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SIMULATION TESTS OF THE PILOT-HELICOPTER SYSTEM IN OVEREXTREME CONDITIONS

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Abstract

The paper deals with investigations in the dynamics of the pilot-helicopter system under extreme conditions, considering cases when the following limits are exceeded. The primary objective is to evaluate helicopter loading and handling technique under the assumed conditions. The scope of investigations covers simulation analyses on mathematical models, simulator tests and flight tests.

Introduction

The paper describes investigations in the area of complex pilot-controlled dynamic systems under extreme conditions as indicated by the structural limits of their respective parts and assemblies. Keen competition imposes increasingly rigorous requirements to be met by those systems so as to exploit all potential capabilities. Frequent occasions of near-limit operation make the user control them as precisely as possible and consider the risk of exceedeng the admінissible extremes.

To define the area of investigations more specifically ot will be helpful to autline the concept of solution for anticipated problems. There are features they share in common contained in the notion of transgression[x/]. For they refer to a process taking place near the limits, situations when limits are exceeded, estimates as to a possibility to return from beyond the limits. Also they embrace the reasons for exceeding limits such as control error, system failure, breaking rules forced by circumstances or deliberate as a result of investigation procedure. Finally they cover cases of unintentional transgression in extreme situations.

Fig.1 illustrates the issue of transgression depicting possible runs of a controlled process which effects phases n, n+1,..., where respective limits and areas could be described as:

- limits and areas of risk - when limit proximity essentially affects the system data so that the way of control has to be modified by this proximity;
- admissible - when having the limit exceeded it is still possible to return to the original process by special way of control with no process changes involved;
- failure - when following limit transgression damage occurs to the system, yet it is possible to interrupt the process safely using emergency control technique at the cost of inability to continue the process as intended before;
- crash - when following limit transgression the system becomes uncontrollable and, if going on, it may destroy the system.

Selection and proper arrangement of transgression issues encourage the attempt of transgression as investigation method under limit conditions. Exceeding the following limits, that is transgression,is the best way to discover and to specify the kind and position of those limits. It provides information on either increase or decrease in the intensity of dangerous phenomena, feasibility of recovery and safety manoeuvres, consequences of transgression and spaces between successive limits.

[x/] Lat. transgressio - in narrow meaning: crossing, in a broader sense: crossing boundries, infringing law and regulations, exceeding one's own limits and competence. The issue of transgression was developed as a theory by the French sociologist Marcel Mauss and, as a doctrine, it was presented in "L'Homme et le Sacré" by Roger Caillois giving the foundation for interdisciplinary synthesis of transgressive problems.

The introduction of system transgression as investigation method will permit the following:

1. strict establishment of its limits /by confirming or denying their existance, position and character/,
2. detection of its weak and critical points,
3. reliable estimation of its limit data and adjustment.

Interdisciplinary approach gives a chance to conduct investigations in a proper direction by introducing the elements of control theory, models of operator's actions from engineering psychology as well as description of multi-purpose and multi-phenomena models of control objects. Failures of automatic system control under transgressive conditions contrary to numerous cases of effective system control performed by human operator in such conditions support, due to interdisciplinary approach, a concept of the use of the system anthropomorphic adjustment for transgressive investigations.

This paper deals, in particular, with analysis and investigation of the dynamics of helicopters under extreme flight conditions. It covers both theoretical analysis and empirical investigations on real systems.

The investigations referred to the human-pilot, his extreme capabilities and flexibility of limitations on the one hand and to the machine-helicopter on the other. For investigator, when unaware of all phenomena taking place in the system and neglecting the influence of handling dynamics, becomes arbitrary in selection of critical flight phases, simplifies their models and considers the dynamics of a helicopter as an isolated object.

The investigations concentrated on the course of tasks assigned and operation of the helicopter systems in selected critical flight phases and under overcritical conditions.

Simulation, anlytical and empirical methods were widely used throughout all investigation phases reflecting limit conditions much more, if not totally, safely. They were employed to investigate the least explored phenomena.

A system was developed of transgressive investigations from analyses to experiments covering:

1. investigations in conventional time on closed mathematical models of pilot-helicopter configuration with the use of numerical methods and computer techniques,
2. laboratory investigations on simulator in real time as an intermediate form before going over to the real object,
3. investigation on the real object including helicopter, measure equipment and crew /test pilot, back-up pilot, observer and board mechanic/.

In the case of investigations on closed mathematical models the handling model reflecting pilot's decisions and execution is combined with the model of the object or systems operation thus making it possible to investigate the pilot-helicopter system simultaneously.

Helicopter simulator of a flexible hybrid-type construction equipped with a stand for ergonomic investigations permits versatile tests of the pilot-helicopter system in real time. The simulator circuit is additionally provided with a model of automatic control based on handling models for investigations in conventional time. This allows to investigate the concept of anthropomorphic auto-pilot and facilitates training of extreme flight conditions using information on transgressive control provided in flight director system.

In order to reduce risk when testing transgressive conditions in flight, alternating investigations are introduced of isolated phases. Empirical simulation of hardly explored phenomena, simulator training and theoretical analyses are used here. They are combined in a uniform program so as to conduct tests as close to the system limit conditions as possible at risk margin not exceeding that involved in conventional investigations.

The model of handling-representation of helicopter flight

Any flight assignment can be presented in the form of a flight profile composed of manoeuvre sequence N. Any n-th manoeuvre can be distinguished as flight phase subjected to fixed set of rules applying between time t_n up to t_{n+1}. A limited set is available to copmpose any flight assignment consisting moduli. The moduli, when solved, give solution for an assignment provided that the final data of a preceding manoeuvre are introductory data for the following one.

Manoeuvre representation consists in calculation of time runs of alterations in helicopter flight data and in establishment of control function for the assumed rule of manoeuvre execution. For this purpose on inverse assignment is executed in closed model converting the manoeuvre rule into extreme allowable impulses controlling in relation to the ground. Translated into the system connected with helicopter they make it possible to specify necessary control function. The solution is conducted step by step in discrete system. A section of flight assignment of a uniform passage technique /Fig.2 items n and n+1/ is divided into a sequence of constant time sections i, i+1 for the assumed time interval Δt.

Anthropomorphic structure of the handling model

The development in the models of human behavior starts with psychological investigations of the operatior's activities. They have resulted in psychological model revealing the notion of an operational image, that is, internal model.

Especially interesting is the model of pilot's activities described by Cavalla /1/ which attempts to diverge from transmittance model.

In the course of the complex control process pilot's anticipation provides information on flight data in the nearest future. Thus it enables him to estimate the difference between the actual and intended levels of state vector and manoeuvre rule indicates the direction of changes in control vector.

In anthropomorphic handling model feedback and reactions based on pilot's anticipations are parallel elements of the control process. The feedback system fulfils the assignment and stabilizes the system whereas the anticipation system, which is normally intended for more complex problems, serves to establish the intended and flexibly corrected state vector to which feedback system is subjected. According to such an extrapolated run feedback system performs its control function for the nearest moment. Anticipation is a permanent process interfering with control decisions depending on current conditions, position of limits and run of the actual system state vector. For the pilot's mind is involved in anticipation process which is neglected by investigations. This process embraces ceonsequences of intended limit control changes being neither mere projection of ewents nor advancing penetration of disturbances. The basic group of phenomena covered by such an anticipation in limit flights refers to the dynamics of changes in state vector limits and to evaluation of anticipation limit time.

The crucial need to control the system in extreme conditions is to develop the helicopter model control so as to maintain required control run in relation ot limitations. This makes it possible to effect different variants of exceeding limits.

Models of anthropomorphic control fall into several types.

In the <u>first variant</u> of control in limit flight conditions with a provision that the envelope of selected system limits is not exceeded, calculated control impulse Δz_j /target impulse/ must not exceed selected system state limits. This is why in each step and for each element it is necessary to calculate set of upper and lower margins of state vector $\Delta x_{Ui} = x_{Ui} - x_i$ and $\Delta x_{Li} = x_i - x_{Li}$ as well as differential quotients $\Delta D_{ij} = \Delta x^o_j / \Delta z^o_i$ for the assumed individual control impulse Δz^o_i /from relation $Z = GX$*/ a proper change in state vector Δx^o_i can be calculated for Δz^o_i/. From calculated set of control margins $\Delta z_{ijU} = \Delta x^o_{Ui} / \Delta D_{ij}$ and $\Delta z_{ijL} = \Delta x^o_{Li} / \Delta D_{ij}$ the minimum control margins $\Delta z_j^{U,L}$ min are selected.

The conditions $|\Delta z_j| \leqslant |\Delta z_j^{U,L}\ \mathrm{min}|$ when fulfilled make it possible to secure the objective within system capabilities and to fly "along limits" without exceeding them.

The principle of limit run between allowable limits have been presented in Fig.3 where z_{U1}, z_{L1}, z_{U2}, z_{L2}, z_{U3}, z_{L3} depict envelopes of top and bottom limit control impulses for the handling model - index 1, helicopter - 2 and environment - 3. On section AB control run z/t/ is effected for the condition $|\Delta z_j| \leqslant |\Delta z_j^{U,L}\ \mathrm{min}|$, the remaining area corresponding to $|\Delta z_j| = |\Delta z_j^{U,L}\mathrm{min}|$. Shaded area indicates the area where flying and control are considerably affected by limit priximity /risk area/.

The <u>second type</u> of control deals with the models of exceeding limits. Having a problem of control along limits developed it is possible, at any time, to exceed the limits. They can be exceeded either by intentional control according to the rule corresponding to structural capabilities of the system or by causing failure in selected system element and assembly. Also it is possible by changing the environmental conditions.

The <u>third type</u> is advance control. The handling model represents the process of complex decisions concerning flight program check /evaluation of performed manoeuvre and passage to another flight phase/, detection of system failure and serious disturbances and, as a result, proper modifications in flight program /alteration in X_n/ and the way of its execution. Any decision as to the choice of flight program modification when approaching serious disturbances or intentional change in control vector requires an adequate representation in the model of anticipation process.

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*/ equations connecting control vector Z with state vector X.

Therefore, it is necessary to calculate extreme possibility of changes in adjustment range so as to penetrate the area in which the process will continue in the nearest future. At the same time some features of extreme changes in adjustment range have to be taken into consideration /Fig.4/

Disturbance magnitude should be converted into magnitude of necessary change in state vector ΔX. Thus a premise is obtained to estimate to moment being a starting point of the control system reaction to compensate disturbance. To do this, it is necessary to estimate time which passes from the onset of the system action using limit control capabilities up to the moment when alteration in adjustment range equals disturbance magnitude ΔX_n. This time is limit time indicated in Fig.4 as t_{gr}. Symbols X_{U1}, X_{L1}, X_{U2}, X_{L2}, X_{U3}, X_{L3} refer to top and bottom limits of system state /model of control system, object and environment/.

All the elementary control actions to couse required change in state vector ΔX are mostly anticipation - type control processes. The handling model then represents characteristic way of handling including action impulse ΔZ_a which initiates alteration in state vector into required direction and advance countreaction of control ΔZ_k to impede movement so that the required level of alteration in state vector ΔX could be achieved.

The fourth variant of anthropomorphic type control deals with decisions to modify flight assignment if, for instance, an unexspected failure occurs to the system. Unlike static type decision processes /as known from literature/, those processes must be synchronized with flight dynamics due to considerable time limitations. The pilot then is forced to modify flight program by selecting the ready flight procedures. The heuristics of assignment structure like this have to be mastered by the pilot to be employed automatically. Making a model in such a case consists in selection of a proper sequence run. Having a proper assignment structure selected, the decision sequence is focused on selection of dynamic data for respective sequences.

Fig.5 illustrates the functioning of feedback circuit while in successive manoeuvres the system compensates the error of the current and target state vector without exceeding the limits imposed.

The assignment, it was provided, had to be effected to the assumed flight program using the limit system capabilities. The limitations assumed were: the use of maximum engine power $P_{r\,max}$ and maximum thrust T_{kr} /stream stall/ when maintaining the limit control data $/d\vartheta_o/dt/_{max}$, $/d\vartheta_y/dt/_{max}$ and $\varphi_{y\,max}$. Flight program has been presented in Fig.5 as a set of altitude - airspeed combinations at the end of each flight phase. They have been indicated on a curve z /t/.

In control sequence from stick displacements to helicopter displacements, causes and effects are subject to the following scheme:

$$\delta_o, \delta_x \longrightarrow \vartheta_o, \vartheta_y \longrightarrow a_{zo}, a_{xo} \longrightarrow a_z, a_x \longrightarrow V_z, V_x \longrightarrow z, x$$

where: δ_o - displacement of collective pitch lever, δ_x - stick displacement in the plane of symmetry, ϑ_o, ϑ_y - displacement of control disc /collective and cyclical inclination pitch/, a_{zo}, a_{xo} - accelerations in helicopter system as immediate /non inertial/ result of control action, a_z, a_x - transposition of accelerations into a system connected with the ground, V_x, V_z, x, z - airspeeds and displacements of helicopter as a result of acceleration effect in time.

Accordingly a_z and a_x accelerations have been assumed as input control impulses in the model, the remaining data have been calculated.

Fig.5a shows control impulses run. It occurs that the minimum impulses a_x or a_z are assumed as limit values. Fig.5b illustrates entrance in the following limit ranges of respective helicopter assemblies /1 - flight with maximum pitching, 2 - initially flight close to stall conditions and then at the engine maximum power, 3 and 4 - flight with maximum power/.

The effect of predictive system in the handling model is illustrated in Fig.6 for bob up - fast elevation to spot hovering at intended altitude[x/]. In a simple single-parameter vertical halicopter movement the elements to be considered are introductory vertical acceleration and subsequent speed reduction so as to maintain hovering at 10 m above the ground.

In order to establish the starting point for braking vertical movement it is necessary to calculate the lower limit of system adjustment for each step /Fig.4/. The advance control action /point B_o in Fig.6/ for time t_{gr} permitted, with the accuracy of numeric solution, to brake climbing speed at required altitude of 10 m /point B/.

[x/] typical NOE /"nap-of-the-earth"/ manoeuvre - bob up /6/.

Dynamics of multi-element discrete helicopter structure

A helicopter model was developed in the form of multi-element discrete structures such as: rotor blades, fuselage structure, models of exciting force generators /e.g. drive, elements of active or passive vibration isolation/, connected to one another by joints /e.g. blade attachment joints/. The dynamics of the whole system was solved by means of systems of equations of motion corresponding to each sub-system. The systems of equations were next connected with equations of constraints.

It is assumed that the whole system is moving unsteadily in relation to inertial system connected with the ground x_o, y_o, z_o and is subject to deformations evaluated in system x_m, y_m, z_m which are connected with selected sub-systems to which due to their digitizing local systems $\bar{x}_{m,i}$, $\bar{y}_{m,i}$, $\bar{z}_{m,i}$ are assigned in each i-th point of the concentrated element state vector.

Fig.7 illustrates mutual interrelations between the system elements in generalized coordinates, where q is generalized displacements, P is generalized force, $\bar{r}$ is positional vector of coordinates system of m-th element, $\bar{r}_{wm,m+1}$ is positional vector of joint connecting elements m and m+1, $\bar{r}_{m,i}$ is positional vector of i-th discrete point in the system conncected with m-th element.

Equations of motion of the helicopter system elements

Equations of motion for m-th assembly in generalized coordinates following left-sided separation of linear elements assume the form:

$$M\ddot{q} + \Lambda\dot{q} + Cq = P/t/ \qquad /1/$$

where M is inertia matrix, Λ is suppression matrix, C is stiffness matrix, P/t/ is generalized force being a non-linear function of aerodynamic loads, kinematic and force inputs resulting from joint reaction, gravity forces, control and friction loads and force generator inputs of equipment installed on the helicopter.

The solution of this system of coupled equations representing non-linear relations of the helicopter dynamics is extremely difficult. Modal coordinates, when introduced, make it possible to obtain for the system of n degrees of freedom n independent differential equations of a single degree of freedom. And this is one of efficient means to solve the system.

By a proper selection of transformation matrix Γ so that its columns are M-orthonormal vectors of free vibrations of non-suppressed system, and substituting

$$q = \Gamma\xi \qquad /2/$$

where: ξ – vector of modal coordinates, and then premultiplying the system of equations in generalized coordinates /1/ by Γ^T we obtain the following system of equations:

$$\Gamma^T M\Gamma\ddot{\xi} + \Gamma^T\Lambda\Gamma\dot{\xi} + \Gamma^T C\Gamma\xi = \Gamma^T P/t/ \qquad /3/$$

which can be transformed into:

$$M^*\ddot{\xi} + \Lambda^*\dot{\xi} + C\xi = Q/t/ \qquad /4/$$

where

$$M^* = \Gamma^T M\Gamma = I; \quad \Lambda^* = \Gamma^T\Lambda\Gamma; \quad C^* = \Gamma^T C\Gamma; \qquad /5/$$

that is into the system of n equations of a single degree of freedom

$$\ddot{\xi} + \lambda_i\dot{\xi}_i + c_i\xi_i = Q_i/t/ \qquad i = 1,2,\ldots,n \qquad /6/$$

Using predictive integration to solve this system in time t, t+Δt it is possible, having accomplished each calculation of modal coordinates vector, to establish vector of the primary generalized coordinates from the formula /2/.

Each equation in main coordinates was solved using Runge-Kutt fourth-order method to determine $\ddot{\xi}_i = f/t_i, \xi_i, \dot{\xi}_i/$ according to relation

$$\ddot{\xi}_i = Q_i/t/ - \lambda_i\dot{\xi}_i - c_i\xi_i \qquad /7/$$

starting with the assumed initial conditions for $t = t_o$, $\xi = \xi_o$ and $\dot{\xi} = \dot{\xi}_o$ while shifting from t_i to $t_{i+1} = t_i + \Delta t$ the following procedure was applied.

Time interval was divided into p sections 1,2...k...p of a magnitude $\Delta t_k = t_k - t_i = \alpha_k\Delta t$ and then the system of equations was solved p-time

$$\ddot{\xi}_k = f/t_k, \xi_k, \dot{\xi}_k/$$

$$/j/ \quad \dot{\xi}_{k+1} = \dot{\xi}_i + \Delta t\alpha_k \sum_{n=1}^{k} a_{j,n}\ddot{\xi}_n \qquad /8/$$

$$/j/ \quad \xi_{k+1} = \xi_i + \Delta t\alpha_k \sum_{n=1}^{k} a_{j,n}\dot{\xi}_n$$

where j and k – successive equations $j = 1,2...p$; $k = 1,2...p$; n – index of term coefficients in following equation $n = 1,2...k$.

The condition is that in each equation $\sum_{n=1}^{k} a_{j,n} = 1$.

Disturbance of air flow round the helicopter

Uniform air flow round the helicopter is disturbed by velocity field induced by a system of wakes generated by the helicopter rotors /main rotor and tail rotor/, lifting areas /wings, stabilizers/, fuselage flow round and atmosphere turbulence.

Velocity field generated by rotary wake depends on wake geometry which is shaped due to the way of its creation and deformation in disturbed medium caused by all disturbing factors.

The whirling surfaces induce velocity field $\overline{V}/x,y,z,t/$ according to Biot and Savart rule

$$\overline{V} = \sum_{n=1}^{N} \iint_{F_n} \Delta\Gamma \times \overline{h} \times \overline{dl} \,,$$

where n – element generating F_n-th whirling surface /blade, wing, etc./, $\overline{dl}$ – length of wake element of rotation curl $\Delta\Gamma$, $\overline{h}$ – projection of distance from elementary rotation curl to the point in which induced speed is determined.

Model verification

Results of investigations of the rotor dynamics under transgressive conditions can only be reliable if the model is tested in well-controlled circumstances close to limit ones and especially carefully are checked those phenomena /model fragments/ which are essential to the system behaviour when exceeding limits.

This chapter includes the outline of verifications, global and partial alike, of the system model by comparison with methods used by world's leading helicopter manufacturers, flight tests and by comparison of numeric solutions with analytical solutions.

Comparison of presented method with the methods used by the world's leading manufacturers /2,3/

Studies /2 and 3/ deal with comparison of calculation methods developed by the world's leading helicopter manufacturers of which methods provided in /3/are considered the most advanced ones.

The rotor hypothetical data provided in /2 and 3/ have been calculated using the method described here in order to verify the data.

Codes of respective companies assumed in diagrams for different calculation methods:

ARC	Ames Research Center
BHC	Bell Helicopter Company
BV	Boeing Vertol Company
HH	Hughes Helicopters
KAC	Kaman Aerospace Corporation
LCC	Lockheed California Company
MIT	Massachusetts Institute of Technology
OR	Office National d'Etudes et de Reserches Aerospatiales
SA	Sikorsky Aircraft
UARL	United Aircraft Research Laboratories
BS	Boeing Stall Method
IL	Instytut Lotnictwa /Poland/

In order to estimate the methods an extreme case has been selected with stream stall on returning blade and compressibility phenomena on attacking blade /$M_{1,90^\circ} = 0,9$/ and at particular rotor position against the air flow round. It has been assumed for high flight speed / $\mu = 0,33$/ that shaft inclination against the stream is $\alpha_w = 0$.

Flexural loads /Fig.8/ reveal conformability for all methods. Deformations and torsional loads as much more sensitive indicator of the method quality show considerable descrepancy from one result to another. This especially applies to methods /2/. Good uniformity of results have been attained for improved methods /3/, including IL method /Fig.9/.

Check of method reliability by comparison with flight test results

Using IL method calculations were made for the cases tested in flight. The results are shown in Fig.10. In the drawing distribution of torque moment affecting helicopter blade root in steady flight has been shown.

This verification of calculations and tests is of particular significance for it concerns low torsional stiffness blade type ACR /4/. Extreme sensitivity of calculation results, in particular for torsional deformation, to method errors /even slight/ and errors in data set for the rotors of this type with simultaneous conformity of calculation results and test results testifies to positive method verification.

Check of numeric solution of blade motion equations by means of analitycal solution

For various frequencies of blade excitation and various suppressions the results of numeric program solutions have been compared analytical solution of funcion type $y = Ae^{-\lambda t}\cos\bar{\nu}\omega t$. Fig.11 shows comparison of solutions for suppression $\lambda = 25$ at frequency $\bar{\nu} = 18$ for solution step $\Delta\psi = 5^{\circ}$. Calculation results are not practically different from accurate solution to $\bar{\nu} = 18$ for $\Delta\psi = 5^{\circ}$. Greater conformity /strict coincidence of numeric and analytical results/ is obtained with decreased step $\Delta\psi = 2.5^{\circ}$.

Examples of simulation investigations of rotordynamics in transgression conditions

This chapter covers examples of investigation possibilities, by means of an accurate simulation model, of the dynamics of helicopter rotors in transgression conditions.

The first example pertains to a hingeless rotor, wherein by reducing the collective pitch, a limit chord instability of FLT /Flap-Lag-Torsion/ type was initially introduced, and with further reduction of the pitch - the limit of the divergent flutter of the blade was exceeded. The feasibility was investigated of returning into the ranges of stability by re-increasing the collective pitch. The enclosed diagrams 12-14 display the methods of observing the system in conditions of transgression.

By /inertialess/ reduction of the collective pitch the chord instability of FLT type /Fig.12/ was being created, whole with further reduction of the pitch, the limit of the divergent flutter of the blade was exceeded /Fig.13/. The investigations of the possibility of returning into the ranges of stability by means of re-increasing the collective pitch are illustrated in Fig.14.

The second example deals with investigations of a two-blades teetering tail rotor, in the ewent of one the blade's tip being damaged. Those cases are concerned with investigating the consequences of rotor damage which may cause exceedeng of the limit of a respective type /Fig.1/. The results of changes in the condition of the system when the blade tip has been injured on about 15% of length, with loss of mass and bending of the trailing section, are displayed in Fig.15 and 16.

Investigations on the simulator

On an investigation simulator /Fig.17/ it is feasible to investigate isolated manoeuvers in normal, extreme, and overextreme conditions of flight, flight tasks, as well as certain closed problems, such as determination of operation limits, estimation of flying qualities - using subjective scales of estimation, investigation of pilot-helicopter configuration from point of view of ergonomics, or of processes of control as performed by a human. All those investigations can be limited to investigations exclusively in terms of real time or they can be extended by analyzing selected and registered fragments in conventional time.

Isolated manoeuvers, being particularly adaptable to investigating on a simulator, include the following: braking, jumping over an obstacle, safety manoeuvers of all kinds following power plant failure, such as landing or fly away with one engine inoperative. Repeatable execution of a selected manoeuver enables - by means of the method of successive approximations - to optimize the technique of control in oreder to utilize the limit possibilities of the system.

The purpose of investigations on a simulator of training character is to check the reality of analytically elaborated control techniques, and to carry out training of crews in flight in order to master the correct control dynamics.

The monitoring on a simulator of new problems, connected with flying helicopters, and solved by other means, constitutes a reliable check of the correctness of the proposed solutions prior to conveying them onto actual systems.

Investigation of system behavior in conditions of transgression consists mainly in resetting the system in selected fragments of the performed limit manoeuver or of controlling the system beyond adminissible limits, and in observation of consequences of that operation, chiefly the rate at which the dangerous effects are building up, so as to have the possibility of estimating the limit of risk, admissible limit, failure limit or limit of catastrophe. The analysis of the vector of a posteriori state in conventional time is - in this case - the principle of investigations.

The possibility of observing on a screen in real time the parameters of helicopter movements permits to investigate the problems of anticipation of helicopter pilotage. By introducing accelerated calculations of limits of changes of state vector in time interval from the current moment to the limit time, it is feasible to estimate the moment of making the decision as to when to begin to change the vector of state to desired magnitude.

Fig.18 illustrates the concept of such investigations by the example of landing of an autorotation helicopter when the pulling-off phase is computed in an accelerated scale of time, and is executed in limit mode in real time in the interval from current moment up to braking the rate of descent down to the admissible. In the event when the accelerated course of limit trajectories on the screen determines solely the sequence of the line - the passive information constitutes for the pilot an indication as to how and when the "next" manoeuver should be initiated.

Limit investigations in flight

The investigations in flight, of limit type, apart from the measurement apparatus /board and on the ground/ registering the helicopter dynamic parameters, involve installing of such apparatus which permits to measure functioning of the pilot; this enables to estimate both his abilities as operator and the degree of risk caused by the limit situation. This equipment also serves to monitor the elements of pilotage of anticipative nature.

An oculographic apparatus was mounted to examine the fixation of the pilot's eyesight, while his psychophysilogical reactions can be estimated by a special set which serves to measure the following:

1. EKG, according to which it is posiible to estimate the degree of excitation, frequency of heart contractions, and selection of Korotkov tones when measuring arterial pressure,
2. ventilation parameters of the lungs /number and volume of successibe inhalations/,
3. arterial pressure of the blood,
4. force of control stick squeeze.

The oculographic apparatus, in addition to routine application to estimate the ergonomic work of the pilot, also serves to analyze the anticipative processes, because the operator's eye, prior to taking the decision of changing the control vector, is the first to reveal the intention - it penetrates the area of future events, the so-called orientation area. Basing on this assumption it is possible to estimate the time of prediction, i.e. the time interval from the moment preceding the visual penetration to the moment of changing the control vector.

The apparatus for measuring the psychophysical reactions is mainly used to estimate the levels of psychophysical stress which is the discriminant of the degree of risk during execution of a flight task.

The chief role in the problem of reducing the excessive degree of risk is performed by an adequate structure of the program of investigations, created in accordance with the principle of optimization of risk gradation when passing over to successive, more difficult phases of investigation.

Joining the flight tests with simulation investigations leads to reduction of the risk of limit tests to an adminissible level. Inclusion of simulation into the investigation system covers the following:

1. numerical simulation- introduction of initial limit investigations of the tests on a closed model in conventional time in order to determine the admissible limits, to detect the critical points of the test, and to elaborate the adequate investigation techniques and techniques of control, which tend to utilize the reserves of the system when it is necessary to increase the safety margin in limit situations,
2. training in real time involving pilotage techniques specified in the test on an investigator flight simulator, indispensable for mastering and storage /in mind/ an adequate stereotype of dynamic control prior to going over to experiments on an actual object,
3. empirical simulation of critical phases of the test in conditions safer than those resulting from the realization of the complete task,
4. simulation of the test by means of a verified /by results from item 3/ closed model and extrapolation of results for extreme and overextreme conditions.

Examples of transgression in experimental investigations

Three types of experiments have been selected as examples illustrating the problems of transgression in flight tests of helicopter:

1. investigating the dynamics of pilot-helicopter configuration in flying low above the ground in the contingency of power plant failure,
2. investigating helicopter turnover during take-off or landing on sloping terrain,
3. investigating limit manoeuverability of a helicopter in hedgehopping.

All those experiments, being significantly risky are excellent displays of transgression problems /multitude of overlapping limits of the system, necessity of mastering safety manoeuvers after transgression, e.g. in the event of power plant failure/ they stress the necessity for an integral approach to the pilot-helicopter configuration /by a visible and equivalent influence on the position of limits both of the pilotage parameters and those of the helicopter/, and justify the adopted method of investigations: alternate conducting of experiments and simulation investigations /theoretical and laboratory/, a well as simulation extrapolation of experiments for extreme conditions.

Investigations of pilot-helicopter configuration in conditions of power plant failure

Those investigations include tests concerning determination of limits of safety zones where it is feasible to safely carry out landing manoeuvers or to continue flight after failure of the power plant, the so-called HV zone /"height-velocity" - due to their determination in co-ordinates altitude - velocity/, tests of interrupted take-off in result of powet plant failure, and cases of power plant failure during operations performed by a helicopter in hovering flight, and at low air speeds /rescue work and flying crane operations/.

Model investigations by means of a closed simulation model determine the courses of the vector of state in the function of time for various types of safety manoeuvers after a failure of the power plant. Analysis of these courses informs about the succession of time phenomena in the neuralgic points of manoeuvers, time balance, and the like.

Indispensable also is the simulation estimation of admissible time of non-reaction following power plant failure /before the rotor revolutions drop below the admissible/. By means of simulation it is also necessary to carry out an estimation of the possibility of a vortex ring being formed.

Using a simulation model it is feasible to determine the limits of a safety zone of helicopter operation in which the failure of the power plant synonymously specifies the possibilities and means by which the safety manoeuvers is performed.

Fig.19 shows the safety zones which it is necessary to obtain, by employing the method of successive repeating for determining the optimal manoeuvers of safety for various initial conditions at the moment of failure. In order to get well acquainted with the stereotype of dynamical control of the helicopter, following power plant failure, for various initial conditions of its occurring, it is necessary to train the individual phases of flight and the complete manoeuvers of safety on a simulator. Successively selecting the initial conditions of altitude and the rapidity of failure occurrence, and performing the safety manoeuver of landing or departure, it is possible to determine the zone limiting points. Utilizing the circuit of anticipation for investigating the limit possibilities of the system, as well as the circuit of automatic control /see Fig.18,22,23/ it is feasible to relatively easily determine and master the technique of pilotage in the more difficult limit phases.

The initial flight tests include investigations of the more difficult phases of flight selected during the simulation analysis by means of a closed model, carried out in conditions easier than during the essential test /the so-called empirical simulation/. Their purpose is to detect phenomena which are either unforeseen or impossible to model, and also to provide material for verification of mathematical models. Those will be initial phases of safety manoeuvers at simulated failure in the vicinity of zone limit, and trying to fly through a vortex ring in order to estimate the possibility of evading it, and to estimate the controllability of the helicopter when flying through the ring, and trials to land autorotationally on reduced air speed in the vicinity of the point of intersection of curves LHV and UHV /recording of state vector - Fig.20, oculogram - Fig.21/.

Determination of system limits by extrapolation of test conditions for limit conditions

By carrying out a transgression by means of a simulation model, and next on an investigation simulator, it is posible to estimate the position of successive zone limits in order to estimate their reciprocal position, as well as simulation areas, and also time reserves and the degree of risk cumulation which influence the process of making decisions, and selecting the type of safety manoeuver.

Transgressions of successive limits performed on a simulator during an emergency manoeuver following the helicopter power plant failure in hovering flight, are displayed in Fig.24. This case concerns landing from the lower limit of HV zone; the limit of admissible landing speed determines the limit of normal operation of the helicopter; further limits pertain to hard landing and safe crash.

By modyfying the pilotage technique so as to optimize the flow of energy in the system and utilize its reserves, it is possible to significantly reduce the risky zones.

Investigations carried out on a simulation model have indicated that better utilization of energy can be obtained when emergency manoeuvers are carried out in a more dynamic manner. Gathering speed with greater pitching, and greater pull-up in pulling-up phase is decisive in a substantial measure for relocating zone limits /Fig.25/.

During the fly away manoeuver it is feasible to reduce the span of levels of energy flow by continuing flight on reduced r.p.m. Such a modification of fly away technique affords a considerable gain in the form of a lesser drop in maximum flight descent from the moment of failure /Fig.26/.

Similar problems are encountered when investigating interrupted take-offs of a helicopter due to power failure. The article only points to the estimation of effectiveness of pilotage technique modofication in the course of such a take-off. The classic techniques of take-off performing, and particularly of safety manoeuvers after engine failure /considerable lowering of flight path/, do not warrant an adequate level of flight safety, and for this reason it is suggested to modify the technique of take-off, consisting in increasing the rate of climb in the initial phase and fly away, following engine failure, by applying the technique of minimum rotor revolutions /lesser lowering of flight path/. The illustration of comparing the classic technique with the modified one of vertical take-off /in the example without utilization of rotor energy in the phase of vertical climb/ is presented in Fig.27.

The effectiveness of introducing limit simulation investigations is illustrated by the results of modifying the pilotage technique of emergency manoeuver after power plant failure of the helicopter when performing flying crane operations. When applying classic technique, the helicopter being initially violently lowered, after reduction of the collective pitch, requires much free space, already occupied by the assembly stand and appliances, as well as by the dropped load, previously hoisted, and by miscellaneous objects in the surroundings. It is, therefore, indicated to search for new techniques of carrying out safety manoeuvers in order to reduce this area.

For the helicopter mass which, after jettisoning the load, little exceeds the empty weight, the moment of inertia of the rotor inertial system is relatively high and the r.p.m. drop for this mass, resulted in the first phase of flight after loss of power due to failure, is substantially lesser than for the take-off mass. It is thus possible to manipulate more freely with the time interval of energy accumulated in the rotor, so that in the first phase of flight, after a failure, the helicopter could be displaced as far as possible from the operational site and gather speed while being slightly lowered. For a modified pilotage technique - meeting those requirements - it was assumed that after the failure and after the time in which the pilot does not react /~ 1 s/, and after jettisoning the load, during 2-3 s, with the collective pitch not reduced, and by pitching the helicopter /by pushing the control stick/ an impulse forwards was caused. Next, by a suitable change of the collective pitch and thrust the rotor revolutions level was established at the optimal value for the next phases of the manoeuver.

Fig.28 shows the procedure of changing the flight parameters in the function of time with one engine inoperative /failure/ by means of a modified technique of flight /first acceleration, then reduction of the collective pitch/ witch speeding up the r.p.m. at the rate of $dU/dt = 2$ m/s^2 /$U = \omega R$/. An estimation of the possibility of colliding with obstacles has been displayed in Fig.29. Visible are substantially magnified /as compared with classic method/ the areas in which the presence of obstacles does not imperil flight safety.

Investigating helicopter turnover during take-off and landing on sloping terrain

The turnover investigations constitute a different issue - as compared with the transgression investigations of HV zones and take-offs - although they also deal with transgression, but their character is more stationary, and the contact of the helicopter with the ground bed presents other research problems. The multitude of overlapping limits /turnover, sideslipping, roll-down/, limitations of blade swinging, limits of unstable equilibrium, irreversibility of building up of dangerous phenomena after transgressing each of the limits, the necessity of elaborating safety manoeuvers following the transgression; all that creates problems which are common with those signalized in the introduction as being characteristic for transgression /typical display of limits - Fig.30/.

In order to verify the members of the model which are difficult to be precisely mathematically represented /this pertains chiefly to rotor aerodynamics/, the equation of turnover has been solved by simulation method. For this purpose, the phases of helicopter turnover were investigated on flat tarrain, during which the vector of state of the system was being registered: the position of the control system elements, angular position of the helicopter, revolution of the helicopter rotor, blade flapping angle, components of reaction forces acting on landing gear wheels, and components of vertical reactions acting on main landing gear wheels by means of tensometric scales /Fig.31/.

Those investigaions resulted in the estimation of the rate of build-up of dangerous phenomena in the vicinity of turnover limit and during its transgression, and also of the techniques of performing safety manoeuvers for prevention of turnover.

The last phase of empirical investigations covered landing operations, and engine and rotor stoppage, as well as starting and take-offs in conditions of natural sloping of terrain, in various configurations with relation to the slope /up the slope, down the slope, with R.H. and L.H. side to the slope/, with various loadings of the helicopter /mass and position of mass center/, with various values of wind velocity and direction, as well as for various inclinations of the slope.

By means of the vefified simulation model – possibilities were estimated of extending the admissible limits by:

- reducing the minimum collective pitch,
- increasing the ranges of maximem displacements of the cyclic pitch of the swash-plate,
- increasing ground bed roughness,
- increasing the wheel braking moment and blocking the wheels,
- increasing the turnover angle /particularly when dealing with "tail" turnover by changing the balance/,
- introducing elasticity in the flapping hinge,
- morring the helicopter in parking grounds during starting phase, and prior to stopping the rotor.

Investigations of the limit manoeuverability of the helicopter in low flying /hedgehopping/

The investigations included analysis of problems pertaining to investigating low flying of the helicopter close to the ground, the so-called NOE /taking place, for instance, when performing agricultural airborne operations/. Limit possibilities of their execution were estimated, with maximum utilization of functional and structural reserves of the pilot-helicopter configuration.

The proximity of the ground makes such flight risky owing to the possibility of helicopter colliding with the earth or with obstacles on the ground. The existence of dangerous zones inside of which flying is not recommended creates additional risk in the ewent of power plant failure in those zones. Such facts are responsible for a significant increase of requirements concerning both the pilot who flies in those conditions and the helicopter, and especially its dynamic qualities. Nearly each flight is featured by such characteristic manoeuvers as: scramble, quick stop /normal, sideways, reversal/, jumping over an obstacle at low speed V = 70–90 km/h, encountered in agricultural airborne operations, and at medium speed V = 120–160 km/h, employing the technique of maximum altitude when hedgehopping, and the technique of minimum altitude over the obstacle, symmetrical hopping, as well as those involving change of direction, agricultural wingover/pedal turn , turns to a target and in a specified direction, slalom, and manoeuver of S type, bob up i.e. a rapid change of altitude in hovering flight, and hit the deck – sudden descent with a sharp passing over to low flying.

An example is displayed in Fig.32–34 for agricultural returns. The oculogram signalizes advanced moments of visual penetration of future areas of the flight course. The technique of performing returns has been utilized for the most effective modification of the braking manoeuver – braking by means of return. The reduction of braking distance as compared with previous techniques is manifold, and moreover a significant bank of the helicopter with relation to the obstacle reduces the risk of collision of the blade tips with the obstacle, and reduces the indispensable braking distance by the radius of the rotor /Fig.34/.

Prediction processes in control of the system during performing limit manoeuvers in low flying /hedgehopping/

The process of prediction in low flying concerns control advance actions /e.g. decision to begin braking, or jumping over an obstacle, or levelling out/ from the point of view of forming the flight path, as well as by means of energy in the system.
In limit low flying, the current phase, in addition to the requirement of being correctly performed, must be a phase which prepares the system for the best possible carrying out of consecutive phases. The prediction limit time will reach those next phases in which the effect of operations in the current phase will be subject to dissipation. Particularly important are the energy-consuming and energy-negative elements of the manoeuver.

In the first case – it is necessary, in the preceding phases, to execute control in such a manner that it would be possible in the critical phase to utilize the maximum of components of the system energy /e.g. by cumulating the energy of the helicopter rotor to increase the rotational speed of the rotor, and by stimulation of the available power along the maximum gradient of acceleration, and – if necessary – change of air speed to the vicinity of energy-saving zone/; in the second case – the preparation of the system for absorption of power /e.g. by reducing the rated rotational speed of the rotor, or by maintaining the air speed in such ranges that will enable substantial absorption of power, accelerations – medium speeds/.

Investigations of prediction processes are extremaly defficult since they pertain to thought processes and imagination, but in some degree the oculographic measurements and measurements of psychophysiological parameters permit to penetrate into the nature of anticipation processes and control thereof, and in particular it is feasible to localize fairly precisely the moments of making advanced decisions as to control operations.

By comparing the eyesight fixation paths on oculograms with the time runs of the vector of state, and analyzing the advance of visual penetration of the display of anticipated changes of the system, it is possible to estimate fairly accurately the limit time of anticipation /see Fig.20 and 33/. In some manoeuvers, in which the predict limit change of the vector of state is not connected with the necessity of visual perusal of the area of future events, it is practicable to utilize the measurements of psychophysiological parameters /building up of stress prior to occurrence of the risky phase/.

Of the physiological parameters, the frequency of heart contractions proved to be the most sensitive indicator of physical and emotional burden during flight. The measurement of arterial pressure, although not reflecting the dynamics of changes occurring in flight, made it possible to deeply inspect the behavior of the circulatory system in selected flight conditions. The examinations of minute ventilation of the lungs and frequency of respiration constitute a source of information about the degree of load caused by flight.

The investigations point to the fact that the greatest psychophysical load on the pilot is incurred by those manoeuvers in which the prediction processes must be carried out very precisely owing to the irreversibility of consequences, particularly dangerous when the limit time is incorrectly estimated. Such case has been observed during the manoeuver of lowering and low levelling out /hit the deck/.

Summary

The presented hypothesis on the advisability of introducing transgression as a method of investigating complex systems, such as helicopters - in result of which it is feasible to achieve a significant progress in the development of science about the subject of investigations - has been supported by providing adequate examples of the investigations.

The created system of transgression investigations, including the set of simulation models of the pilot-helicopter configuration, the laboratory station of the helicopter investigation simulator, as well as the prepared process of limit flight tests of helicopters, enable in a large range the realization of the presented problem in an effective manner and with adequate precision required in that type of research.

Due to a holistic approach, with an interdisciplinary connection of the subject problems, it was possible a.o. to work out an integral model of the helicopter as a multielement elastic structure controlled by an anthropomorphic model of pilotage, and to build a hybrid laboratory station - imitator of limit processes of the pilot-helicopter configuration, and a safe execution of numerous and multilateral flight tests, including the system of transgression investigations into those flight tests which were featured by a particularly high degree of risk.

The performed processes for verifying the produced mathematical models and systems which substituted actual objects, confirm the likelihood of utilizing the aforementioned system, as a multi-role device for investigating the helicopter system.

The herein mentioned examples of techniques and types of investigations as well as thellimit cases of helicopter flight signalize the research possibilities of the system and the character of achieved results.

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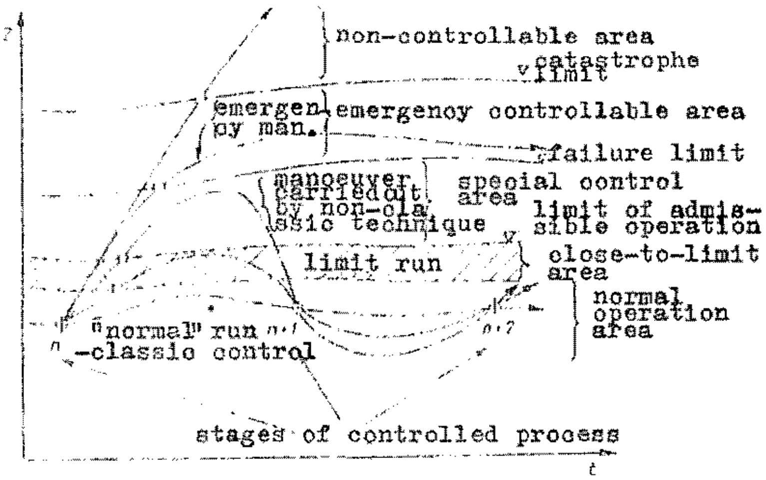
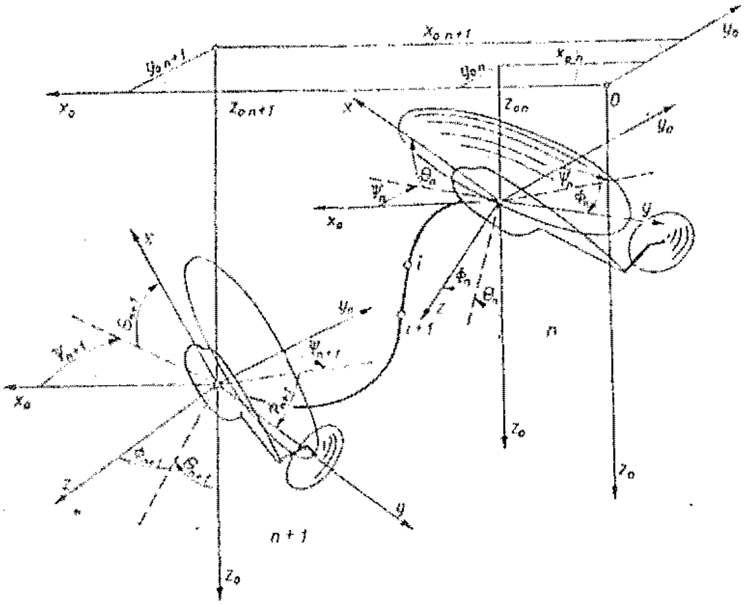
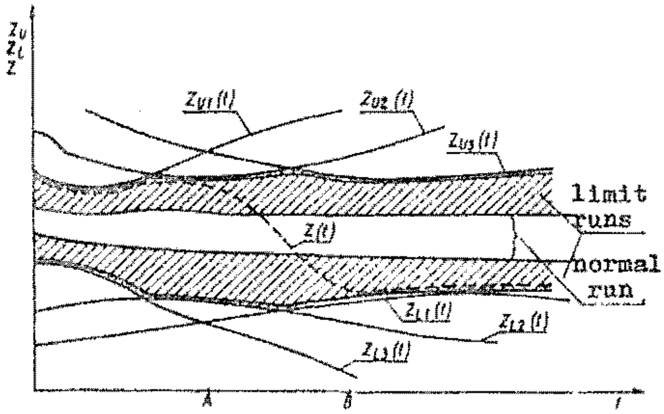


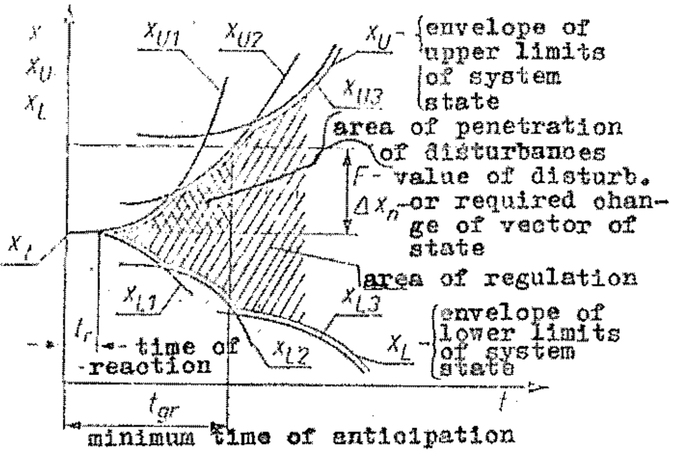
1. Types of control process runs for various cases of transgression.



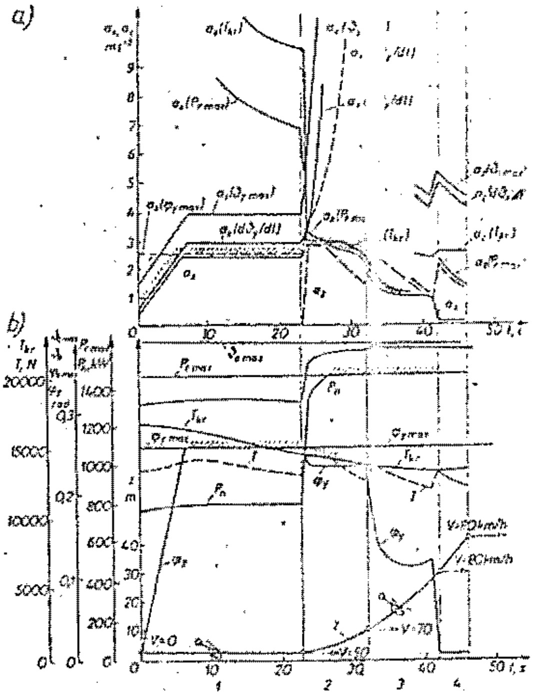
2. Diagram of adopted designations for overflight of sector "n".



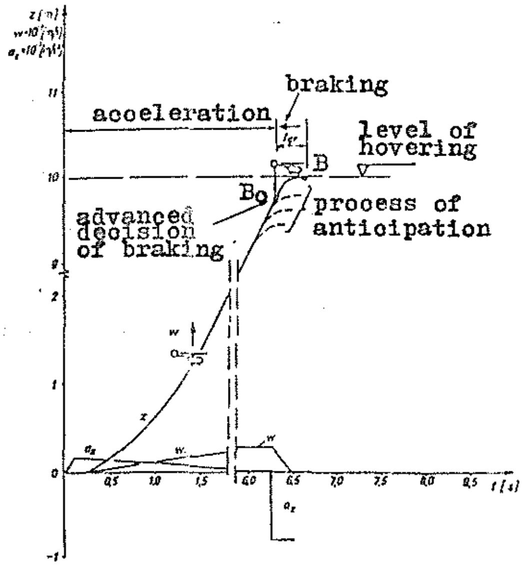
3. Diagram of a limit run.

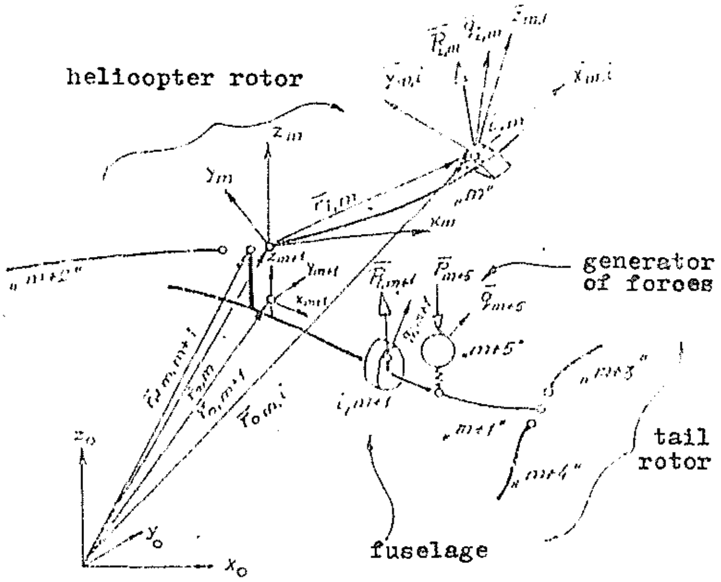


4. Variation of system regulation range according to time elapse from the moment of intervention of control system.



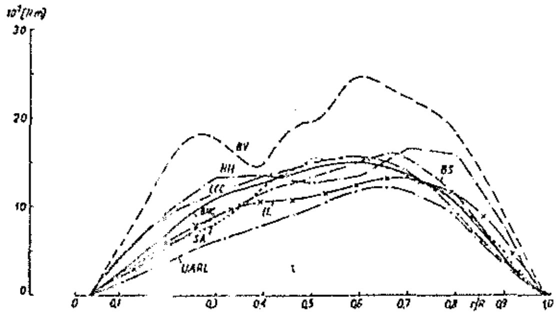
5. Illustration of flight solution "along limitations" on the example of a normal take-off of the helicopter: a - function of control impulses, b - run of change of parameters of system state.

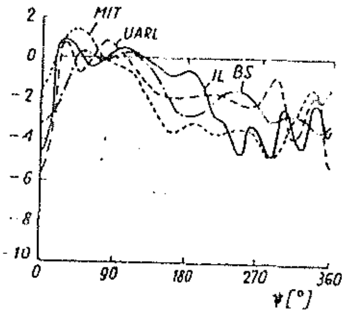




6. Manoeuver of helicopter bob up. Example of functioning of prediction circuit.

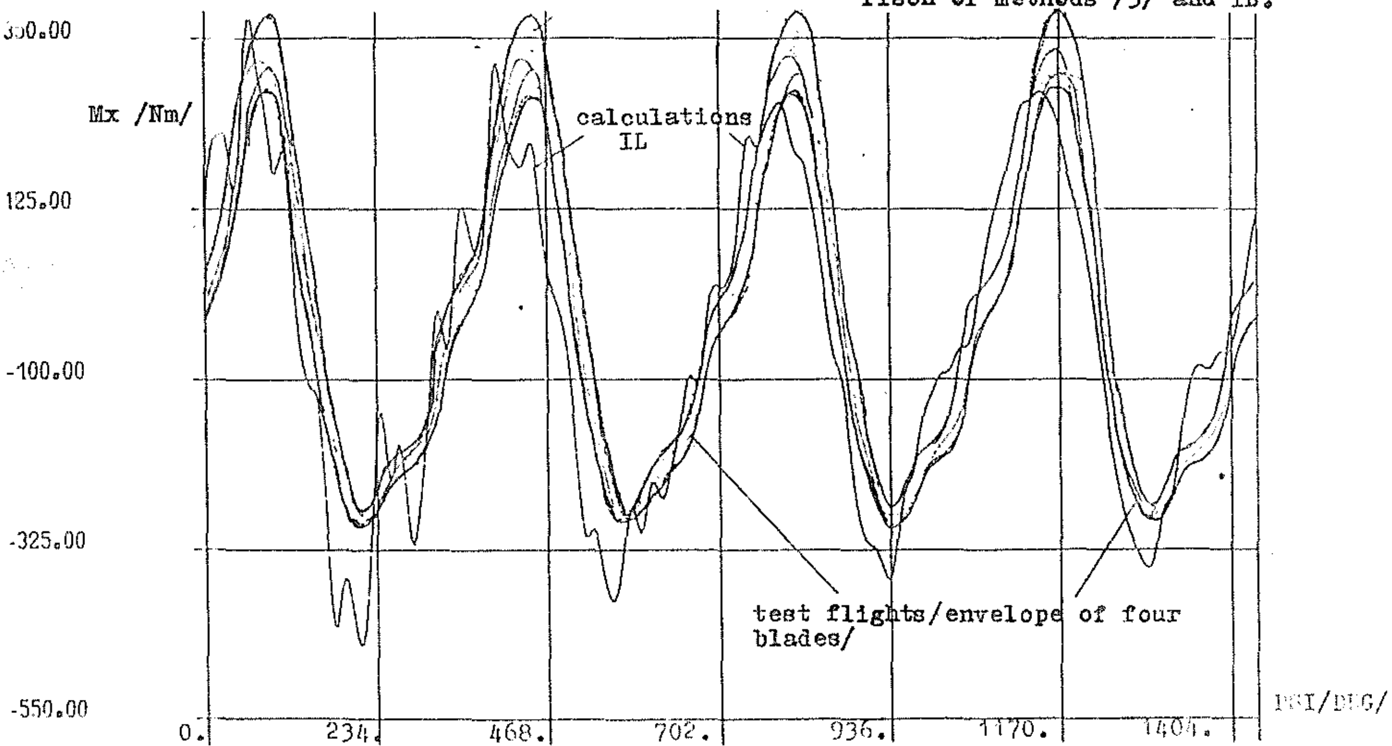
7. Diagram of connections of the structure of deformable elements of the helicopter.



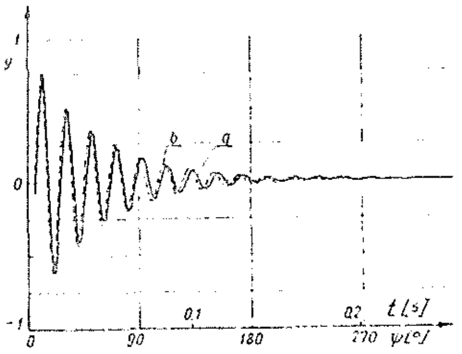


8. Amplitude of bending moments in plane of thrust. Comparison of methods acc. to /2 3/ and IL.

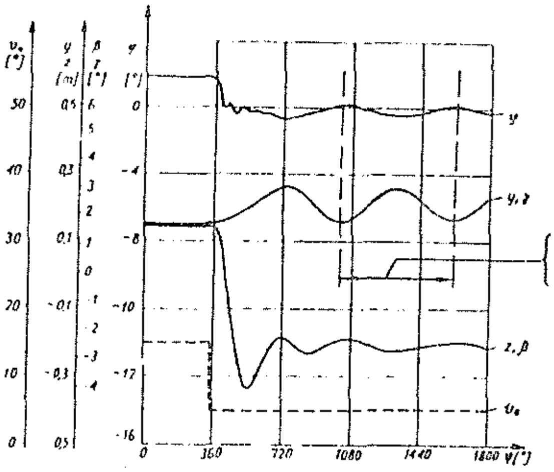
9. Distributions of blade tip torsional deffexion with relation to the azimuth; comparison of methods /3/ and IL.



10. Distribution of blade twisting moments at the blade root. Rotor of ACR type, horizontal flight, V = 140 km/h. Comparison of results of the flight tests with the result of calculations. Visible is the decay of initial conditions for the second torsional form /about the 8-th harmonic/, through about 2.5 of rotor revolution.

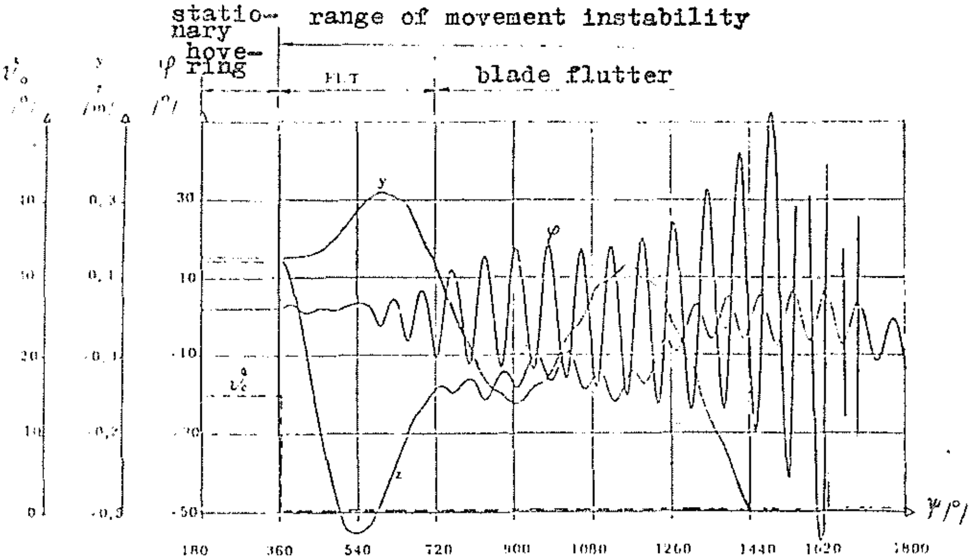


11. Inspection of the correctness of the solution of the differential equations system of blade movement; a - numerical solution /IL/, b - analytical solution.

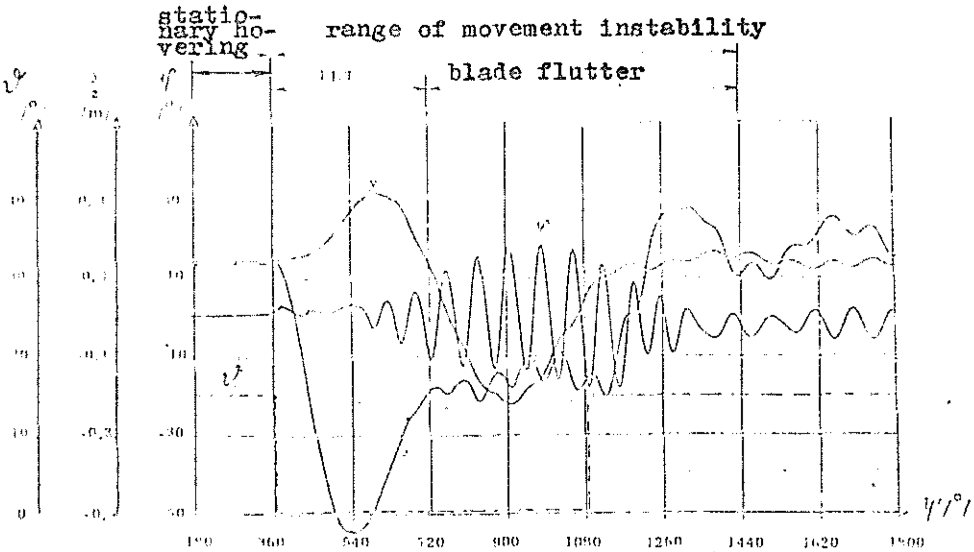


the first frequency of free vibrations in the plane of revolutions

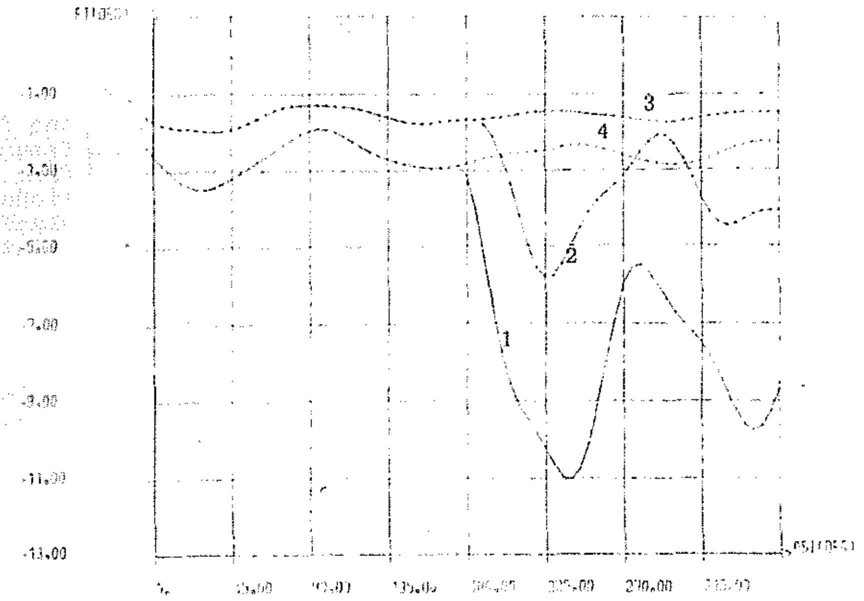
12. Run of instability FLT for the hingeless rotor at reduction of collective pitch by $\Delta\vartheta_0 = -10°$.



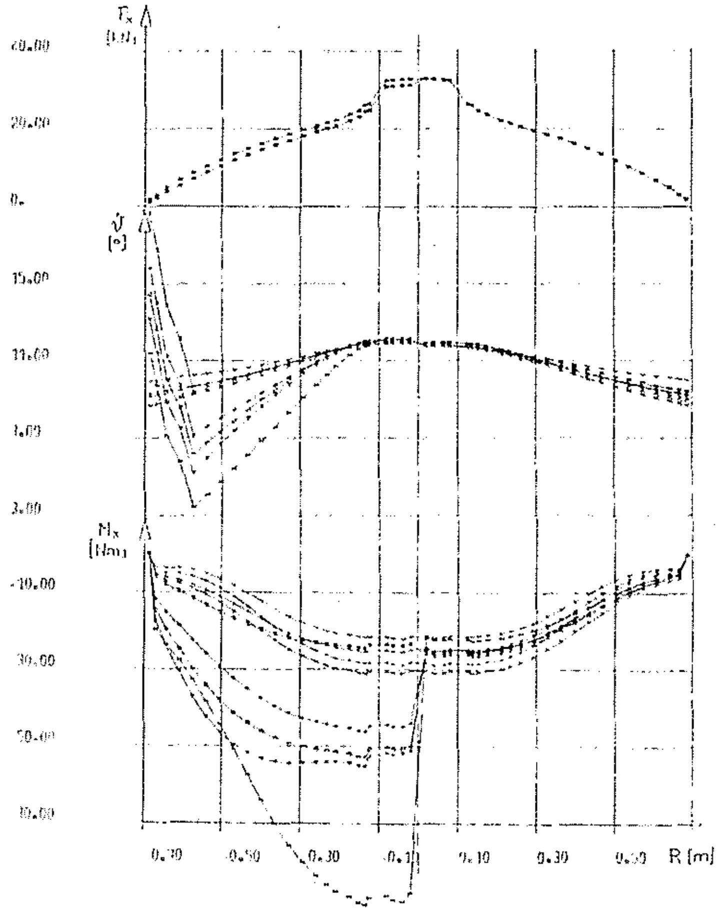
13. Transgression of aeroelastic instability of the hingeless rotor /blade flutter/ caussed by a substantial reduction of the collective pitch.



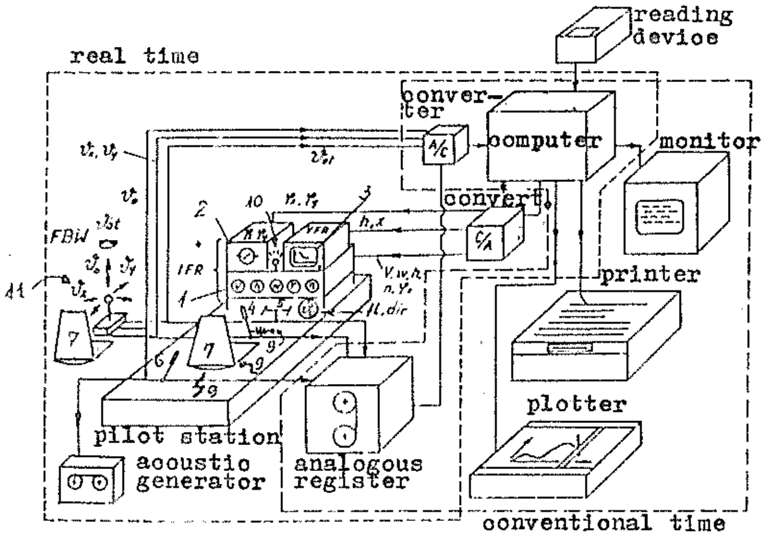
14. Trangression of aeroelastic instability of the hingeless rotor blade in result of the reduction of the collective pitch and return into the ranges of stability of movement of the blade which is subject to violent flutter /Fig.13/ by re-increasing the collective pitch to initial value.



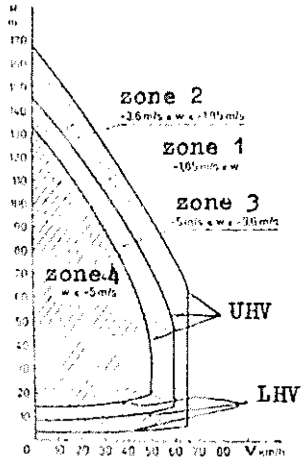
15. Distributions of tail rotor blade tips torsions /two-blade teetering tail rotor/ in the event of failure of the blade tip at an azimuth 180° /15% of blade tip damage - with loss of mass - causing its torsional deformation displayed in Fig.16/ 1- damaged blade tip, 2-0.5 R of damaged blade, 3 - 0,5 R of undamaged opposite blade, 4 - tip of undamaged opposite blade.



16. Distributions along the radius: Px - of centrifugal force, ϑ - of pitch angle, Mx - of torsion moment for case described. in Fig.15. Mark symbols every 45° in sequence: + x Y λ X ⋈ ◇ ○ ▽

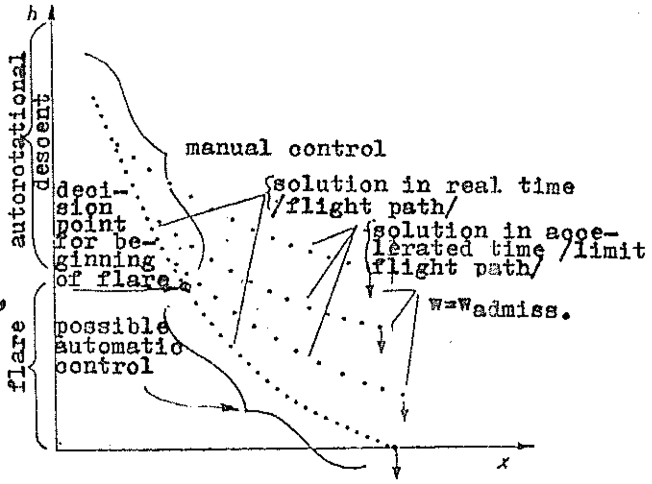


17. Diagram of the physical system of a simulator. Station of operator of investigation simulator of the helicopter: 1-board instruments V,h,n,w,φ; 2- artificial horizon φ_x, φ_y; 3- flight path h-x; 4 - control stick; 5 - pedals; 6 - lever - pitch-power; 7 - adjistable seat for pilot; 8 - force imitator - trim tab; 9 - lever and knobs for ergonomic regulation of operator station; 10 - signalling of power plan failure; 11 - miniaturized, integrated controller.

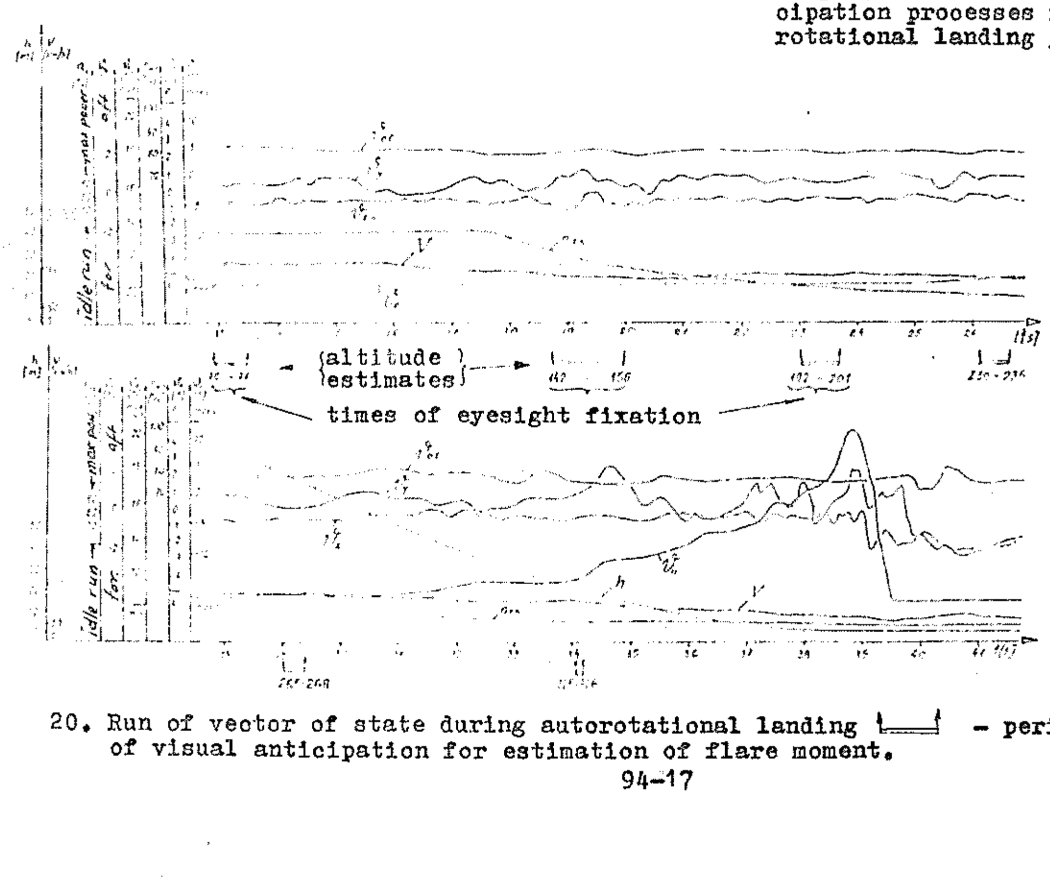


19. Types of limits of zones H-V /equivalent of Fig.1/. As the criterium adopted was the admissible landing speed /example for heavy lift helicopter - failure of two engines/.

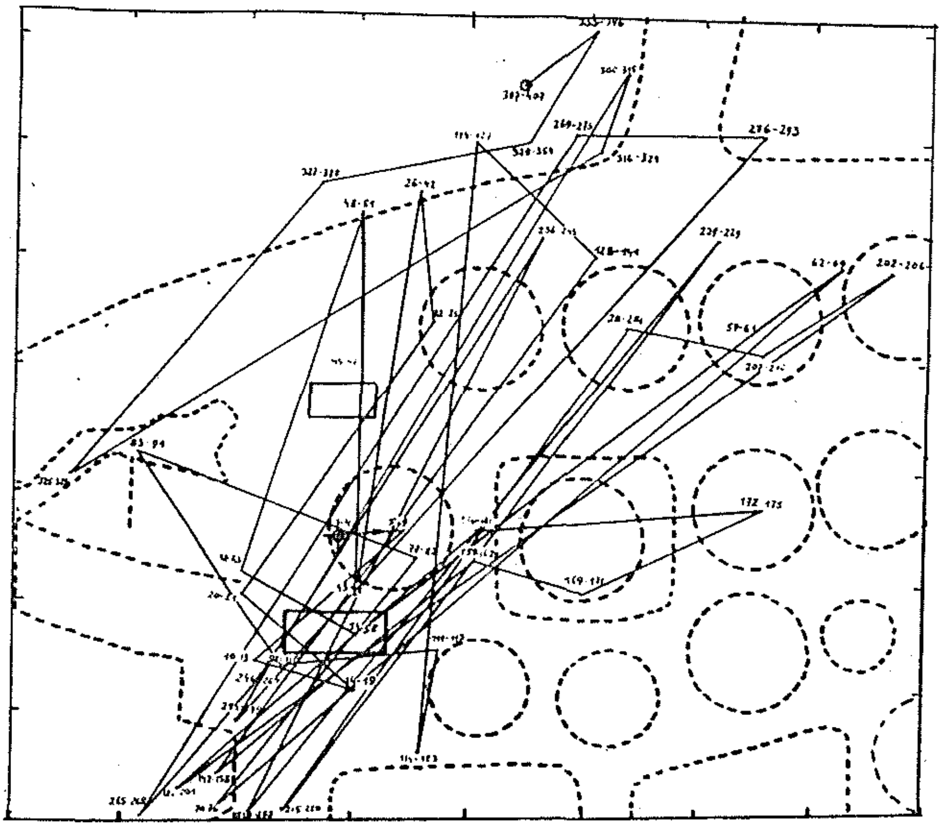
Zones: 1 - soft landing, 2- hard landing, 3 - admissible crash landing, 4 - area of catastrophe.



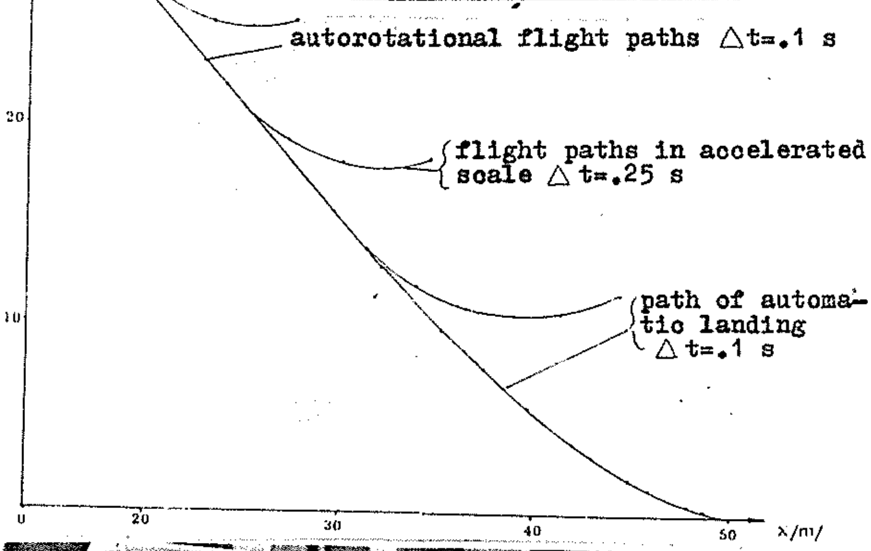
18. Display on oscilloscope screen of anticipation processes for the case of autorotational landing /information diagram/.



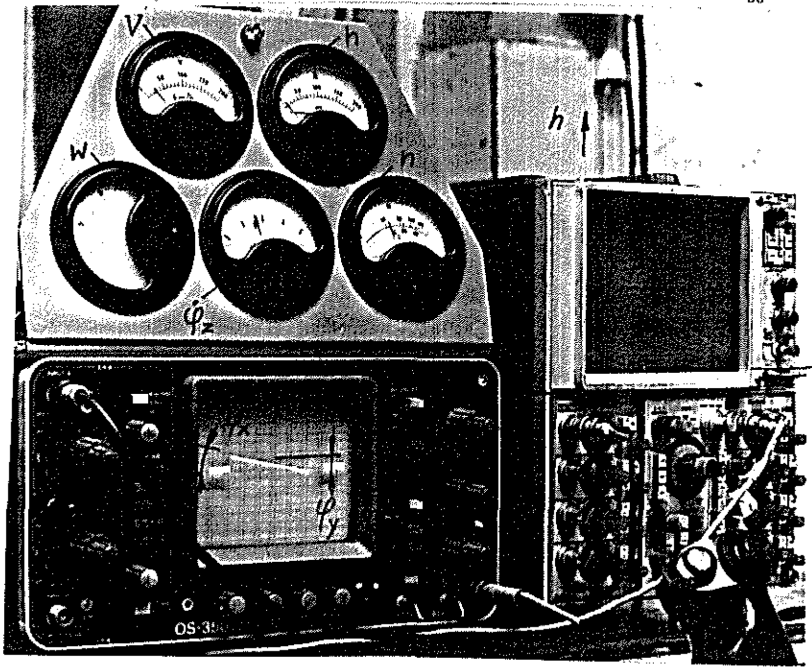
20. Run of vector of state during autorotational landing ⌊___⌋ - periods of visual anticipation for estimation of flare moment.



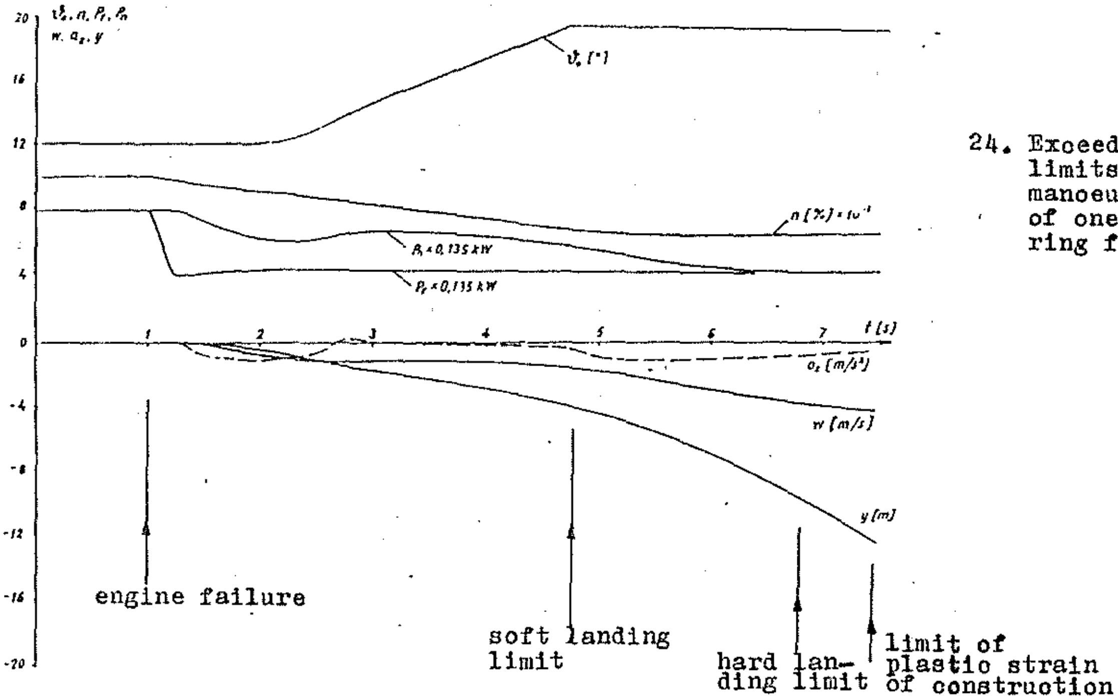
21. Oculogram of autorotational landing from Fig.20.



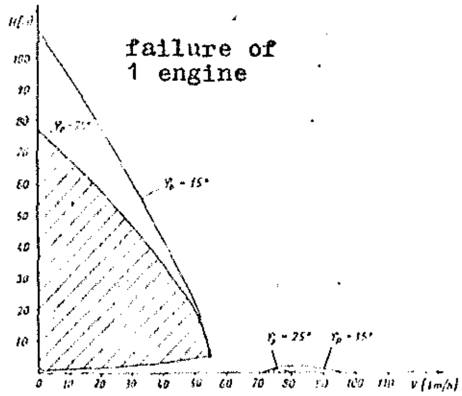
22. Illustration of anticipation processes and automatic landing on the diagram of helicopter autorotational landing flight paths.



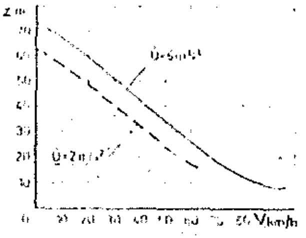
23. Picture of a simulator instrument panel after autorotational landing from hovering at the altitude of h=130 m. Touchdown parameters read from instrument panel: banking φ_x = 7°, pitch φ_y = 5°, angular velocity of deflection φ_z = 5°/s, rate of descent w = 1.5 m/s, horizontal speed V = 25 km/h, rotor r.p.m. n = 60%.



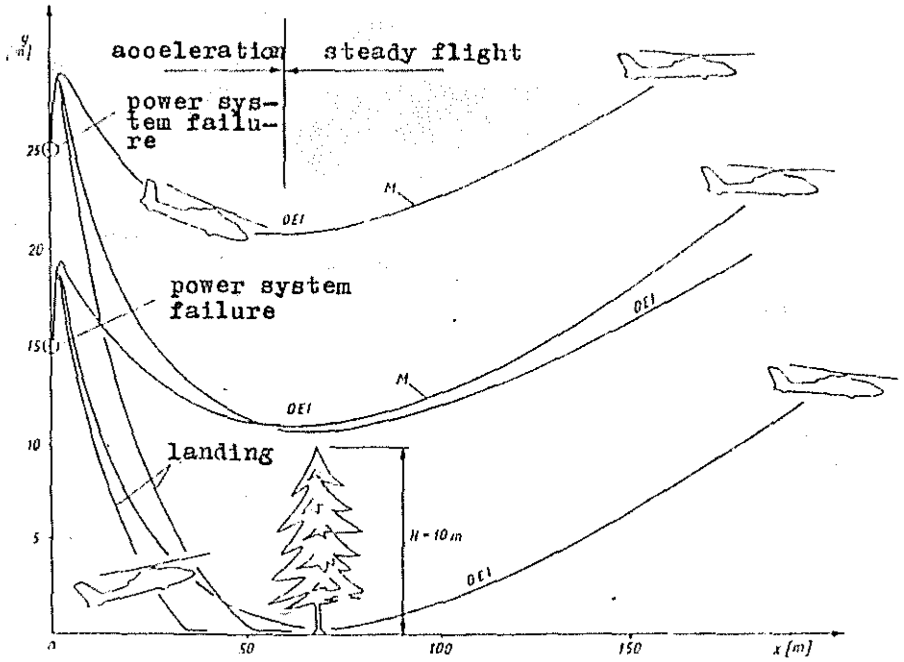
24. Exceeding successive limits in simulated manoeuver after failure of one engine in hovering flight, Q = 3600 kg.



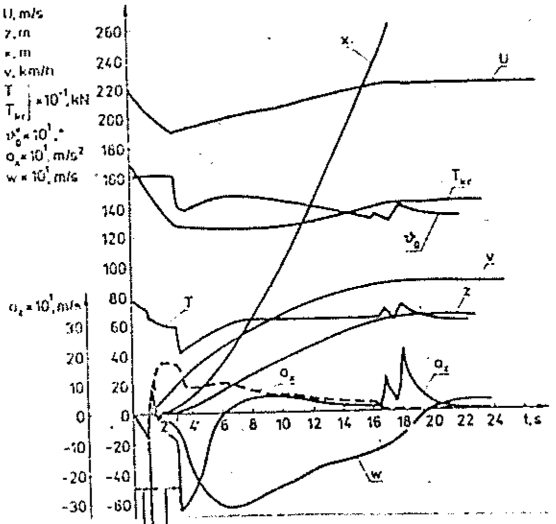
25. Influence of dynamics of performing a safety manoeuver on the size of H-V zone.



26. The curve of maximum altitude loss in phase of bringing up to speed from the rate of one engine failure to the moment of attaining the steady rate of climb. Full line-altitude losses at speeding-up the rotor after failure at the rate of $\dot{U} = dU/dt =$ 6 m/s^2; broken line for $\dot{U}$ = 2 m/s^2.

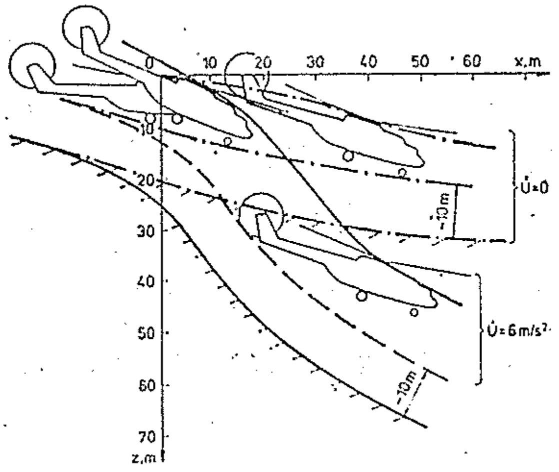


27. Influence of modification of handling technique on flight path during interrupted vertical take-off of the I category helicopter. M - modified technique.

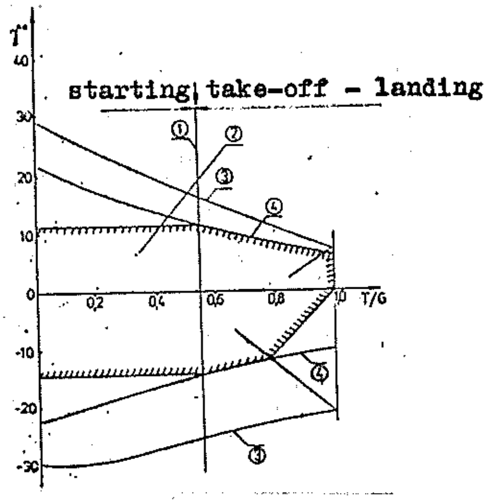


acceleration without decrease in collective pitch
jettisoning the load
time of pilot's reaction

28. The course of alterations in helicopter system data following failure of one engine by a modified handling technique.

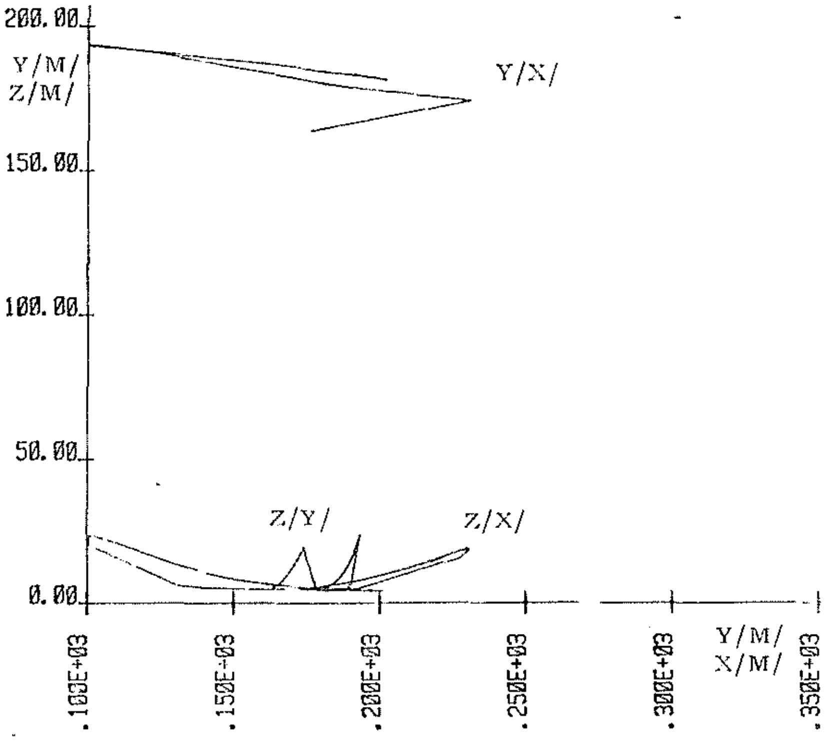


29. Flight paths of the helicopter following failure of one engine by a modified handling technique.

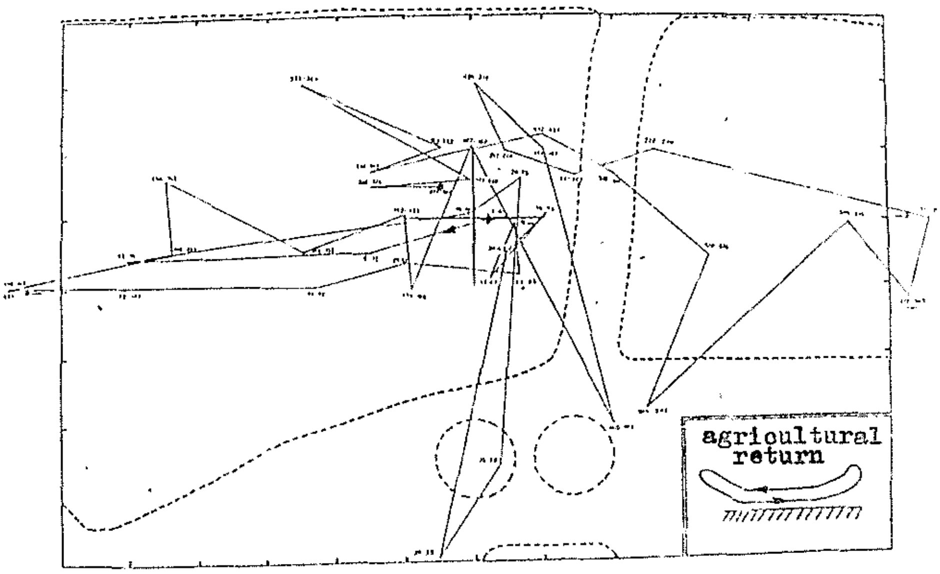


30. Limits of helicopter operation in lateral position in relation to slope. Helicopter mass Q = 3000 kg, coefficient of friction of wheels and landing gear f_{tr} = .4, admissible wind velocity from adverse direction:
1 - lightening at $\vartheta_{o\ min}=7^o$, ω_{nom} and wind V=5 m/s up the slope,
2 - area of admissible operation,
3 - turnover for wind V=5 m/s down the slope, 4 - sideslipping f_{tr}=.4, wind V=5 m/s down dle slope.

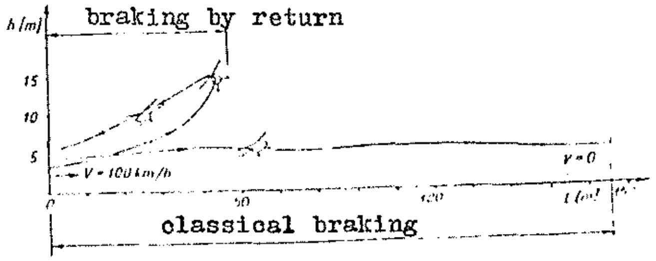
31. A helicopter loosing balance while turning over to the left. 1,2 - extensometer balances.



32. Flight path /in three projections/ of two agricultural manoeuvres – wingover/pedal turn /from kinetheodolite measurements/.



33. Oculogram of agricultural return /wingover/pedal turn/.



34. Comparison of classical braking and braking by return.