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RISK: INTERACTIVE MULTIDISCIPLINARY SYSTEM FOR DESIGNING AIRFRAMES *

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Abstract

This paper describes major concepts and the state of the art of the interactive system for a structural analysis of airframes - RISK. The system is developed at TsAGI starting from 1989.

The present option is aimed at the following main objectives:

- development of a complete mathematical model of dynamics of an elastic airplane for typical operational modes (take-off, maneuvering flight, flight in turbulent atmosphere, landing, ground handling) with different configurations of attachment of elastic weights under a fuselage and/or a wing;
- determination of extreme dynamic and static loads acting on the airplane and the suspended weights;
- determination of reasonable values of parameters of the primary structure subjected to the extreme loads;
- investigation into stability and controllability of an elastic airplane for various flight conditions.

RISK is developed as an integrated system including a finite-element representation of the elastic structure, the panel method for computing the aerodynamic flow over the airplane at $M < 1$ and $M > 1$, a description of an airborne automatic/remote control system, nonlinear models of a landing gear.

RISK is an interactive system operating on personal computers and working stations with dot-matrix colour displays and the "mouse", under the UNIX operating system.

The programming language is "C". The size is some 120,000 lines.

I Introduction

The development of finite element analysis programs for modelling of elastic airframes, and the progress in numerical methods for calculation of aerodynamics and flight dynamics from 1970s stimulated the attempts to develop the software for the multidisciplinary analysis of airplanes.

This is first related to the interaction of the elasticity, the aerodynamics and the airborne automatic/remote control systems:

- the elasticity of an airframe affects the aerodynamic coefficients, data from of feedback transducers, the effectiveness of control surfaces;
- the control laws established for the automatic/remote control systems affect the loads acting on the airframe;
- the elasticity of structures affects the loads and the aeroelasticity phenomena (reversal of controls, flutter, divergence);
- the loads govern the structural weight and stiffness, etc.

The main obstacles on the way to integration of these disciplines within the limits of unified programs include the following:

- up-to-date airplanes have very complex structures as to the geometry, topology and stiffnesses, so it cannot be described at early stages of design; this makes it difficult to use the FEM in its usual formulation;
- the assumed displacement shape method on which the analyses of aeroservoelasticity are traditionally built depends wholly on the quality of determination of the shapes and the natural frequencies that are difficult to predict without fine models of the structure.

The use of common finite-element analysis systems (that now may be valued as classical, for example, NASTRAN, ASKA, ANSYS, etc.) for modelling of airframes seems to be doubtful even when there are supercomputers (such as CRAY) since data input (or change) requires much working despite the presence of high-performance pre- and postprocessors such as PATRAN/G, FEMGEN/FEMVIEW, etc.

This circumstance grows in importance if a modal analysis must be fulfilled; here all errors of an analyst "come up" in the form of parasitic modes, not characteristic of the structures, and upgrading the dynamic finite-element model becomes a very expensive operation.

The group of developers (including the present authors) tried, throughout the period from 1980 to 1986, to implement the multidisciplinary approach on the basis of the classical finite-element technology, however, this project was unsuccessful.

Since 1987 the period of investigation into that trouble began, and since 1989, the period of designing a new complex; it is named RISK, according to the initial letters of its Russian name: "Analytical Investigation of Airframes". This name, simultaneously, emphasizes the degree of a technical risk the authors felt when solving the above problem. In 1989 and 1990, an extensive scientific research was performed to form a basis of RISK.

In 1991, the programming began. By the end of 1991, RISK has made it possible to conduct the analyses for the highly maneuverable airplane of the A.I. Mikoyan Design Office; the main concern was with the local load factors for suspended weights under the action of tur-

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bulence. In this case, use was made of a special-purpose finite element method (for describing the elastic airframe), the discrete panel method (to calculate the aerodynamics at Mach numbers $M < 1$ and $M > 1$), and the model of the longitudinal control channel. In total, the system of differential equations had the order 64. In the computations, 22 lower symmetric modes of elastic vibrations were accounted.

RISK is used on IBM-PC/AT-386 computers under the UNIX operating system. Below, we consider the basic concepts of the RISK complex.

II Elastic structure

The elastic structure to be analyzed by RISK can be represented as a tree of substructures. A typical example of such a tree is shown in Fig. 1. The tree-like description makes it possible to organize a very effective algorithm for solving the partial eigenvalue problem, a version of the substructures component mode synthesis method.

Three types of substructures, now present in RISK, allow us to model practically any possible configuration of aircraft.

Figs. 2a, b, c show substructures TNP (a thin lifting surface), ERB (models of adapter beams, launch devices, and weights), and TUT (a fuselage).

The type TNP substructure is used for modeling the wings, the vertical and horizontal stabilizers, and other lifting surfaces. It may be completely characterized by its planform. The longitudinal axis, x, of the plane of TNP is assumed to be directed forward. Along the span (the z-axis) the TNP is divided into strips. Every strip is automatically divided into a set of aerodynamic panels. The panels form a grid for the panel method. The elastic displacement field is approximated as follows.

At each boundary between two neighbouring strips (ie a chord), the generalized displacements corresponding to displacements in the xz-plane and along the y-axis are specified, as well as rotations about the x-axis.

Here, the shape functions are monomials $\{1, x, x^2, ...\}$. For example, displacements of a jth chord along the y-axis are approximated as

$$V(x) = \sum_{i=0}^{m} V_i^{(j)} x^i$$

where $V_i^{(j)}$ are generalized displacements of jth chord along the y-axis.

The approximation of displacements along the z-axis is based on shape functions -- the linear Lagrange polynomials for displacements $U(x, z)$ and $W(x, z)$ along the axes x and z, respectively, and cubic polynomials for $V(x, z)$.

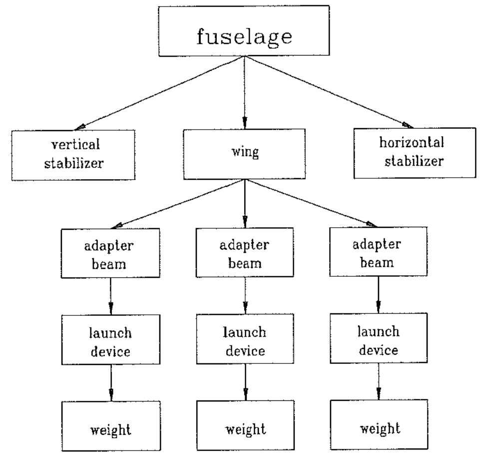

FIGURE 1. Tree of substructures

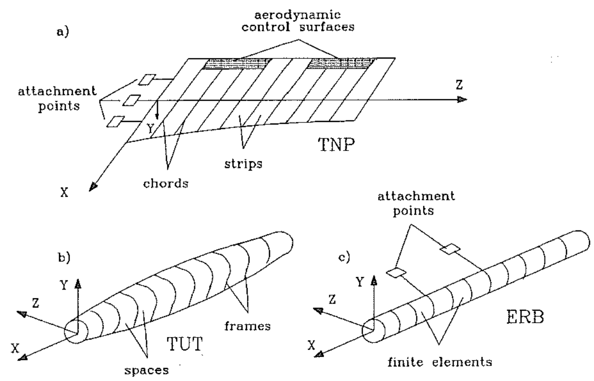

FIGURE 2. Types of substructures

For example, displacements along the y-axis are approximated as

$$V(x,z) = \sum_{i=0}^{m} V_i^{(j)} H_{00}(z) + A_i^{(j)} H_{01}(z) + V_i^{(j+1)} H_{10}(z) + A_i^{(j+1)} H_{11}(z) \; x^i$$

where $A_i^{(j)}$ are rotations of the jth chord about the x-axis,

H_{00}, H_{01}, H_{10}, H_{11} are the Hermitian polynomials.

Such a choice of approximations for the mid-surface of a TNP is very convenient:

- organization of the interface between the aerodynamic calculation program and the finite-element program simplifies essentially;
- the finite-element model becomes much softer in comparison with the results of the traditional method of polynomials, where inherent is the use of global shape functions $x^p z^q$, where p and q are integers; such approach is known to generate stiffness matrices of Hilbert type, ill-conditioned matrices;
- in comparison with the classical FEM the approximation to the displacement fields is not related to a structural concept of a TNP composed of spars, ribs, walls and panels; this drastically (by an order of magnitude) simplifies preparation of input data on a finite-element model.

After computing the stiffness and mass matrices, the incomplete eigenproblem is solved:

$$\begin{vmatrix} K_{ii} & K_{ij} \\ K_{ji} & K_{jj} \end{vmatrix} \begin{vmatrix} V_i \\ V_j \end{vmatrix} = \omega^2 \begin{vmatrix} M_{ii} & 0 \\ 0 & 0 \end{vmatrix} \begin{vmatrix} V_i \\ V_j \end{vmatrix}, \quad V_j = 0,$$

where the index i denotes the generalized displacements of the chord, the index j denotes displacements of the points at which the TNP is attached to substructures of a previous level in the tree of substructures.

A TNP can incorporate deflectable control surfaces for which generalized stiffnesses of drives and the generalized masses may be specified.

Substructures of ERB type are used to model the adapter beams, launch devices, weights, containers, fuel tanks, etc.

The finite-element model is built as a set of one-dimensional finite elements, with linear Lagrange polynomials being taken as shape functions for x-displacements and a rotation about the x-axis, and cubic Hermitian polynomials for displacements along the axes y and z. Just as for TNP-type substructures, after computation of stiffness/mass matrices the partial eigen-value problem is solved for determining the local oscillation modes.

The TUT type substructure is used for modeling the fuselage. Here, the construction line (ie the x-axis) is subdivided into a set of frame spacings by using the planes of frames. The displacement fields of shells and frames are approximated treating them well analogously to those of TNP; note that the role of shape functions in the form of the monomials $\{1, x, x^2, \dots\}$ is performed by the shape functions for deformation of external contours of the frames.

Just as in substructures of ERB and TNP types, the local modes are determined using the Lanczos method. If the spectrum includes zero frequencies (corresponding to a motion of a TUT as a rigid body), use is made of a spectrum shift.

III Modal analysis

The spectrum and natural vibration shapes are determined by a new technique that may be qualified as a component mode synthesis method based on modes of substructures. The tree-like configuration of connections between the substructures makes it possible to implement a very effective algorithm. The degree of the generalized stiffness/mass matrices is equal to a sum of the total numbers of the local modes of the substructures.

Taken as generalized displacements are amplitudes of these modes. As a result of a solution of incomplete eigen-value problem (by the Lanczos method), we get the characteristic values equal to squared frequencies of natural vibrations, and the components of eigen vectors indicate what amplitudes must be attributed to the local modes in order to synthesize the vibration for a certain mode of the structure as a whole.

Note that the reported concepts taken together have made it possible to construct an extremely effective technique for performing the modal analysis.

Let us exemplify the said above by the modal analysis for a highly maneuverable airplane. The task including computation of the stiffness/mass matrices for 11 substructures (up to 500 generalized unknowns in each), the search for local modes (10 modes at an average in each), computation of generalized stiffness/mass matrices of the structure, the search for 25 symmetric modes took 17 minutes on the 25-MHz IBM PC/AT-386 computer.

IV Aerodynamic computations

The aerodynamic performance analysis is based on the panel method developed by L.L. Teperin at TsAGI. The nearest analog is the well-known Woodwort method. A representative analysis of a highly maneuverable airplane with the total number of panels of approximately 300 takes 45 minutes on the 25 MHz IBM PC/AT-386 computer. This time includes the computation of the aerodynamic influence matrix, a decomposition (using the Gauss method) and the solution with 60 right-hand sides corresponding to displacements of the airplane as a rigid body and to elastic deformation for determining the complete set of aerodynamic coefficients among which we should note

- coefficients $C_y^{\alpha}, \dots, m_z^{\alpha}, \dots$
- coefficients $C_y^{\delta_i}, C_y^{\dot{\delta}_i}, \dots, m_z^{\delta_i}, m_z^{\dot{\delta}_i}, \dots$
- coefficients $C_y^{q_i}, C_y^{\dot{q}_i}, \dots$
- coefficients $C_{q_i}^{q_i}, C_{q_i}^{\dot{q}_i}, C_{q_i}^{\delta_i}, C_{q_i}^{\dot{\delta}_i}$
- coefficients $C_q^{\alpha}, C_q^{\overline{\omega}_z}, \dots$

where α is an angle of attack,

ω_z is an angular speed of rotation about the z-axis,

δ_i is a deflection of the ith control surface,

q_i is the amplitude at the ith mode of natural vibrations,

C_y^{α} is the derivative of the lift with respect to the angle of attack,

m_z^{α} is the derivative of the longitudinal moment with respect to the angle of attack, etc.

At present time, the analyses of dynamics of elastic structures is based on the linear aerodynamic model and on the hypothesis of the flow being quasistationary: according to it, the aerodynamic forces and the moments depend on the instant values of kinematic parameters describing the motion of the airplane as a rigid body and its elastic deformations. Such approach cannot be valued as satisfactory even at early stages of design because of non-linearity of the aircraft aerodynamics at many operation modes and because of insufficient accuracy of computation of such [those] "thin" aerodynamic coefficients as the hinge moments of control surfaces. All these considerations are given a proper attention when designing the RISK system, however, in order for the complex not to be unnecessarily complicated, some subsystems are not incorporated into the first version. Nevertheless, there is an interface that will allow us to easily link more sophisticated aerodynamic models, including nonstationarity in the time domain and taking into account the Sh number at the frequency domain analysis (this is necessary to study the aeroelastic stability and the transient processes); we plan to incorporate a data base on aerodynamic coefficients obtained in wind tunnels, and to give the user some interactive options for correcting the total and distributed aerodynamic forces obtained by computation, by the aerodynamic experiment, or from analogous aircraft designs.

V Flight dynamics of elastic structure

Any advanced aircraft has the airborne automatic control system and the remote control system, therefore the vector of state variables of an elastic airplane is assumed to contain the following (between the brackets, we indicate dimensions of the groups):

- kinematic parameters of a finite motion of the airplane as a rigid body (up to 9 coordinates);
- amplitudes and rates of amplitudes of small elastic deformations to be represented as portion of a series in forms of vibrations (2 * the total number of modes);
- positions and speeds of displacement of deflectable control surfaces (2 * the total number of control surfaces);
- phase coordinates of the automatic/remote control system (depending on complexity of this system).

The complete system of differential equations may be described by using the "language" of mimic panels adopted in the automatic control theory. For this purpose the user is provided with a library of standardized elements: summers, multipliers, amplifiers, integrators, filters, limiters, etc. As well, there are special elements: "rigid airplane", "elastic airplane", "standard atmosphere", etc.

A specialized interactive editor for the elastic aircraft dynamics included as a component in RISK gives the user the possibility to easily introduce these elements by means of a "mouse", to join the entries and outputs of elements by lines, to symbolize the entries and the outputs, and to carry into effect other necessary actions. Analogous style of work may be seen in the known programs AUTOCAD and P-CAD.

The description of a dynamic model is employed by RISK to automatically define the composition of the vector of state variables and perform all the necessary operations to build the system of nonlinear differential equations.

In RISK, the equations of motion may be integrated by means of four techniques:

1) a direct integration of a nonlinear system by an implicit Euler algorithm of the second order;

2) a direct integration of a system linearized at a certain point of the state space, by an implicit Euler algorithm of the second order with reduction to an explicit scheme;

3) restoring the solution of the linearized system by means of the inverse Laplace transform, the search for natural frequencies and the right and left eigen vectors of the system matrix through the familiar HQR algorithm;

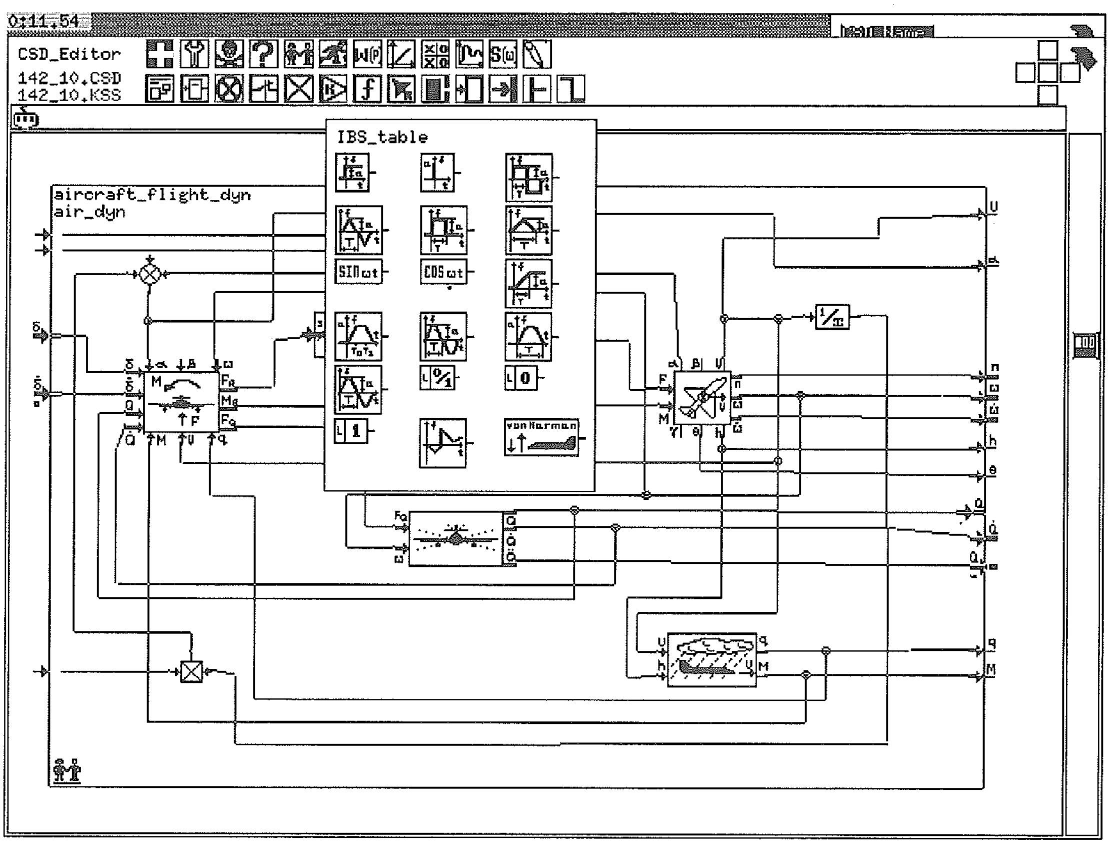

FIGURE 3. Fragment of mimic panels: dynamics of elastic airplane. Foreground: the library of types of input signals

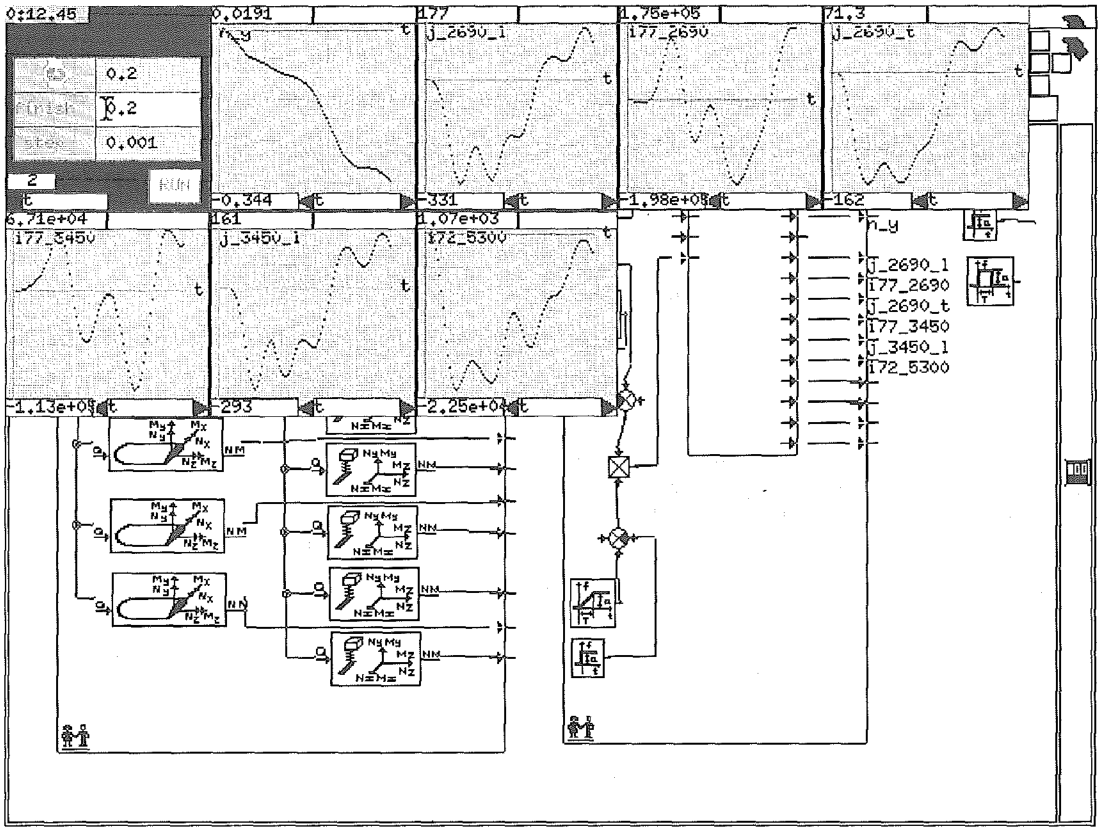

FIGURE 4. Visualization of transient processes.

4) restoring the periodic solutions of the linearized system for inputs with narrow-band spectra by means of the fast Fourier transform (FFT).

As an example characterizing the rate of integration, we could note a solution of a system of differential equations of order 64; it has been integrated by the implicit Euler algorithm (the nonlinear version) with the step size dt=0.001 s and has taken 5 minutes on a 25 MHz PC/AT-386 for simulating 10 s of flight of an elastic airplane. This time includes the computation of the load level transducer data and the graphic representation on the display screen. The quickest method of integration -- on the basis of the FFT (the linear version) -- solves this problem for 2 minutes.

The analyses may be carrying out not only in the time domain but also in the frequency domain. In particular, RISK can use the transfer functions written in a symbolic form to plot the root loci and to draw the amplitude/phase - frequency response functions. Flights in permanent turbulence may be modelled within the limits of the common model by Karman facilitated by the option for obtaining random realizations of the vertical gusts by using the FFT.

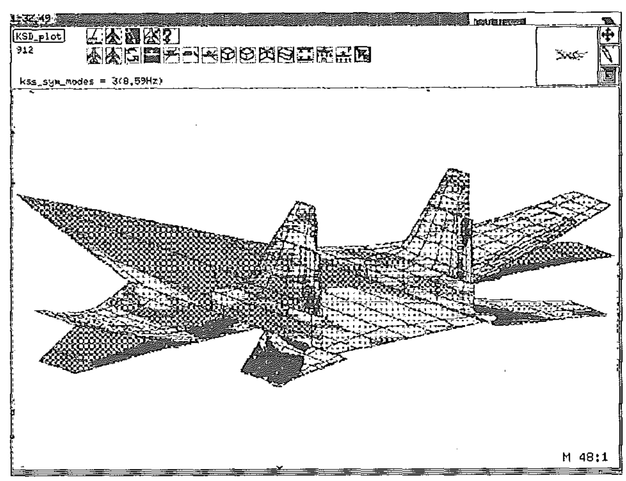

FIGURE 5. Visualization of MiG-29 airplane vibration forms

VI Composition of RISK

Below, we list briefly the major components of the first version of RISK:

- block for defining the dynamic model on the basis of a special-purpose FEM;
- block for modal analysis by the multilevel dynamic decomposition utilizing the Lanczos method;
- block of computation of aerodynamic forces by the panel method (M < 1, M > 1);
- interactive block for solving nonlinear systems of differential equations of motion (by the implicit Euler scheme) and linearized systems (by the implicit Euler algorithm, inverse Laplace transform, FFT);
- interactive module for specifying the primary structure concept;
- interactive subsystem for visualizing the processes, the load level transducer data, etc.

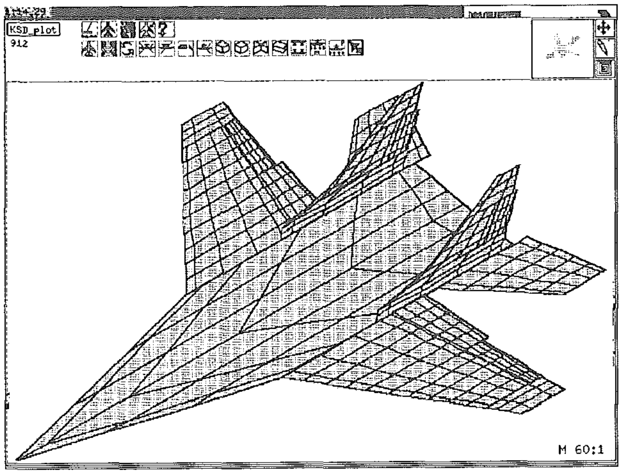

FIGURE 6. Aerodynamic analytical model for MiG-29 airplane

Let us note also some features of RISK:

- substantial reduction of the amount of the input data for describing the finite-element models (in comparison with the existing finite-element programs) due to the application of special-purpose substructures (fuselages, wings, external weights, etc.);
- high quality of simulation of dynamic properties at modest dimensions of analytical models, due to the application of the special-purpose finite element method;
- the possibility to flexibly restructure the analytical models;
- automatic mesh generation for aerodynamics analysis;
- automatic definition of dynamic models in interactive mode assisted by mimic panels.

VII Some programming issues

The RISK system is written in the "C" and is designed to function in the environment of UNIX on IBM PC/AT-386 and AT-486. It can be readily adapted to any computer of "working station" type with the UNIX operating system.

RISK is designed in the main by the present authors. Programming is performed by a team of 12 specialists in the mechanics, the aerodynamics, the computer-aided geometry, and the computer graphics.

Currently, the size of programs is 120 thousand statements. The kernel of RISK is comprised of a spe-

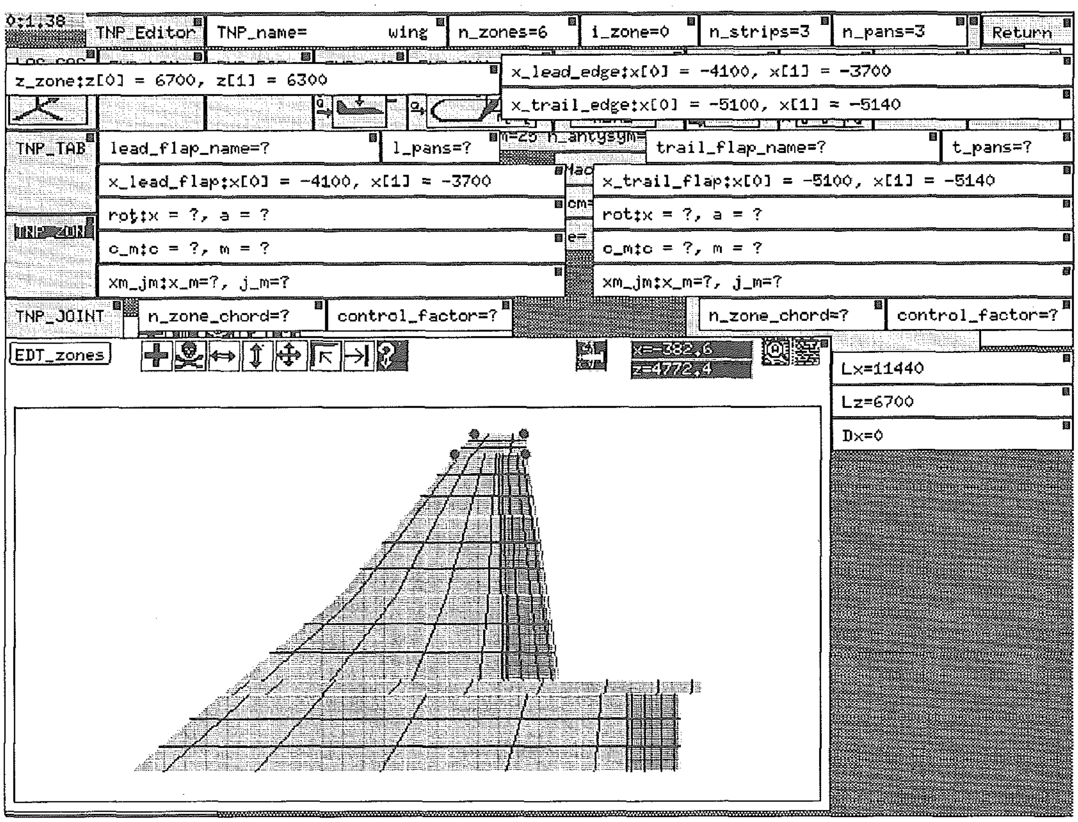

FIGURE 7. Editor of primary structure concept.

cially developed applications software -- the subsystem of interactive graphics.

Externally, in operation this subsystem looks like X-WINDOWS, but is much more effective as to the dynamics of restructuring the picture on the screen. Very wide is use of glyphs, ie special rectangular multi-coloured patterns out of pixels; they are used as menu items or easily readable elements of the mimic panels dynamically changed depending on the position of the cursor on the screen.

To work with different objects, two- and three-dimensional scenes are prepared. The software for organizing the three-dimensional scenes includes effective algorithms for removing the invisible surfaces (the yxz-sorting algorithms).

Disposition of scene elements is accomplished simultaneously with allocation of both the zones and the cursor glyphs for selection; this allows the analyst to conveniently select the necessary element by moving the cursor to an element and making the necessary glyph appear on the display.

VIII Alternative applications

RISK can be successfully applied to the modelling of dynamics of various objects including the automatic servosystems and the remote control systems with feedback; as well, dynamics of three-dimensional elastic objects subjected to external force input may be studied.

IX Developers

RISK was designed, programmed, and tested by specialists of TsAGI, Mikoyan Design Office, and the SDC, Ltd.

X Concluding remarks

At present time, RISK is intensively developed. The developers see their main problem in exploring algorithms and programs for designing the structures subjected to the specified set of ultimate loads.

XI Acknowledgement

The authors wish, on behalf of the group of developers, to thank the Mikoyan design office for support of the present efforts.