INTERACTIVE COMPUTER GRAPHICS SYSTEM FOR STRUCTURAL SIZING AND ANALYSIS OF AIRCRAFT STRUCTURES

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SUMMARY

A computerized system for preliminary sizing and analysis of aircraft wing and fuselage structures is described. The system is based upon repeated application of analytical program modules, which are interactively interfaced and sequence-controlled during the iterative design process with the aid of design-oriented graphics software modules. The entire process is initiated and controlled via low-cost interactive graphics terminals driven by a remote computer in a time-sharing mode.

INTRODUCTION

The macro design process of flight vehicle structures is typified by a hierarchy of intra and inter-disciplinary iterative procedures involving numerous design modifications and repeated execution of sophisticated computerized analyses. Some of the major disciplines involved in this process are those dealing with geometry, aerodynamics, weights, loads, structural design, stress and aeroelasticity.

One of the major bottlenecks and common sources of errors, delays and frustrations in the iterative structural design process is associated with the preparation of massive geometry-oriented data required as input to the computerized analyses, and the subsequent reduction of the numerical output data into meaningful decision-worthy form. Indeed, the advent of the digital computer, while permitting for the solution of hitherto unsolved problems, also led to the inadvertent creation of a new breed of engineer. This unfortunate and misdirected creature, commonly referred to as an "I/O Engineer", may be glimpsed running to and fro carrying heavily laden boxes of input cards and output stacks instead of concentrating on his main tasks:

- Creation of a technically acceptable discretized math model generally required for the response solution of complex structures.
- Evaluation of the analysis results and the application of engineering judgement and creativity in modifying the design to better meet the required criteria.

Ideally, the ultimate objective in design should not be the analysis of a given configuration, but rather the systematic synthesis of a design, starting from a set of given requirements, and satisfying the specified design criteria. However, since true synthesis is not as yet a viable technology, near optimum designs can be achieved only through iterative analysis. Thus, any truly successful computerized design system should provide the engineer with the capability of performing analyses, evaluations, and design modifications in rapid interactive succession, without having to preoccupy himself with the laborious and time-consuming chore of massive geometric I/O preparation and data reduction - an activity which dulls his engineering creativity and restrains him from performing his true functions as an engineer.

In attempting to meet these objectives, IAI is developing ISSAS (Interactive Structural Sizing and Analysis System), which is a modular and highly flexible computerized system for preliminary sizing and design of flight-vehicle wing and fuselage structures. The system is based upon the use of analytical program modules, which may be interactively interfaced and sequence-controlled during the iterative design process through the use of low-cost interactive graphics terminals driven by a large computer in a time-sharing mode.

In developing the ISSAS concept, IAI has followed many of the guidelines layed down in similar computerized structural analysis systems developed over the past five years (references 1-6). However, in ISSAS, major emphasis was placed on enhancing the interactive design capability while at the same time retaining the computing power of the analytical modules. Another major feature is the extensive use of low-cost time-sharing ICG terminals, both for program-control and as an aid to I/O generation, reduction, and interfacing.

GENERAL SYSTEM DESCRIPTION

The system consists of six major analytical modules interfaced with six ICG (Interactive Computer Graphics) modules, as depicted in figure 1. The analytical modules are:

AERO: Aerodynamic analysis module.
WEIGHTS: Mass properties analysis module.
LOADS: Intergrated loads analysis module.
FESA: Structural analysis and automated design module.
FAMOS: Frequencies and mode shapes module.
AEROLAS: Aeroelastic analysis module.

The interactive graphics modules are:

AEROMOD: AEROdynamic MODeling module.
AEROPOST: AEROdynamic POST-processing module.
ISLADE: Interactive Structural LAyout and DEsign module.
SMOG: Structural Modeling Oriented Graphics module.
GRASP: GRaphics Augmented Structural Post-processing module.
MODIS: MOde shape DISplay module.

These ICG Modules provide the following capabilities:

- Automated/ICG generation and visual checkout of 3-d geometric discretization data required for aerodynamic analysis
- ICG visualization of aerodynamic loads and flow parameters
- ICG design, layout and modification of primary lifting surface and fuselage structures
- Automated/ICG generation, visual checkout and modification of 3-d structural analysis models
- ICG visualization of structural strength response parameters
- ICG visualization of vibration mode shapes

The system is structured such that an engineer working at the graphics console can supply the system with data from the central data base and execute one or more of the analytic or ICG modules in any technically feasible sequence he may choose. The engineer may at any time discontinue the process and restart it later at the previous termination point. Figure 2 depicts a typical ISSAS sequence flow for the design of a lifting surface structure.

Permanent records of alphanumeric and graphic information may be obtained either on-line using a hard copy device or off-line using a line printer or large drum plotter.

SYSTEM MODULE DESCRIPTION

Geometry Data Base

The ISSAS geometry data bank, which is stored on-line, contains the external surface definition of the entire aircraft categorized in terms of its major assemblies and sub-assemblies, such as wing, flap, aileron, nose, cockpit, aft-fuselage, tail, etc. Each such item may be interrogated separately or in fused form as to a variety of geometrical parameters. These are presented to the engineer interactively either in alphanumeric form and/or as an on-line picture which may be rotated in space, translated, zoomed, windowed or otherwise manipulated as required. The digital information describing the geometry may be easily interfaced as input data to analytic or ICG modules of the system.

AEROMOD - The Aerodynamic Modeling Module

AEROMOD is an ICG module that permits the engineer to rapidly generate aerodynamic panel meshes required for subsequent aerodynamic analyses. The program provides for a combination of both automated and interactive mesh generation on selected flight vehicle surfaces. The automated option requires the engineer to specify only the basic parameters defining the mesh spacing and shape, while the massive numeric data defining the geometry and location of each individual panel is automatically generated by the program using the basic surface definitions extracted from the geometry data base. The interactive option of the module may be used by the engineer to draw the required aerodynamic mesh lines directly on a displayed view of the wing or fuselage. In either case the idealization may be viewed in 3-d (figure 3), rotated, zoomed or otherwise manipulated on the graphic display before the configuration is used in any subsequent analysis.

AERO - The Aerodynamic Analysis Module

The aerodynamic analysis module is based upon discrete element analysis procedures as outlined in reference 7. It solves many wing-body and wing-body-tail flow configurations over a wide range of subsonic and supersonic Mach numbers. Bodies, nacelles, engine pods or external stores are represented by a system of line sources and doublets located along the appropriate body axis. Wings and horizontal tails are represented by a system of sources and vortices distributed on panels located in the plane of the wing or tail. Interference effects between the bodies and the wings are provided by placing additional vortex distributions on the body surfaces. Output includes the aerodynamic influence matrices for various Mach numbers as well as pressure distribution and flow-visualization parameters.

AEROPOST - The Aerodynamics Post-processing Module

AEROPOST is an ICG module that displays various results of the aerodynamic analysis module in graphical form on the CRT. The following features are highlighted:

- Tri-metric display of the pressure distribution on the lifting surfaces, with 3-d rotate, translate, and zoom capability
- Planform display of lifting surfaces with isobar contour plots
- Display of load distribution along the isolated body
- Display of pressure distribution along and around the interference body
- Visualization of the streamlines in the vehicle flow field by virtue of a dense display of the velocity vectors at many points in any selected plane.

ISLADE - The Interactive Structural Layout and Design Module

ISLADE is an ICG module which greatly enhances the structural engineer's capability in designing and laying out the primary structure of a lifting surface or fuselage section of given surface geometry. The workings of this module may best be explained by resorting to an example of a delta wing:

The external geometry of the wing is first extracted from the geometry data base and its planform is displayed on the screen. The next step is to define the principal lines of the wing, which are reference lines along which, or between which, structural design elements may by defined. The purpose of these lines is to define the main guidelines required for constructing the structural layout. The principal lines and their grid points are automatically numbered as they are defined by the designer. After defining a minimum number of principal lines (e.g. figure 4), the designer may start defining the structural elements in either of two basic methods: (a) Separate definition of each element, or (b) automatic generation of a group of elements after a minimum number of parameters describing the generation pattern are input. Thus, during the entire process, two distinct models exist: the framework of principal lines (dotted), and the structural layout consisting of the defined design elements (dashed lines). The two models may be displayed on the screen either separately or superimposed.

The types of structural design elements presently available in the ISLADE module are: I-beams, stringers, triangular, and quadrilateral thin panels. When the designer desires to define a design element grid point on one of the principal lines, he need only point the cursor in the vicinity of the principal line and the program will automatically place the point directly on the line. After defining the element grid points, their properties and material types may be keyed in.

The designer may at any time make major modifications to the structural arrangement by changing the position of element or principal line grid points, by deleting or adding elements, or by deleting and adding principal lines. Once the structural design is completed a data base defining all structural design elements and principal lines is created and may be saved for use by other ISSAS modules.

WEIGHTS - The Mass Properties Analysis Module

The WEIGHTS analysis module is a multipurpose collection of routines which optionally compute the following mass properties:

- Given an ISLADE design data base, the total weight, CG location and moment-of-inertia matrix of the structure is computed, including non-optimum allowances.
- Given a structural finite element idealization from a SMOG data base, a diagonal (lumped) mass matrix is computed in terms of all or a selected number of structural degrees of freedom. Total weight, CG location and moment-of-inertia matrix of both the idealized and lumped structure are also computed. All computations include non-optimum weight factors.

SMOG - The Finite-Element Structural Modeling Module

SMOG is an ICG module which greatly enhances the capability of the engineer in generating a finite-element math model required for ensuing structural analyses. Grid point positions and element topology may be generated by selective or combined use of interactive and automated methods. The automated option requires the engineer to specify only those basic parameters which define the mesh boundaries, spacing, and pattern. The interactive option may be used by the engineer when no recognizable pattern is evident. In this mode he may generate grid points or elements directly on the screen with the aid of the cursor. When a fuselage-type structure is being idealized, another SMOG feature allows for automatic development of the structure into a two-dimensional surface (e.g. figure 10), upon which either of the two modeling options may again be employed. Irrespective of the modeling option used, the engineer need not at any stage concern himself with such matters as grid point numbering and coordinates.

When the math model is completed, or during any stage of its generation, the idealized structure may be visually checked and interactively corrected in a manner similar to that described in reference 8. The displayed picture may at all times be rotated in space, zoomed, translated, windowed, etc., and views of the structure with selected element types may also be displayed either separately or selectively superimposed. Examples of such displays are depicted in figures 5-8. Application of the SMOG module in the ISSAS environment can save weeks and sometimes months of valuable calender time per design as compared with the use of manual procedures for finite-element math model preparation and checkout.

LOADS - The Integrated Loads Analysis Module

The LOADS module generates the design loads for the flight vehicle as a superposition of aerodynamic, inertia, and other loads. These are calculated only for cases on the periphery of and within the flight envelope which are deemed to be critical. Data for these cases are obtained from the master data base in conjunction with other required input data extracted from previously formed AERO, WEIGHTS, and SMOG data bases. The LOADS module output consists of (a) Net panel loads on the lifting surfaces, optionally represented as discrete forces acting at the structural grid points, (b) Discrete reaction forces between the lifting surfaces and fuselage, (c) Load distribution on the fuselage, optionally represented as discrete forces acting at given fuselage stations, (d) Shear and bending moment diagrams for the fuselage, (e) Envelopes of the critical cases that were analyzed.

FESA/FSD - The Finite-Element Structural Analysis and Automated Design Module

The FESA/FSD finite-element structural analysis and design module revolves around an efficient scaled-down version of an IAI batch mode analysis program. It is based upon the displacement method, and it features advanced element technology in conjunction with efficient solution algorithms. By virtue of its dynamic storage allocation feature, small problems may be executed with minimum core-storage requirements, while large problems may be allocated larger core blocks. As is the case with all other IAI finite-element programs, FESA optionally accepts input data in NASTRAN format. This provides for full compatibility with this large scale program that is presently being employed as the major batch mode structural analysis tool at IAI. Input data for FESA is extracted directly from the SMOG and LOADS data base previously produced for the structure.

The FESA module may be employed either as a 'one-shot' analysis tool, or as the basic module in the automated resizing process of the structure. Two automated optimization modules are presently available: FSD (Fully Stressed Design) and DLD (Displacement Limited Design). The dominant resizing step is usually determined by the first fully stressed design cycle. These results may be displayed, and based upon them, the engineer may either introduce modifications or allow the FSD routine to continue, with the option of being able to display the results (using the GRASP module) after each resizing. If displacement constraints are also placed on the structure and the engineer finds that they are being violated, he may reroute the process via application of the DLD routine that will reduce the critical displacements by increasing the structure's stiffness. In this way the advantages of both automated optimization and interactive modifications are combined to efficiently produce the required structural design.

GRASP - The Graphics Augmented Structural Post-Processing Module

GRASP is an ICG module which displays structural response parameters resulting from the FESA/FSD analysis. Selected element sets of the structure under consideration may be displayed with superimposed values of stress or force components on each element. For example, the stress components in a quadrilateral membrane may consist of one or more of the following displays: (a) Normal and shear stress components at the elements' midpoints, or optionally at the midpoints of the elements' sides, (b) Principal stresses and directions at the elements' midpoints, or optionally at the midpoints of the elements' sides, and (c) A plot of iso-stress contours for any (or all) stress component(s). Figure 9 depicts a delta-wing skin idealization with superimposed shear stresses at the center of each panel.

Figure 10 depicts a developed surface of an aircraft aft-fuselage finite-element idealization showing superimposed values of maximum and minimum stresses in the rod elements. Figure 11 depicts a typical idealized bulkhead of the same aircraft with a plot of the stress distribution superimposed over the bar elements.

Structural deformations may be displayed with the GRASP module in two fashions: (a) Vectors proportional to the displacements at the grid points are superimposed at those points over the undeformed structure, (b) The deformed structure geometry is displayed (solid lines) over the undeformed geometry (dashed lines).

Loads data may also be extracted from the LOADS module data base, and various load distributions may be viewed superimposed upon the structural idealization. All pictures displayed in the GRASP module may be zoomed, rotated and otherwise manipulated for viewing expediency.

FAMOS - The Frequencies and Mode Shapes Module

The FAMOS module computes the natural frequencies and mode shapes of the structure employing eigensolution procedures described in reference 9. The program is based on an efficient automatic reduction scheme whereby the lower modes of structures with many degrees of freedom can be accurately extracted from a tri-diagonal eigenvalue problem whose size is of the same order of magnitude as the number of required modes. The process is effected without arbitrary lumping of masses at selected node points or selection of nodes to be retained in the analysis set. The stiffness and mass matrices required for the analysis may be extracted from the FESA and WEIGHTS data bases, respectively. The FAMOS module outputs the requested natural frequencies, the corresponding normalized mode shapes and the generalized masses and stiffness and stores them in the data base for subsequent use by other modules.

MODIS - The Mode Shape Display Module

MODIS is an ICG module which displays the natural vibration modes of a given structure as computed by the FAMOS module. Each requested mode shape is displayed by superimposing the zero node lines and relative amplitude vectors at each grid point, over the undeformed structure.

AEROLAS - The Aeroelastic Analysis Module

The aeroelastic analysis module is essentially a collection of flutter analysis programs of varying methodology and complexity. These include a supersonic flutter routine which employs the MACHBOX technique, and subsonic analyses using kernel function, doublet lattice or simple strip theory methods. The engineer selects the method to be used, and a post-processor within AEROLAS converts data extracted from WEIGHTS and FAMOS to the required input form.

COMPUTER HARDWARE CONFIGURATION

The ISSAS system is presently supported by a hardware configuration consisting of an XDS Sigma-7 computer which drives a total of 50 teletype and 10 DVST graphics terminals supported by the CP-V time-sharing operating system. Peripheral I/O equipment consists of the standard devices, including a large high-speed drum plotter. Direct data links connecting the Sigma-7 to an automatic drafting machine and a Gerber IDS (Interactive Design System) are also being planned. The DVST (Direct View Storage Tube) display terminals are Tektronix 4010 (11") and 4014 (19") models operating from remote locations over voice-grade 1200 baud communication lines. On-line hard copy units are used with most of the terminals. The mainframe computer is to be replaced within the next year by a much larger and more powerful machine, and time-shared C.A.D. capability is expected to be enhanced.

IAI has been operating DVSTs for the past five years, and much experience has been gathered with their effective utilization. It has in fact been IAI's experience that most picture editing operations, including 'pick' and 'track' functions, may be effectively carried out with a DVST by clever use of the cursor or data tablet in conjunction with appropriate software. However, one of the known disadvantages of the DVST is that the non-refreshable nature of the CRT requires the picture to be repainted each time an item is deleted or modified. At the slow communication rate of 1200 baud, dictated by the present mainframe configuration, this has proven to be a somewhat frustrating procedure in cases where busy pictures are to be edited. Another shortcoming of the present configuration is that operations such as 3-d rotations must be software executed in the Sigma-7, with computing time being shared among the 50 users.

A study of IAI's present and future C.A.D. requirements has revealed that utilization of 4014 displays operated at their capacity rate of 9600 baud, would present a satisfactory and cost-effective solution to most of IAI's ICG needs. Higher performance refreshed CRT terminals would be required for the remainder. In the light of this study, IAI is in the process of evaluating a DVST configuration in which a Tektronix 4014 is connected to a 32K word low-cost mini-computer via a 9600 baud line. The mini in turn is connected to the Sigma-7 at 1200 bauds. This configuration allows the user at the DVST terminal to transfer a picture from the Sigma to the mini-computer, and then to carry out picture editing operations using the compute power of the local mini, which repaints the pictures at 9600 baud.

IAI has also been evaluating an Imlac PDS-4 graphics display system. This is a refreshed CRT display with a mini-processor, with interaction by means of a keyboard and light-pen. The remote PDS-4 is linked on-line (at 1200 bauds) in a time-sharing mode to the Sigma-7. An engineer sitting at the display may communicate with the Sigma in a time-sharing mode as if it were a teletype. He may at any time transfer a picture file to the PDS-4 memory and locally edit or otherwise manipulate it (figure 12), while benefiting from all the capabilities of a refreshed CRT with a local processor. The PDS-4 is being considered as a replacement for the DVST display as the graphics terminal for the ISSAS system.

FUTURE DEVELOPMENTS

Two of the main principles in the development philosophy of the ISSAS system have been its modular construction and its computer independence. Preliminary studies are already under way at IAI with the objective of modifying certain modules or completely replacing them by others featuring more advanced technology. The modularity and flexibility of the system make this a straightforward and routine task. Thus, ISSAS is presently considered as a pilot system, which over the years is expected to grow, mature, and continuously extend its capabilities according to the advancing state of technology.

Further stages in the development of a major optimization capability within the ISSAS system will involve work along two major paths: (1) Derivation and application of additional optimality criteria for other response phenomena such as buckling, divergence, and flutter, and (2) The development of optimization programs based on mathematical programming methods to deal with more sophisticated classes of variables, e.g. geometry and topology. A rational blend of these two types of optimization techniques with interactive capability will provide a powerful tool for the design optimization of aircraft structures in future levels of ISSAS.

As part of the general program of introducing C.A.D. methods and technology at all levels of the design/analysis/manufacturing process at IAI, development is also presently being undertaken in the area of CADD (Computer Aided Design Drafting). In a predictable effort to increase the interactive design capability in ISSAS, the future will most probably see a 'coming together' of both systems via the computer. Thus, while certain analytic capabilities in ISSAS may be employed in the detail design of structures, certain interactive design routines and data bases are sure to be 'lifted' by ISSAS users from the CADD system.

As more and more modules are added to ISSAS, and with the growing size of the user community and number of new projects, it is expected that major efforts in the future will also be placed on the development of an advanced executive control system for data base management. This effort is expected to start within the coming year with the replacement of the present computer configuration.

Another foreseen development which will aid the ISSAS system is the implementation of an advanced high-level Fortran-based graphics language, which would appear to be device-independent to the user. One such language is presently under evaluation at IAI.

Finally, an additional area of increased capability for ISSAS is provision for the use of flexible aircraft loads in the design and analysis of primary aircraft structures.

CONCLUDING REMARKS

An overview of an interdisciplinary structural design and analysis system which is being developed at IAI has been presented. As emphasized throughout the presentation, the use of graphic display terminals is the key to the success of such a system, since it provides the most natural and most effective mode of communication between the engineer and the computer. The engineer is then free to concentrate on his primary role as key decision maker, being able to observe the progress of the design and analysis process as it is presented pictorially on the screen, while having the option of altering its direction when undesirable trends are observed.

The ISSAS system is presently in advanced stages of development. Many of the modules which have already been completed are presently in operational use at IAI and their merits have been established. Other modules are in various stages of development and have yet to be proven in practical use. The entire system operating as an integral unit has yet to be fully evaluated, and any final conclusions regarding expected savings in engineering and computer costs would at this time be premature.

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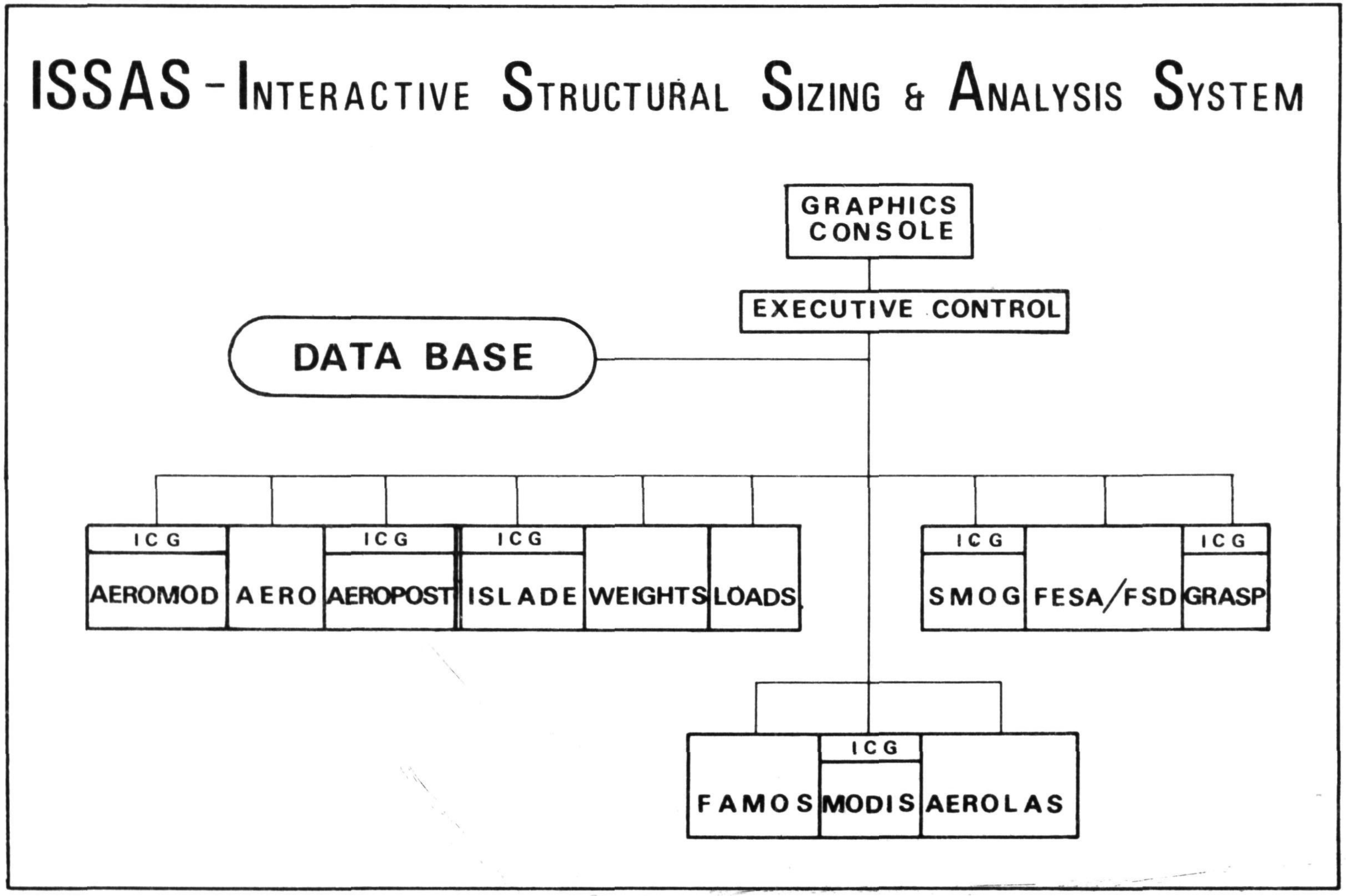


Figure 1.- Major ISSAS Modules.

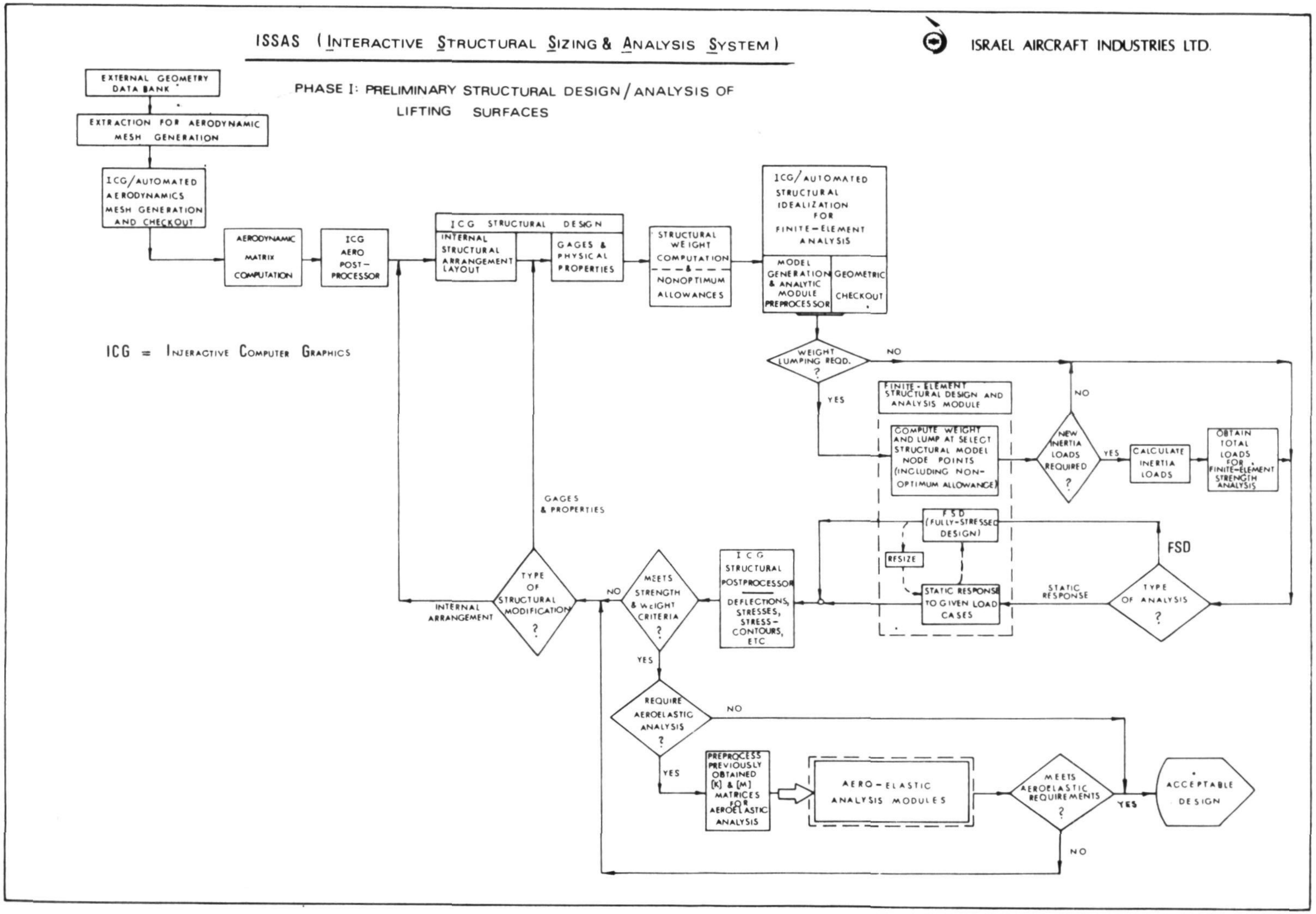


Figure 2.- Typical ISSAS sequence flow for aircraft wing structure design.

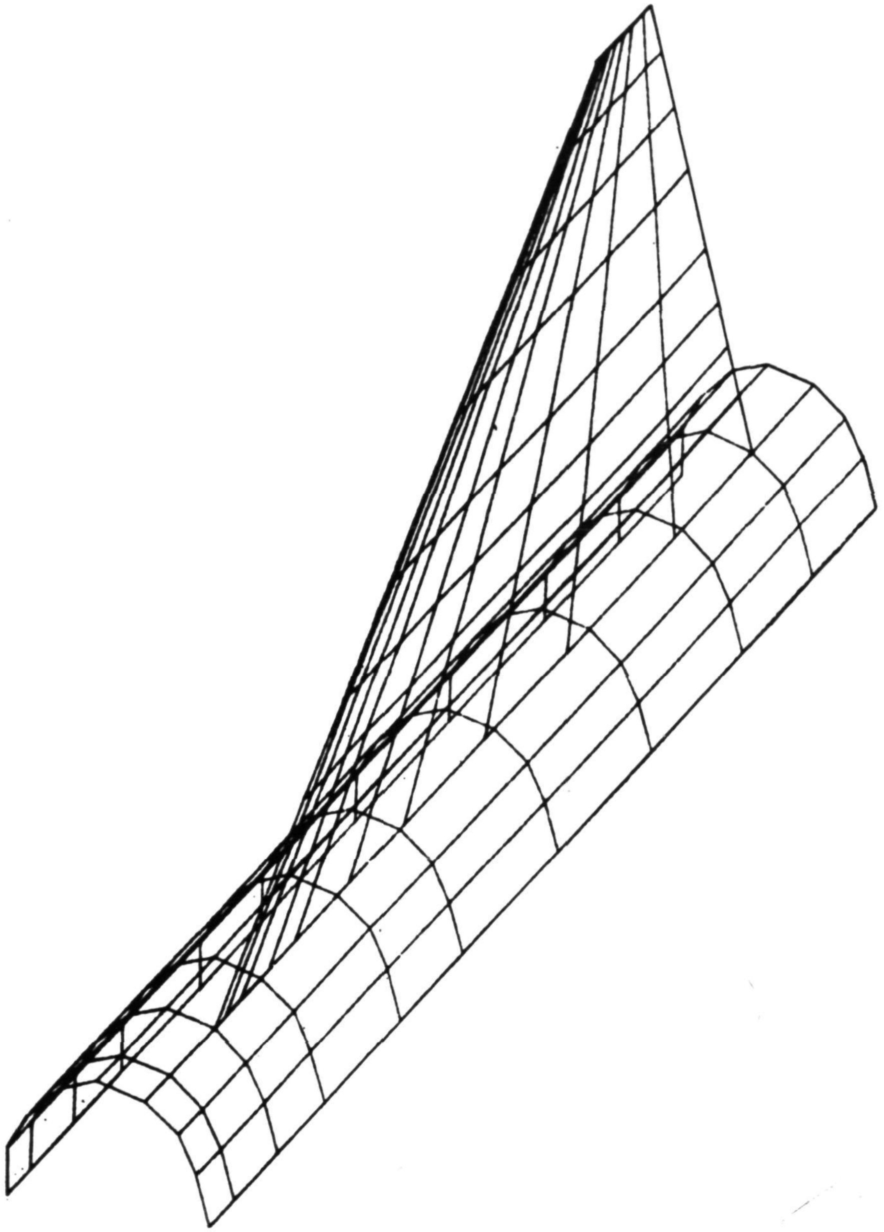


Figure 3.- Aerodynamics Modeling Module: wing-body combination.

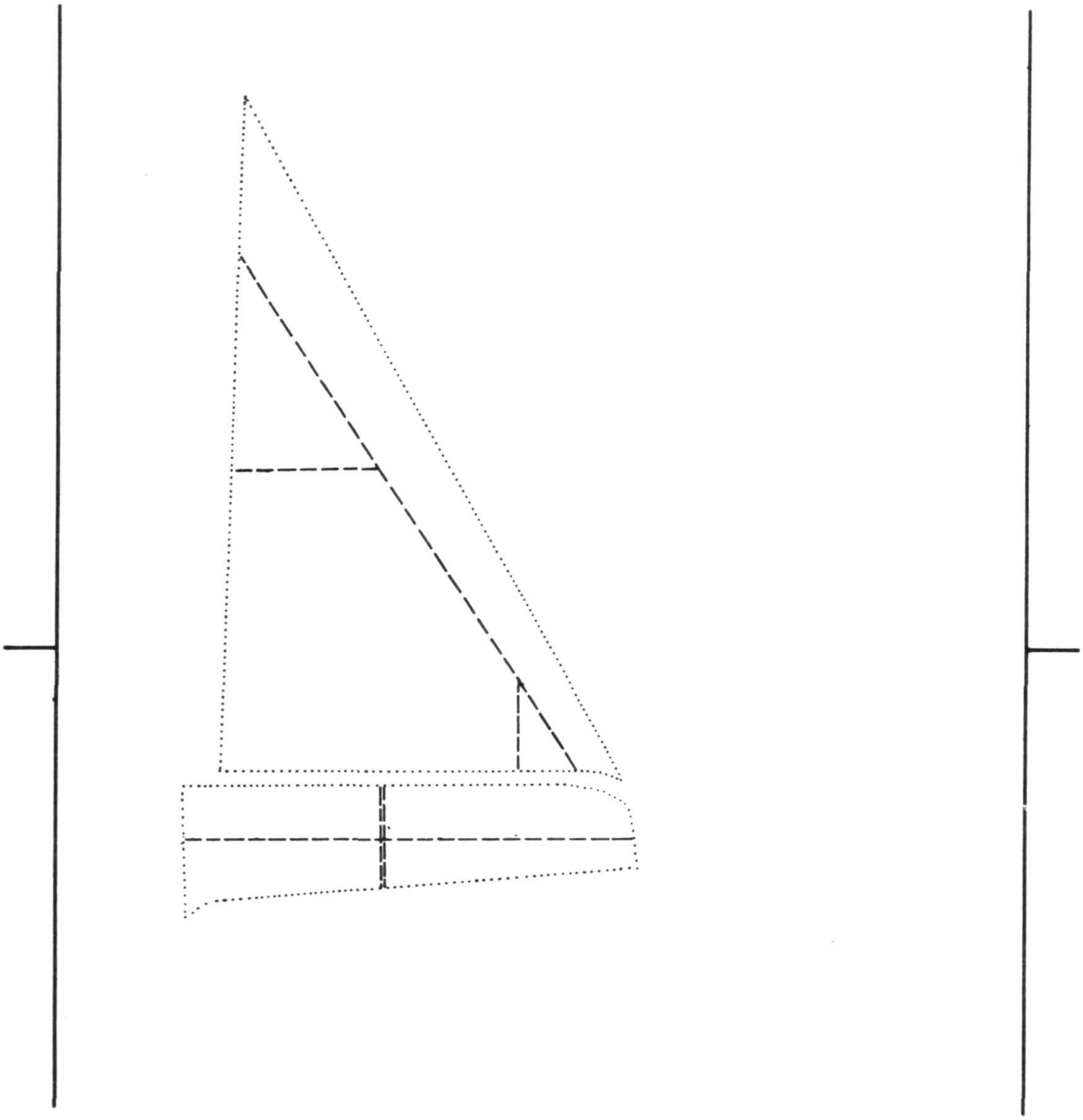


Figure 4.- Structural Design and Layout Module: delta wing.

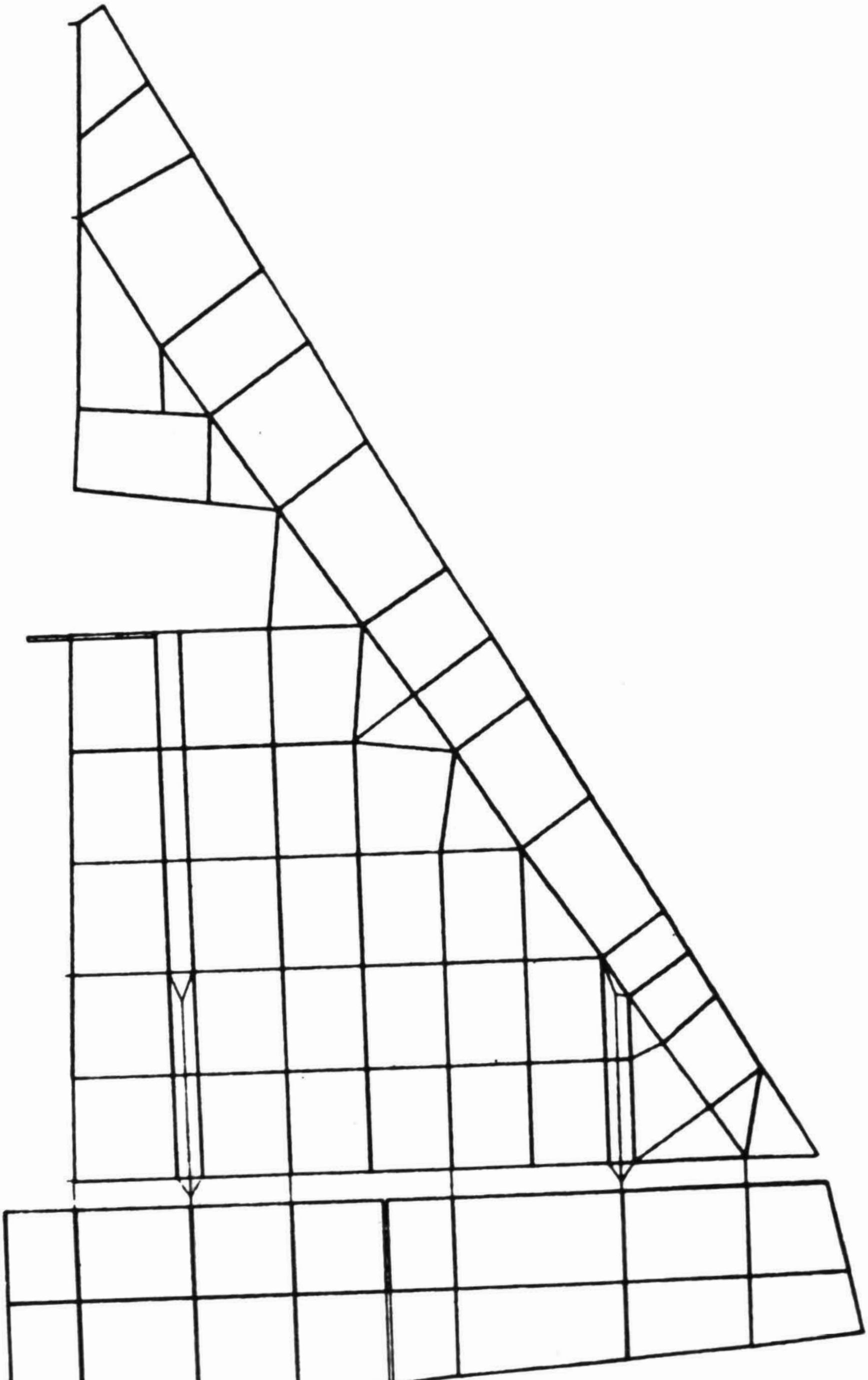


Figure 5.- Structural Modeling Module: plan view of idealized delta wing.

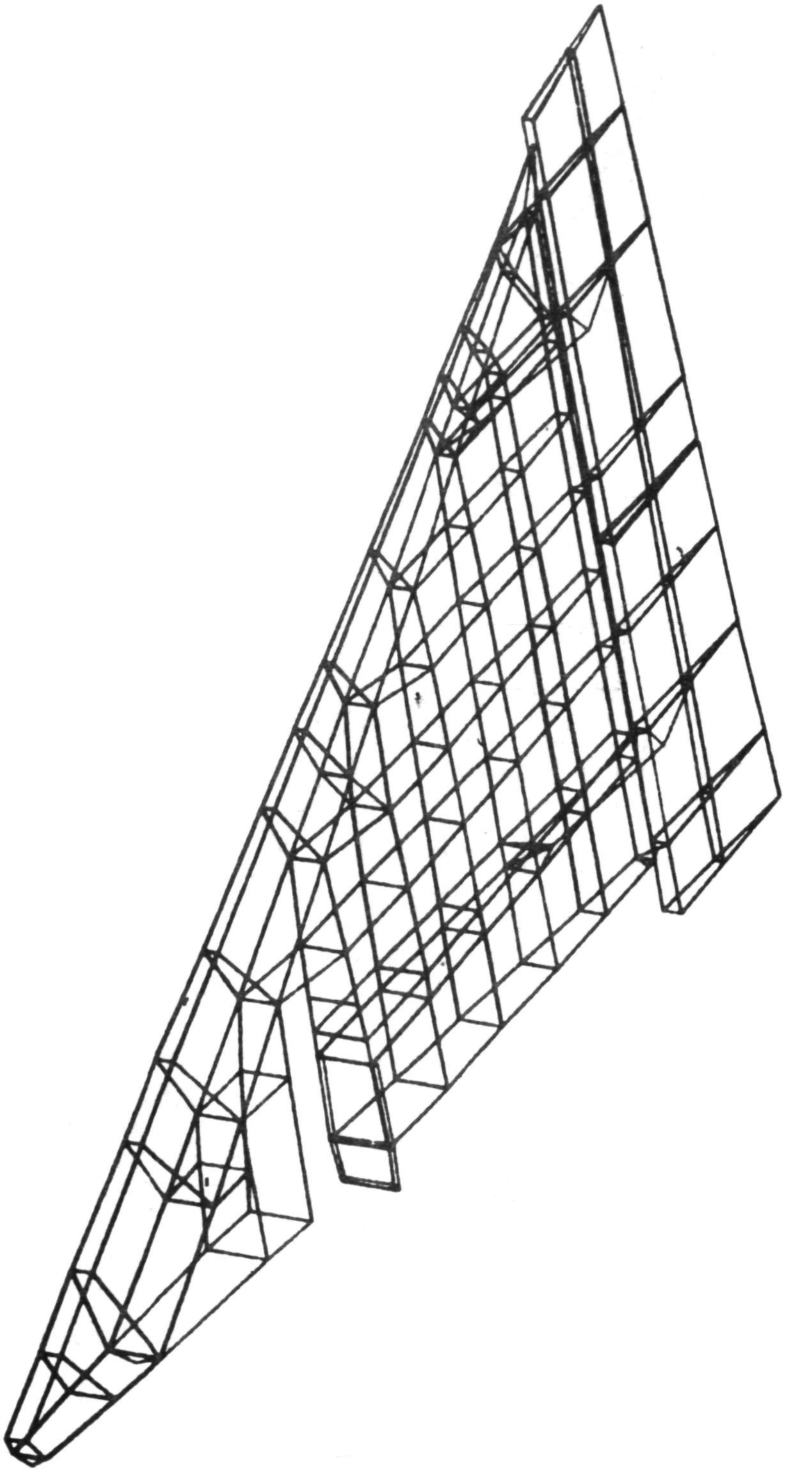


Figure 6.- Structural Modeling Module: 3-d view of idealized delta wing.

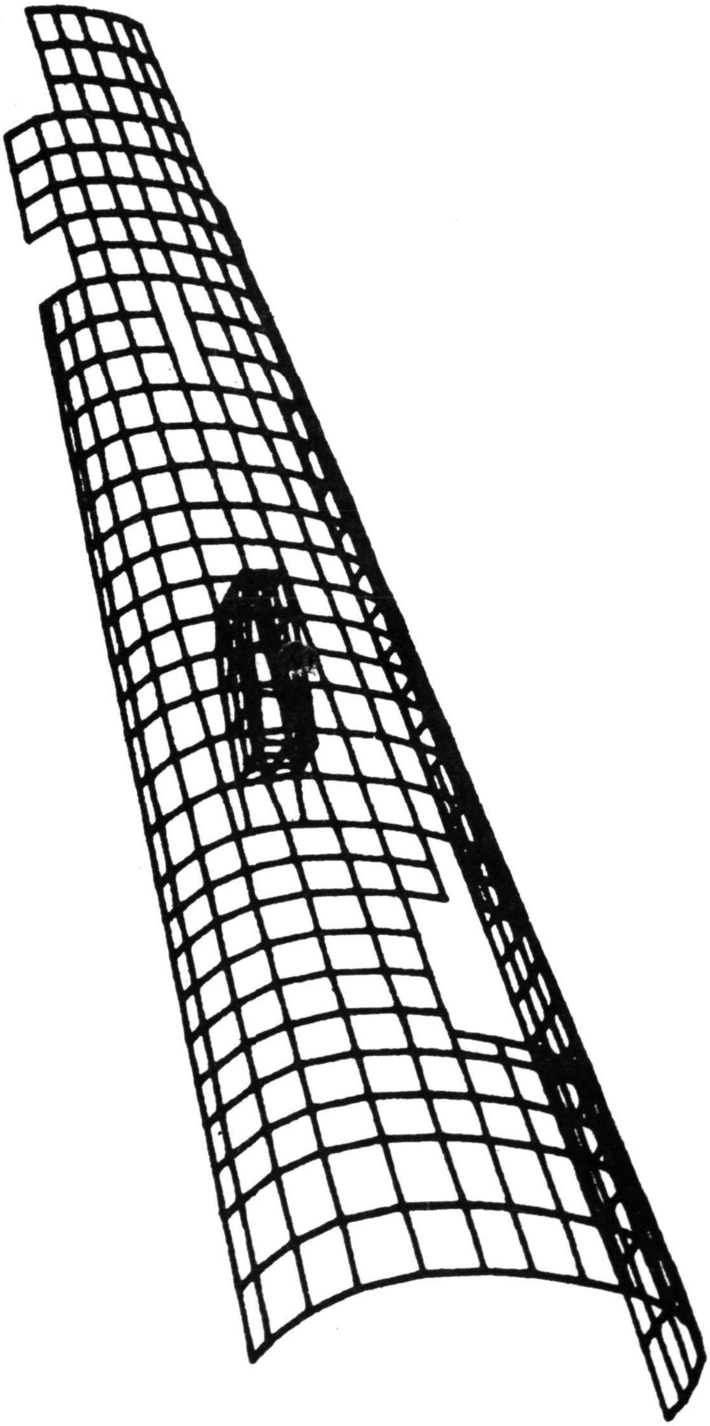


Figure 7.- Structural Modeling Module: 3-d view of westwind aft-fuselage.

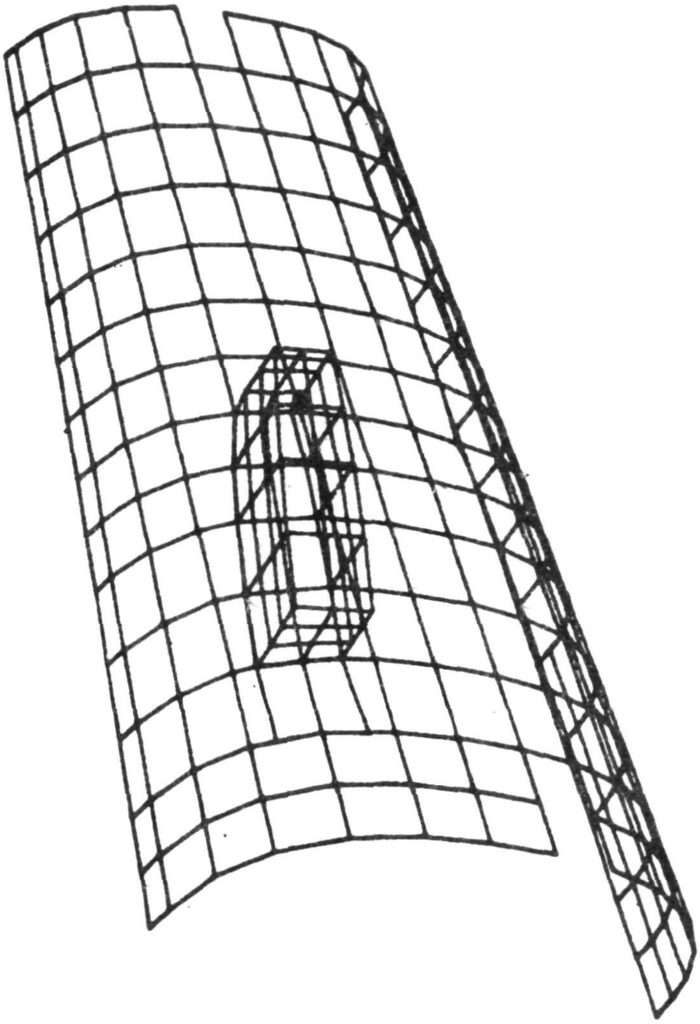


Figure 8.- Structural Modeling Module: 3-d blowup of westwind aft-fuselage.

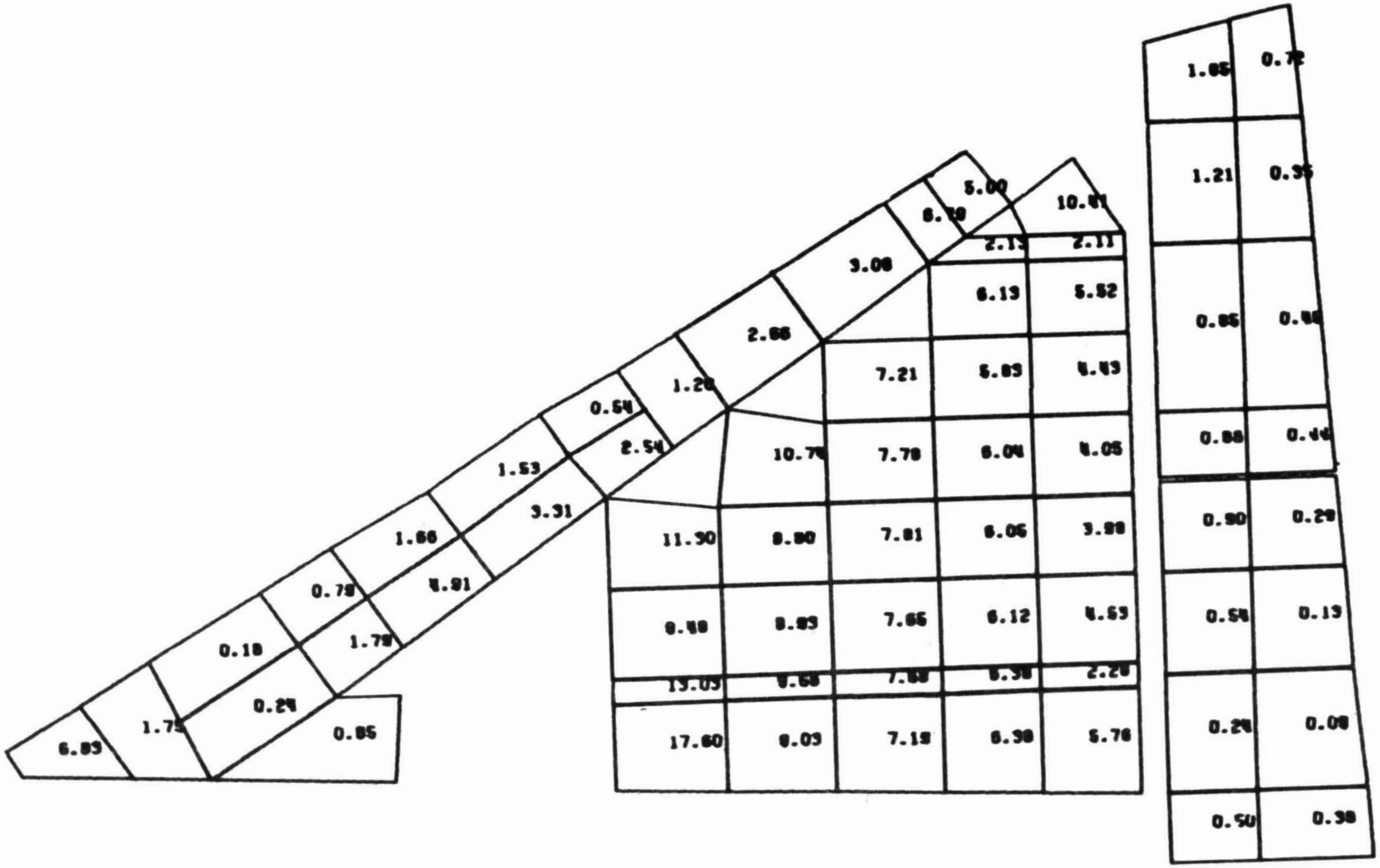
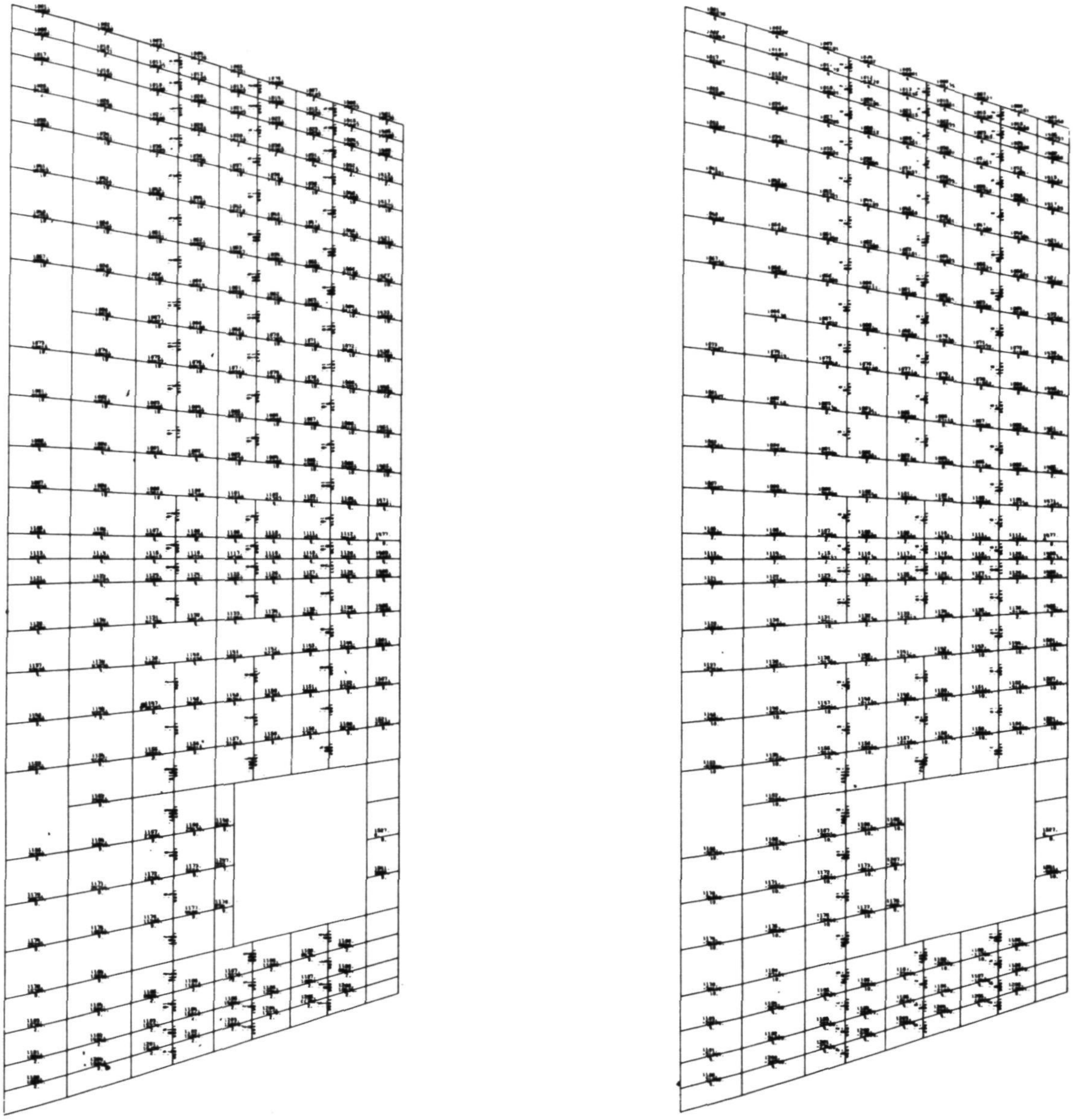


Figure 9.- Structural Post-processing Module: shear stress distribution in delta wing.



WESTWIND SUBSTRUCTURE
ENVELOPE FOR MAXIMUM
STRESSES IN ROD ELEMENTS

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Figure 10.- Structural Post-processing Module: shear stress distribution in developed surface of westwind aft-fuselage.

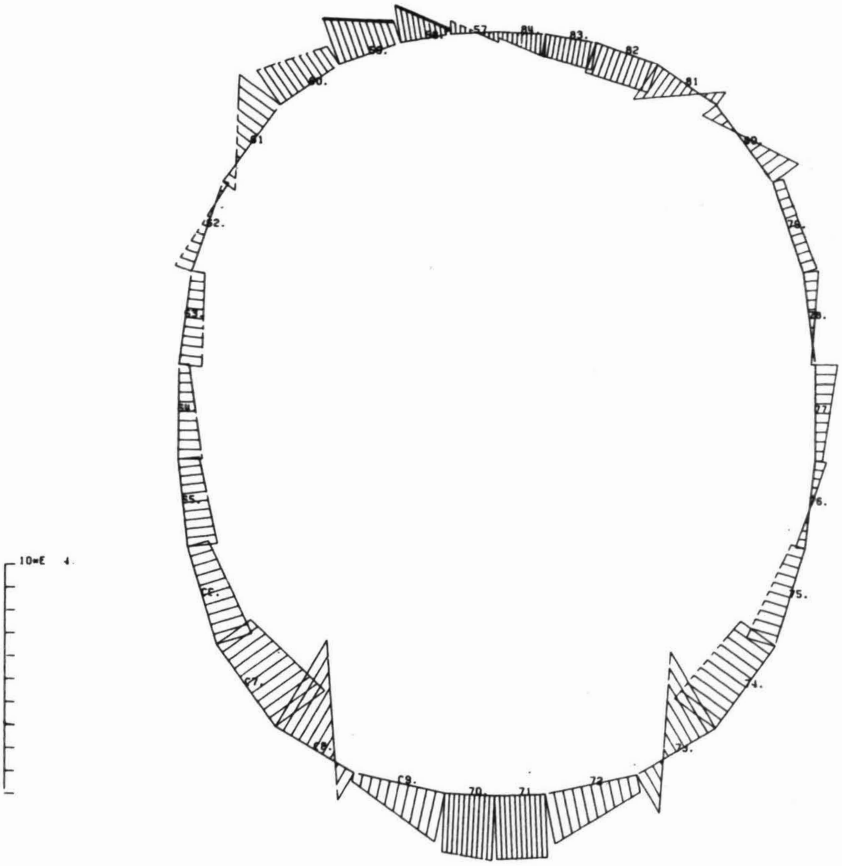

Figure 11.- Structural Post-processing Module: bending moment distribution in westwind fuselage frame.

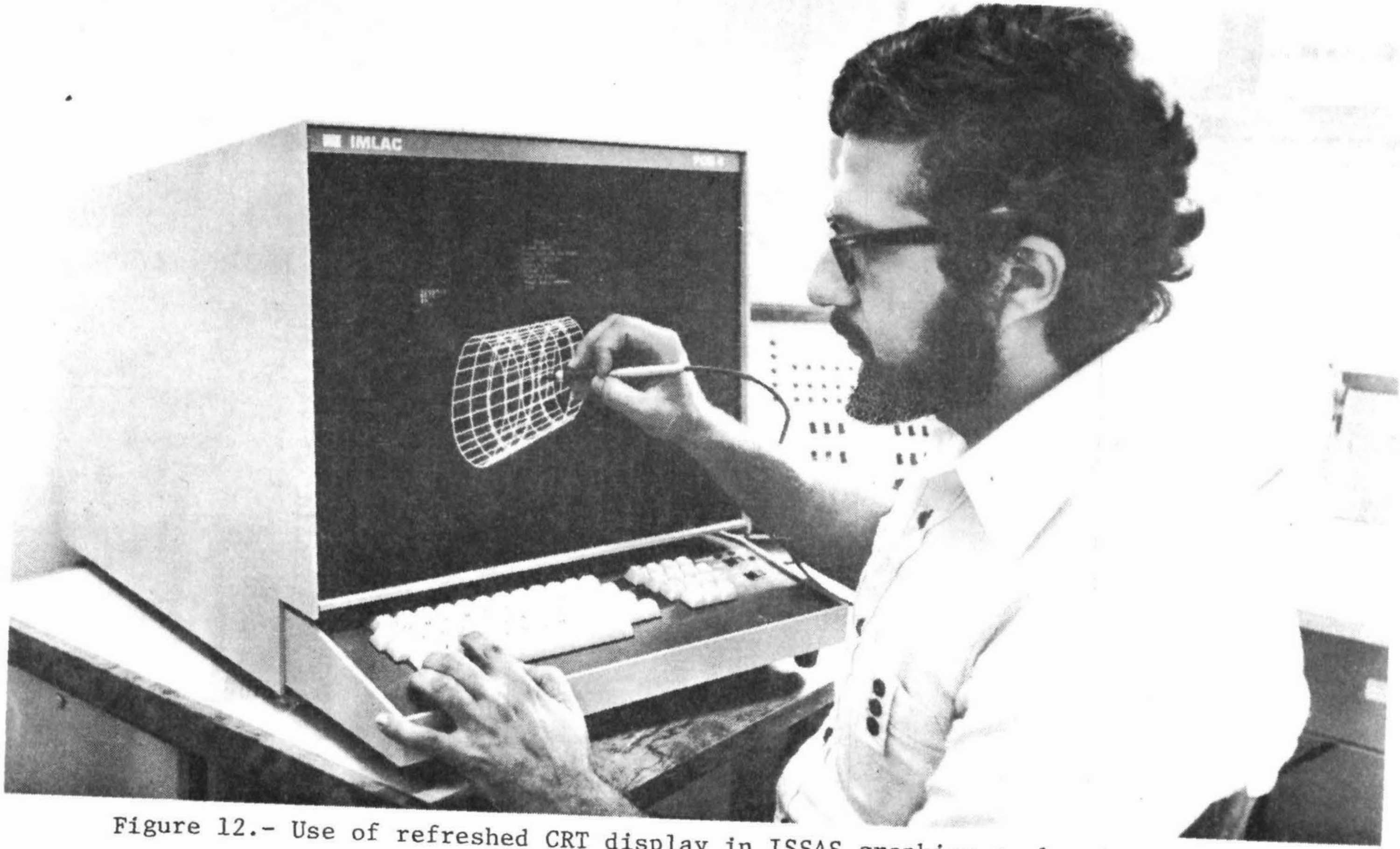

Figure 12.- Use of refreshed CRT display in ISSAS graphics evaluation program.