th Annual Forum and Technology Display, 1992.

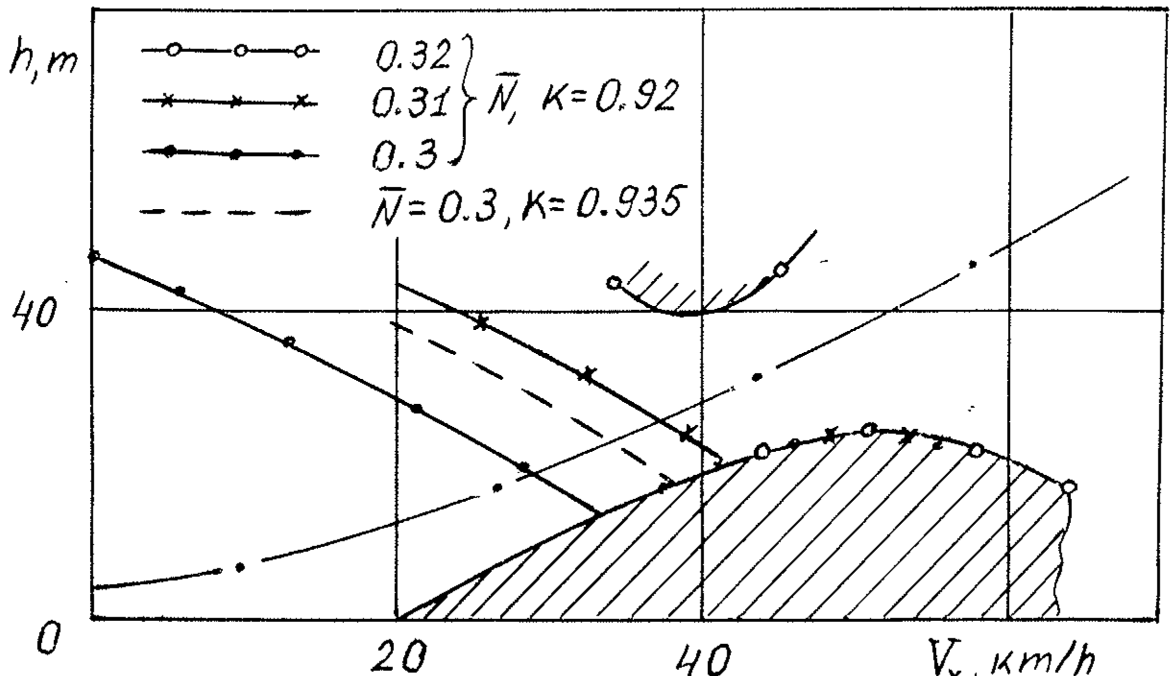

h, m
0.32
0.31
0.3
$\bar{N}$, K=0.92
$\bar{N}$=0.3, K=0.935
40
0
20
40
V_x, km/h

Fig. 1

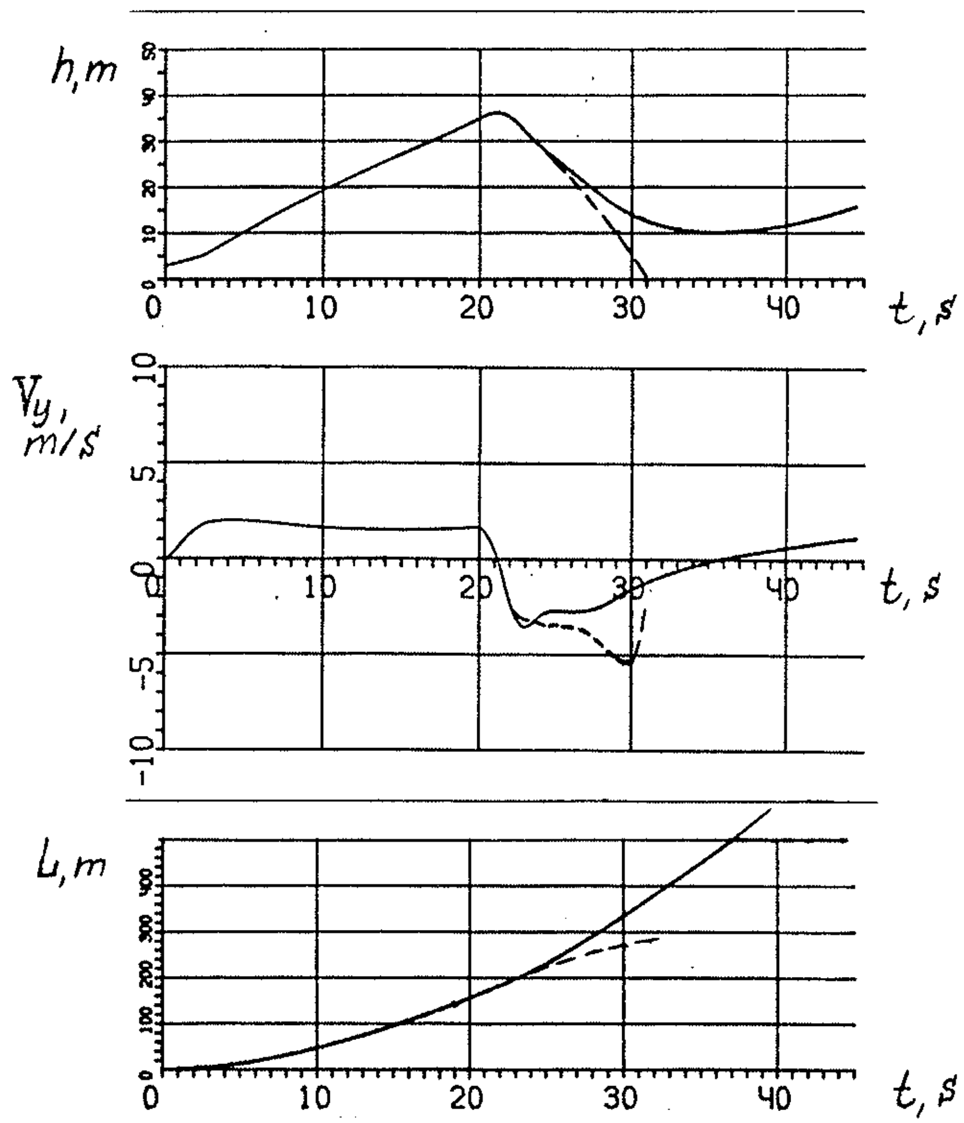

h, m
t, s
V_y, m/s
t, s
L, m
t, s

Fig. 2

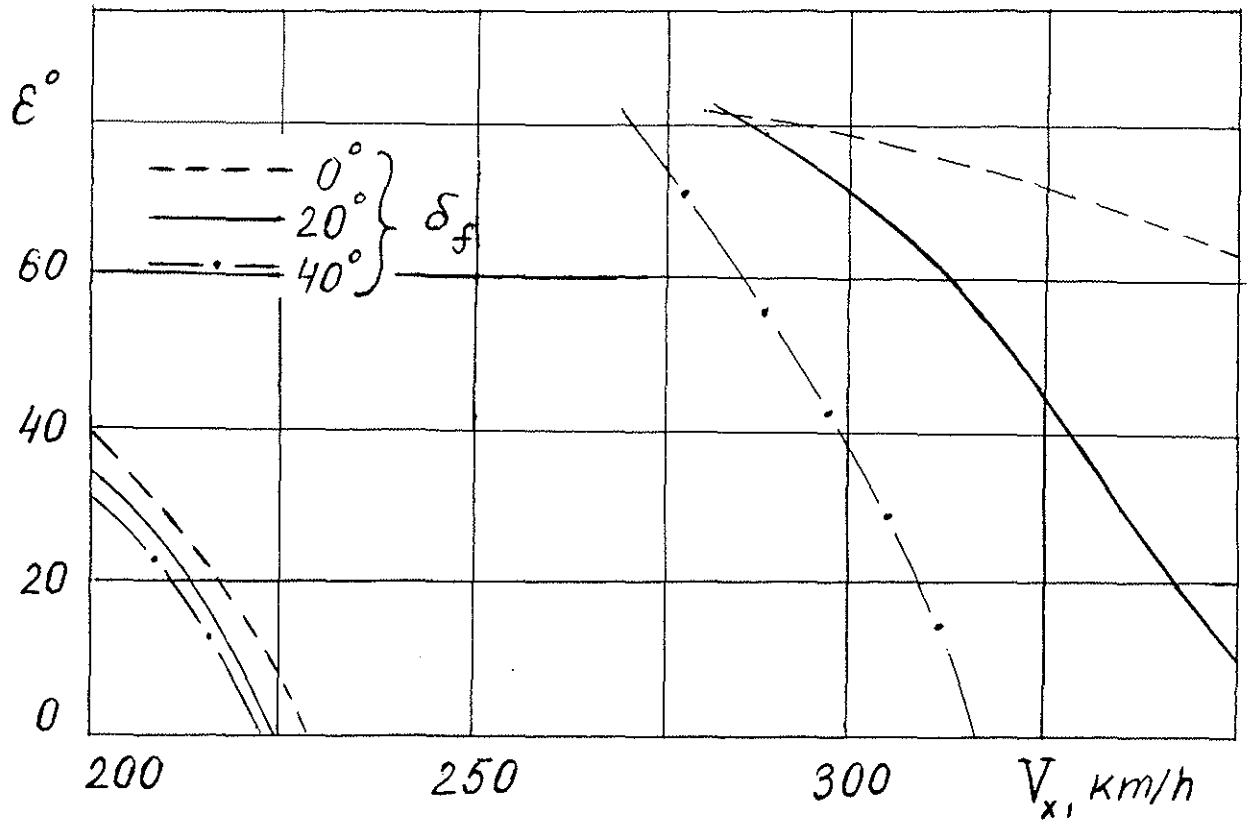


Fig. 3

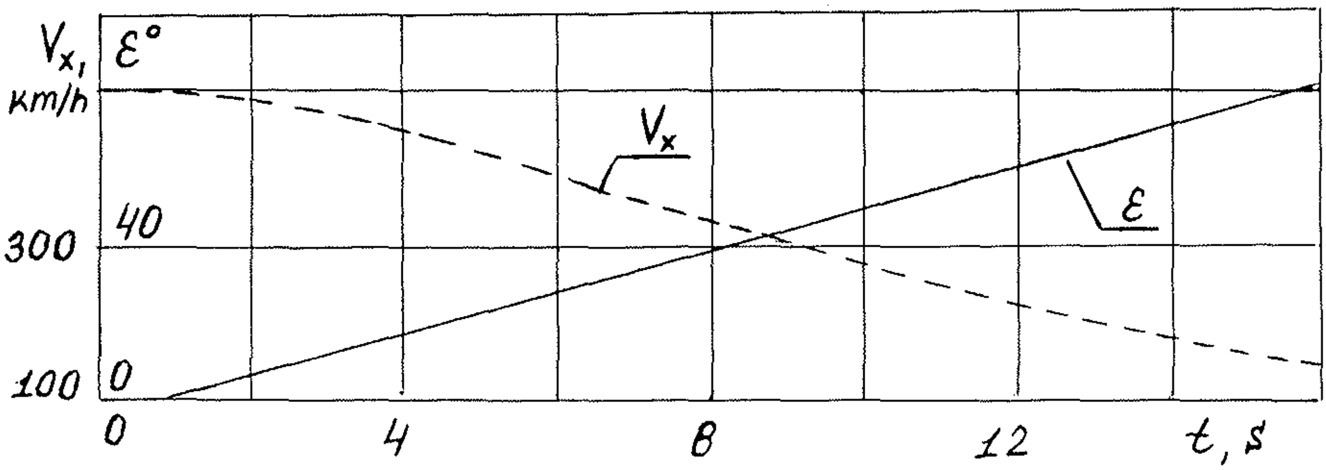


Fig. 4, a

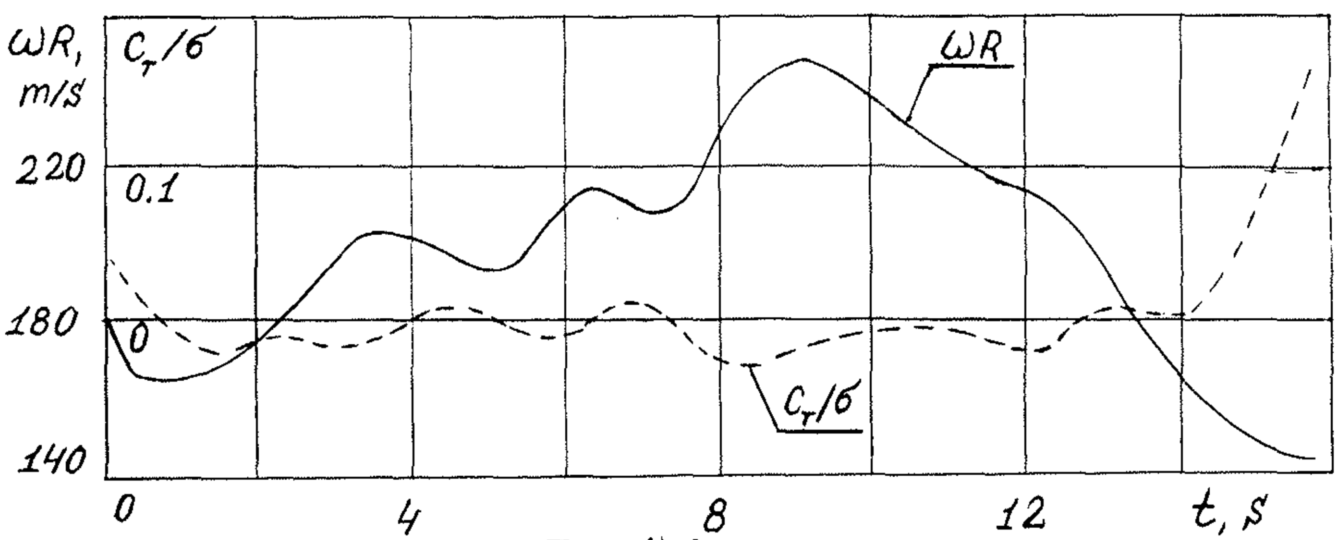


Fig. 4, в

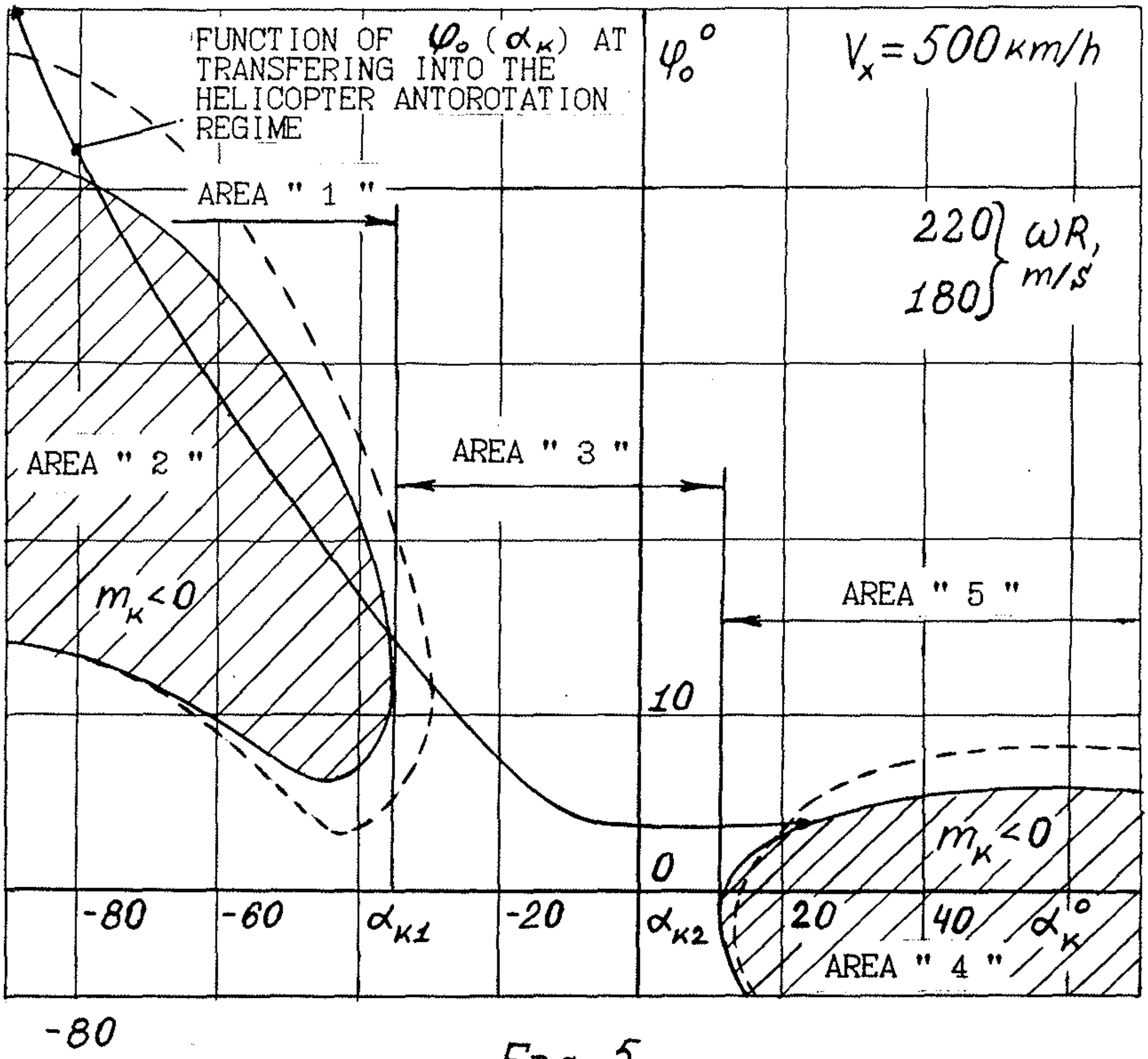

FUNCTION OF $\varphi_o(\alpha_\kappa)$ AT TRANSFERING INTO THE HELICOPTER ANTOROTATION REGIME
φ_o°
$V_x = 500$ km/h
220
180
ωR, m/s
AREA " 1 "
AREA " 2 "
AREA " 3 "
AREA " 5 "
AREA " 4 "
$m_\kappa < 0$
$m_\kappa < 0$
10
0
-80
-60
$\alpha_{\kappa 1}$
-20
$\alpha_{\kappa 2}$
20
40
α_κ°
-80

Fig. 5

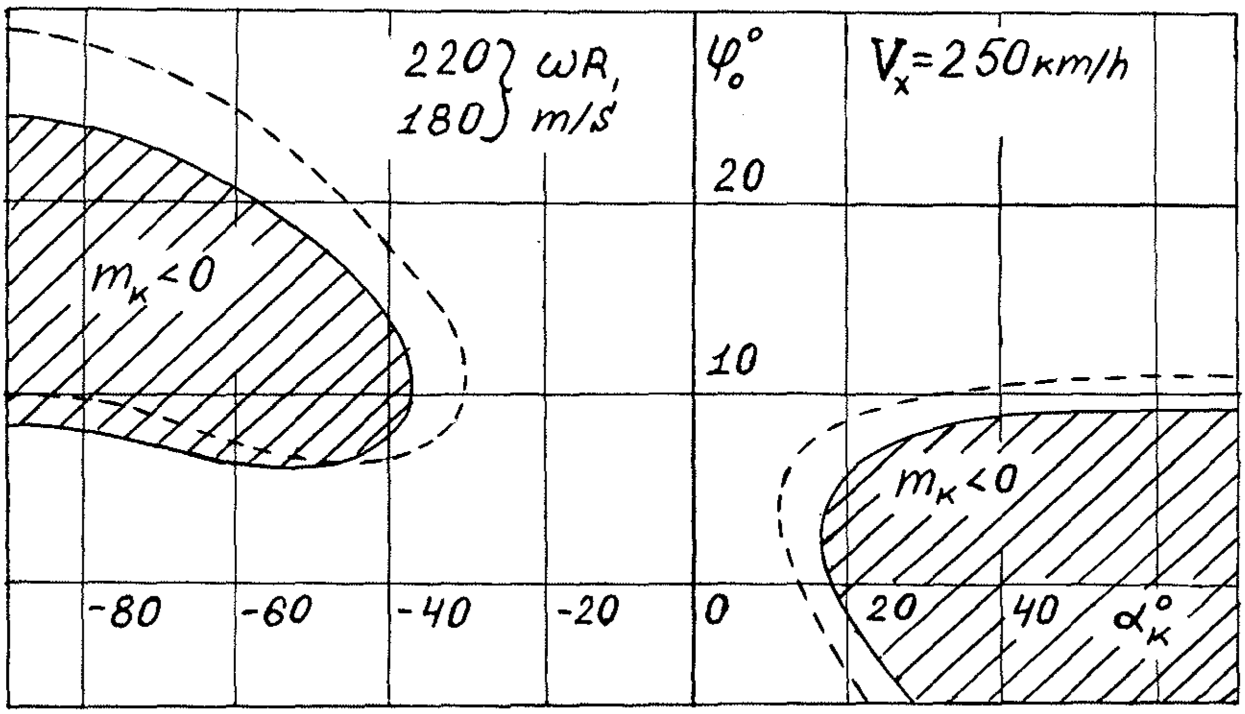
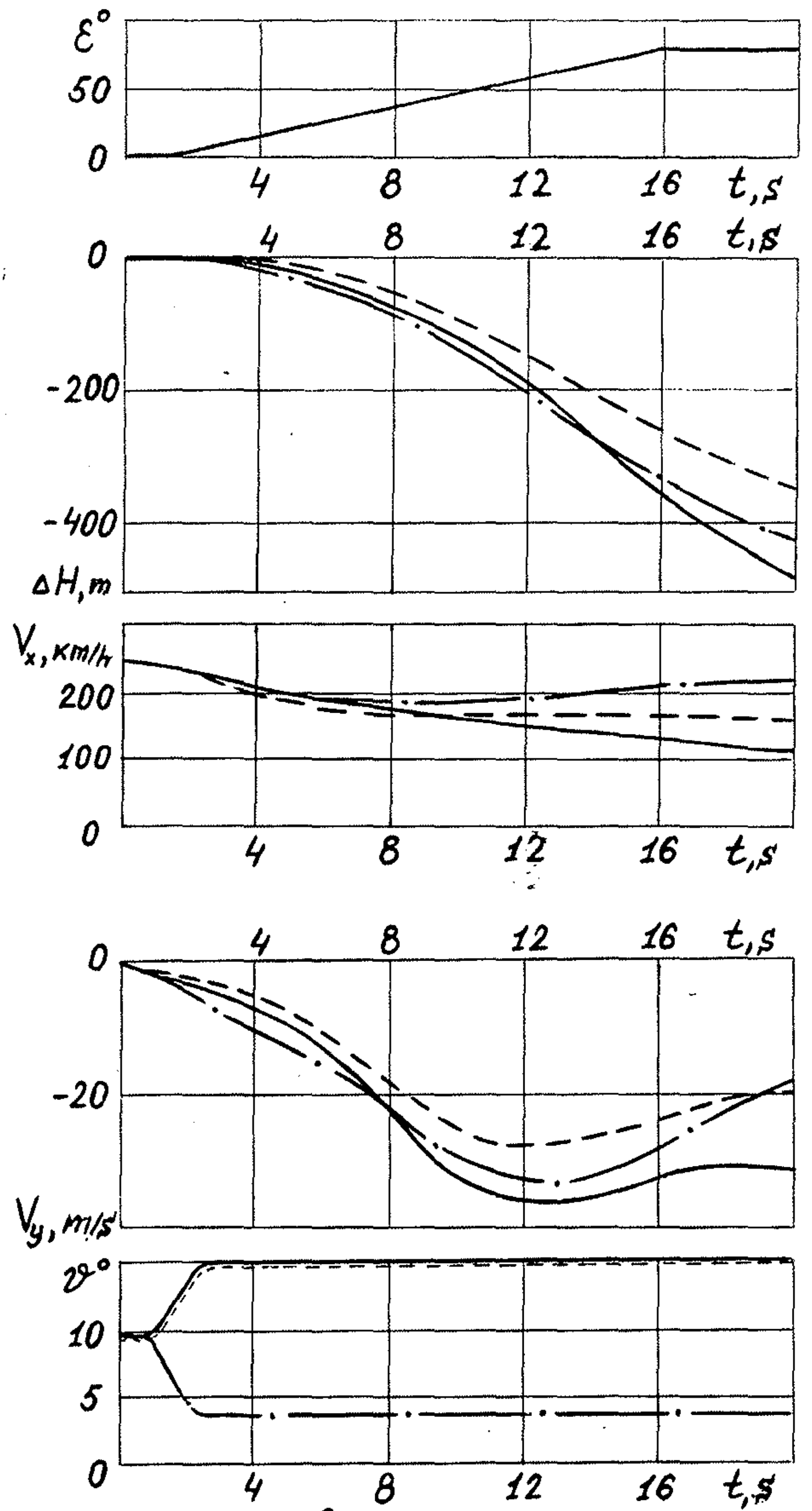

220
180
ωR, m/s
φ_o°
$V_x = 250$ km/h
20
10
$m_\kappa < 0$
$m_\kappa < 0$
-80
-60
-40
-20
0
20
40
α_κ°

Fig. 6

$V_{xo} = 250\,km/h,\ H = 2000\,m$



---- $\delta_{flap} = 20°$

Fig. 7,a

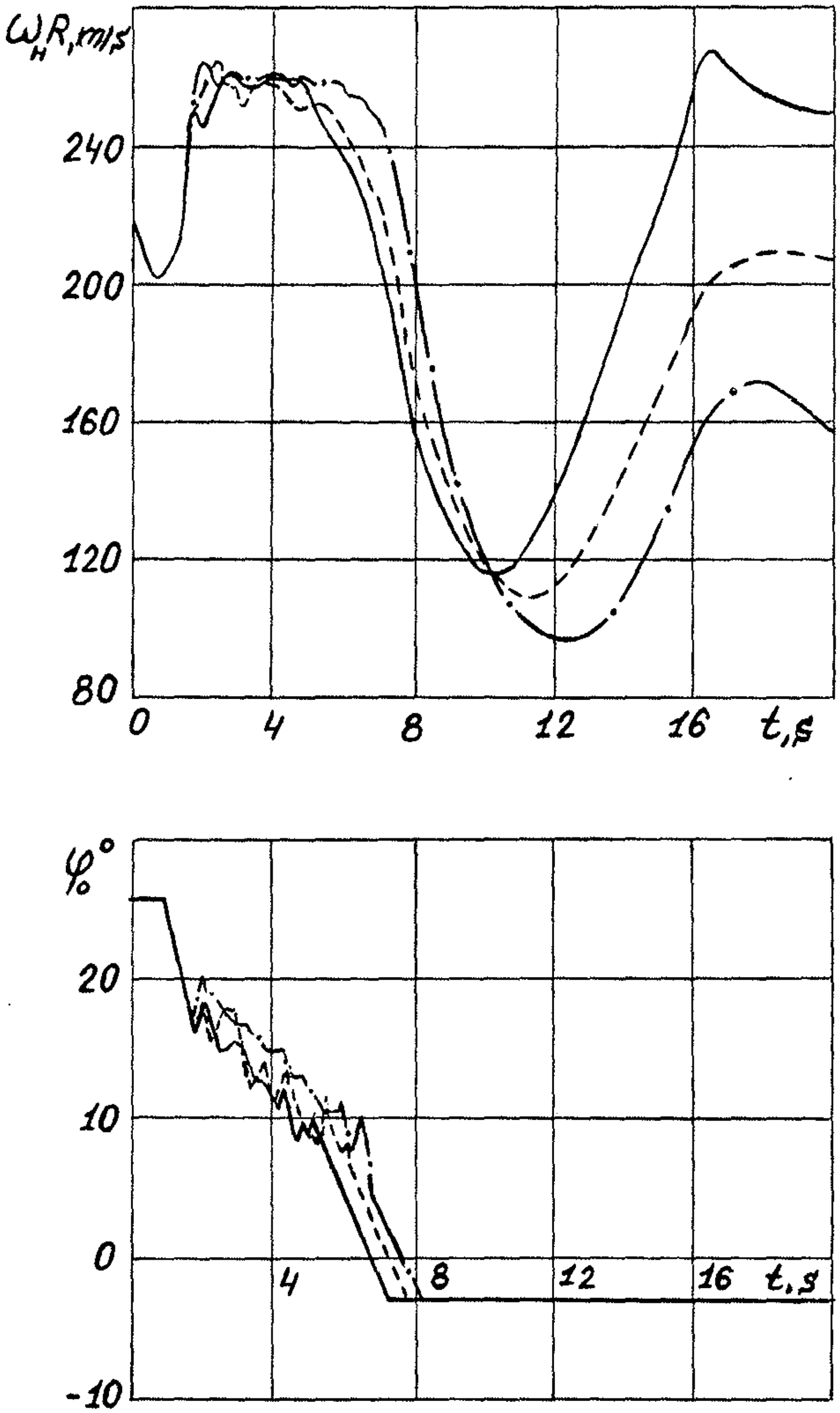


Fig. 7,в

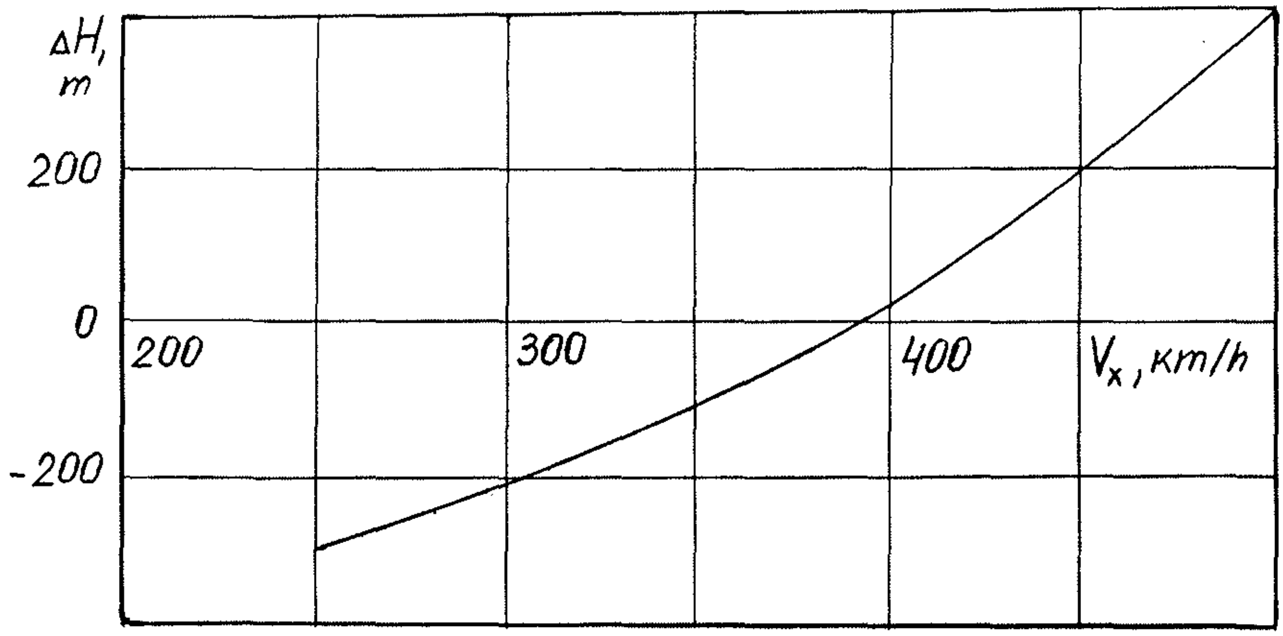


Fig. 8

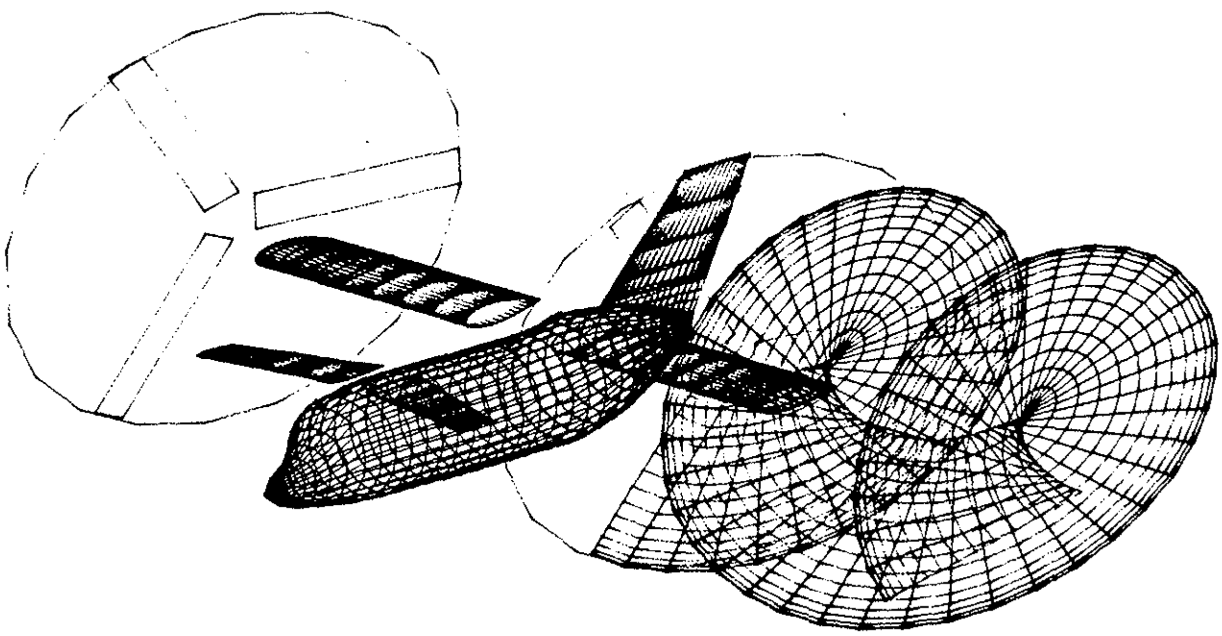
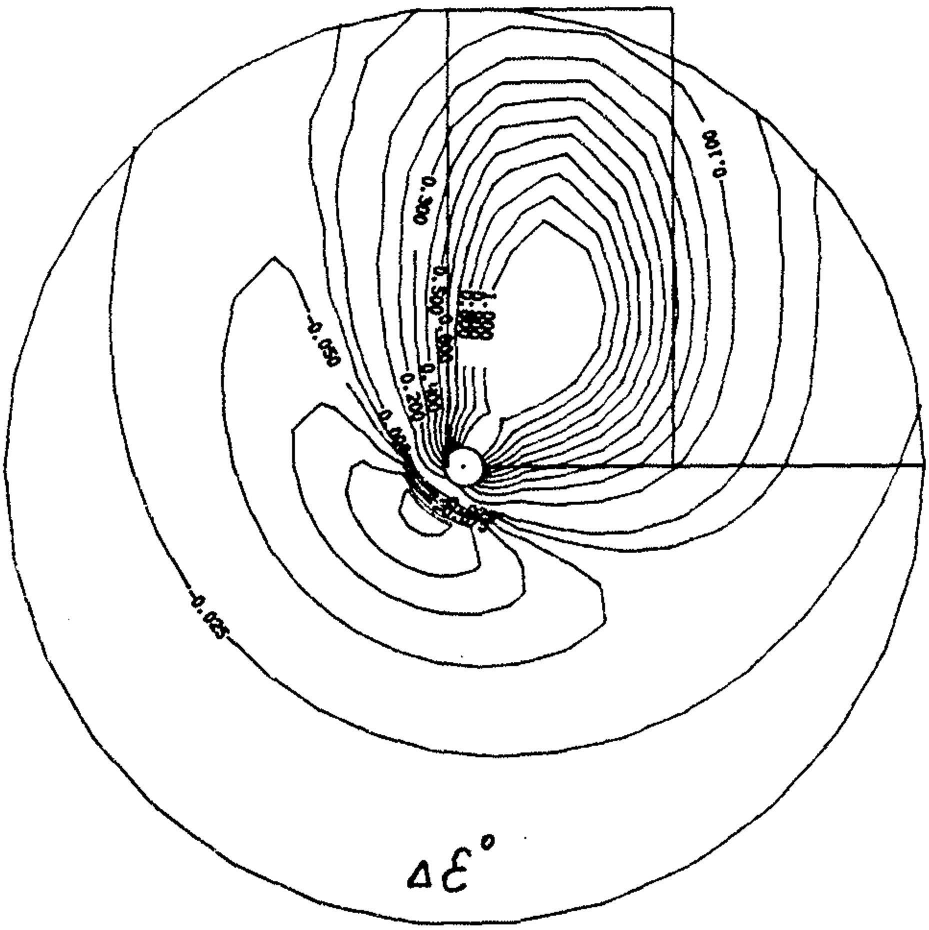


Fig. 9



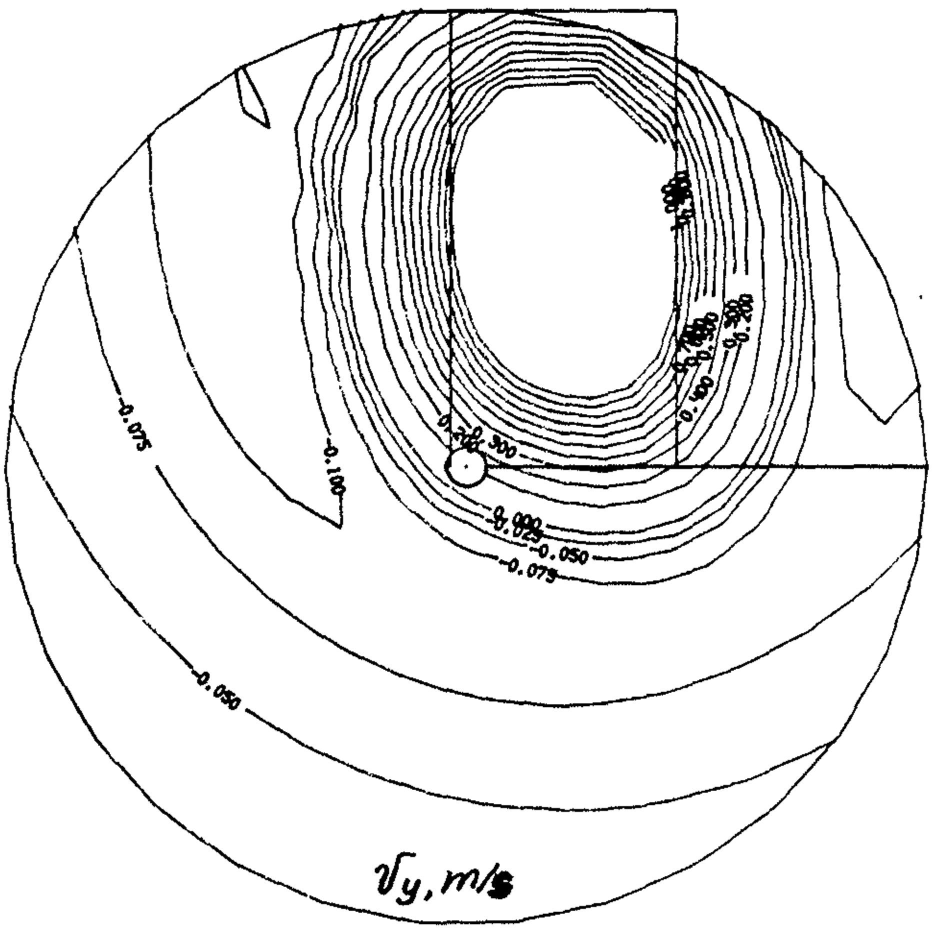


Fig. 10

UX= 0.000 UY= 0.000 UZ= 0.000

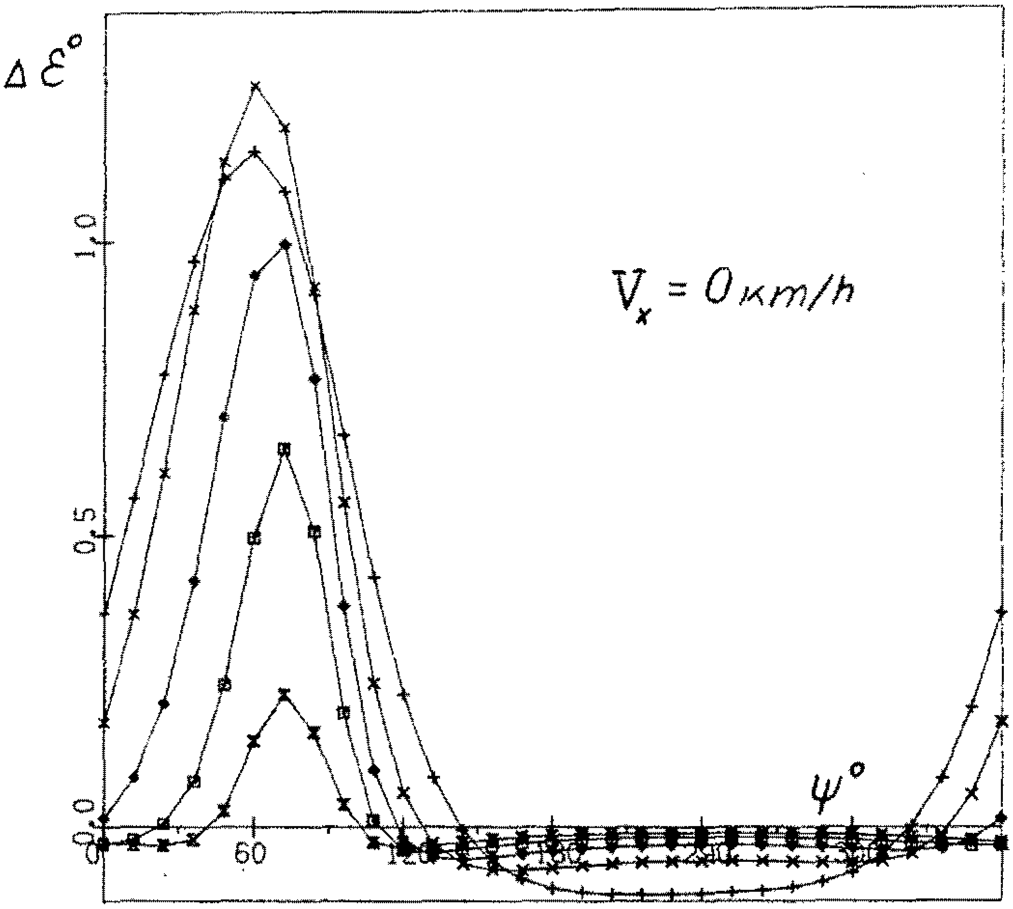


Fig. 11

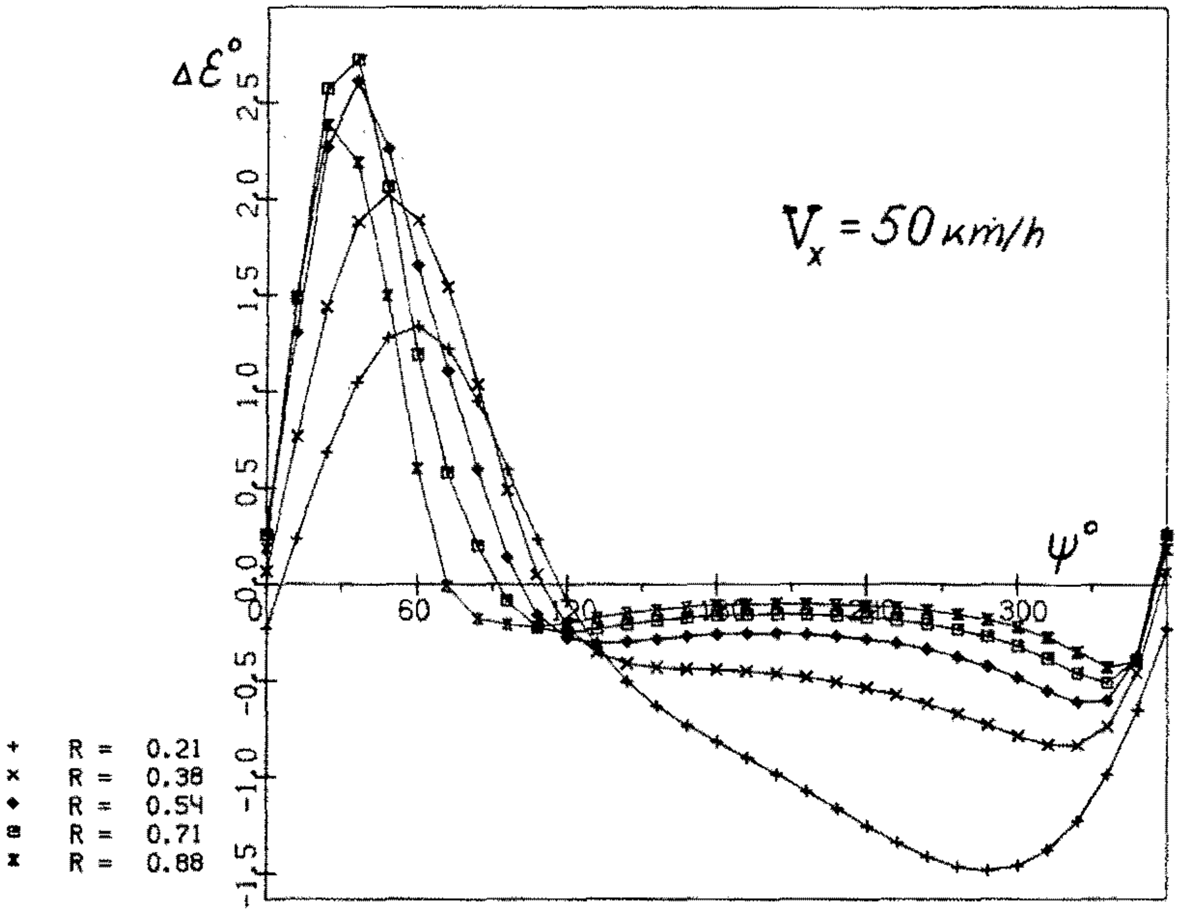


Fig. 12

C11-12