INTERACTIVE COMPUTER AIDED TECHNOLOGY: EVOLUTION IN THE DESIGN/MANUFACTURING PROCESS

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ABSTRACT

A description is given of a powerful computer-operated three dimensional graphic system and associated auxiliary computer equipment used in advanced design, production design, and manufacturing at McDonnell Aircraft Company in St. Louis, Missouri. This system has made these activities more productive than when using older and more conventional methods to design and build aerospace vehicles.

The process of designing and manufacturing the complex parts of the aerospace industry requires the coordinated efforts of many technical disciplines. Effective interface among these groups demands that each understand the design engineer's concept completely. Heretofore, the only medium for communicating the concept has been the two dimensional engineering drawing; however, it was difficult to ensure that every discipline was working with the latest revision to the drawing and that every individual interpreted the drawing the same way. This leads to the possibility of erroneous drawing interpretations, mis-machined hardware, and many pieces of corrective action paperwork, all contributing needless increased costs and program schedule delays.

Today, designers are no longer restricted to creating part, or entire vehicle definitions within the constraints of 2-dimensional descriptive geometry. With the use of this graphic system, they are now able to define parts using a wide variety of geometric entities, define parts as fully surfaced 3-dimensional models as well as "wire-frame" models. Once geometrically defined, the designer is able to take section cuts of the surfaced model and automatically determine all of the section properties of the planar cut, lightpen detect all of the surface patches and automatically determine the volume and weight of the part. He may also view the model from any vantage point desired by rotating it about any designated spatial axis, thus providing better visibility of its geometric definition. Further, his designs are defined mathematically at a degree of accuracy never before achievable. The mathematically defined model, stored in the central computer, is accessible to other engineering disciplines, tool designers, loft, manufacturing planning, quality assurance, and other personnel having a need for these data. This provides them with a single source set of geometric data with which they are able to address the tasks of analyzing the designs for performance, structural integrity, fit and function, part fabrication, and inspection of parts after fabrication. These tasks are accomplished using various computer aided techniques, software modules, and computer hardware, each tailored to do the job for which it is best suited.

The use of this computerized system has proved to be both cost and time effective in the conduct of our business. With continued use and development, even greater cost and time saving techniques are anticipated.

INTRODUCTION

In today's very competitive business world, each business firm must continually seek improved methods of conducting its varied activities if it is to survive and retain its competitive position. These improved methods are normally measured in terms of reduced costs, reduced manhours, reduced lead-time, better products, and maintenance of a creative work environment.

The design of an aerospace vehicle is predicated on a multitude of requirements of each of the systems and technical disciplines comprising the total design activity. In order that each technical discipline be properly interfaced with all other disciplines, and the integrity of the vehicle performance and specification requirements maintained, close intergroup coordination is mandatory.

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During any design program, several design interactions are required as a result of loads analysis, weight and balance requirements, aerodynamic considerations, and other design ramifications. As a result of these necessary design interactions, there is often difficulty in effecting a smooth and orderly response to the required alignment of the specific design tasks to satisfy these requirements. Reaction time by all affected parties must be closely coordinated to prevent jeopardizing major program milestone schedules. Design changes vary from being minor in nature to the very complex, but all require that we exploit every available technique, talent, and design tool at our disposal to assure that the changes are made on a timely basis to prevent schedule compromises. Computer Aided Technology, which is comprised of numerous types of computer hardware and software, and used by our engineering and manufacturing disciplines at MCAIR, is helping us to meet these goals.

MCAIR has formed a Computer Aided Technology (CAT) project, made up of representatives from departments that use computers in their work, for the purpose of providing the coordination necessary to effect smooth and cost effective interfaces between each of the activities and to identify and eliminate duplication of efforts in the development of software. Our CAT project activities are similar to those of other companies currently developing interactive computer graphic capabilities, but is probably structured differently. Our organizational structure is shown in Fig. 1.

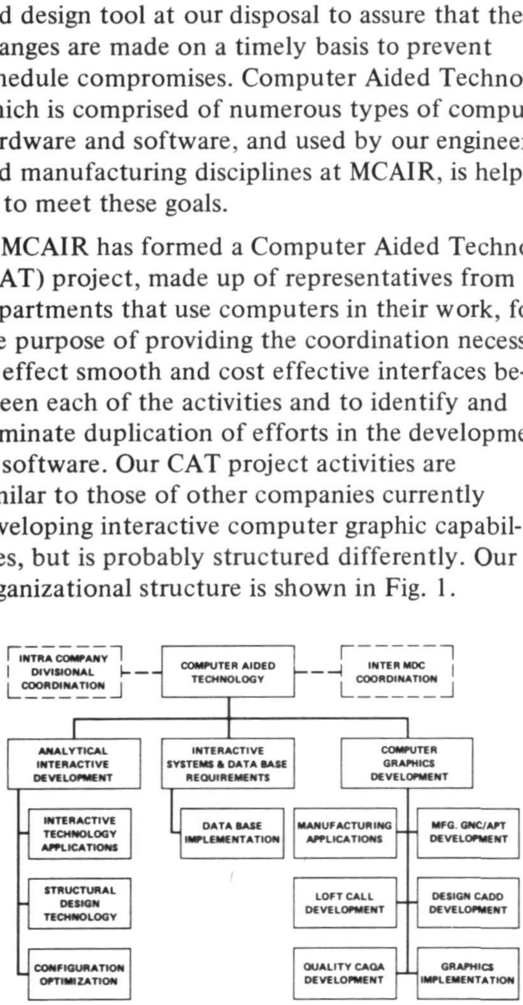

Fig. 1 CAT Organization Chart

Our computer system has been modularized into several specific packages in order that each department using computer graphics be required to develop and maintain only the software necessary to accomplish its required departmental tasks. Training of the console operators for each module is therefore simplified compared with having to instruct the operators how to use a single large module that would be used by all departments.

Our CAT project personnel are co-located, providing close coordination and a direct line of communication between the various disciplines in the development of their modules.

There are currently six basic graphic modules under development or coordination by the CAT project. They are Computer Aided Design-Drafting (CADD), Interactive Computer Aided Design Evaluation (ICADE), Computer Aided Loft Lines (CALL), Computer Graphics Structural Analysis (CGSA), Graphic Numerical Control (GNC), and Computer Aided Quality Assurance (CAQA). Their interrelations are depicted in Fig. 2. Each of these modules is discussed in the following paragraphs.

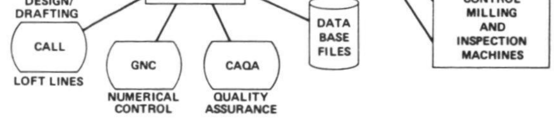

Fig. 2 McDonnell Aircraft Computer Aided Technology

Computer Aided Design-Drafting (CADD)

The term CADD (pronounced caddy) denotes various computer techniques and applications where data are either presented or accepted by a computer in a geometric form as opposed to alphanumerics only. CADD is "interactive", which implies that there is an efficient, real time interplay of actions between the console operator and the system hardware devices. CADD therefore describes an interactive and conversational mode of operation, utilizing a display console where the engineer may describe his design, perform analysis procedures, and make changes to the design if he so chooses.

A designer is normally concerned with creating a geometric representation of a physical object. In the drawing board mode, these are lines drawn on paper or mylar in two dimensions. This representation, when the CADD package is used, is in terms of an exact mathematical description in the computer's memory, either as a two dimensional lines drawing, a three-dimensional wireframe drawing, or as a completely surfaced definition of the model in three dimensions. In addition, the graphic representation is displayed on the cathode ray tube (CRT) (Fig. 3). Hardware and software features enable the operator to converse with the computer by detecting, with a light pen, elements displayed on the CRT screen and by inputting specific instructions with the alphanumeric and functional keyboards.

Fig. 3 Model Graphically Displayed

The CADD system places the designer in command of the computer while he retains the essence of his normal working environment. As a result, he is able to address and solve problems in a geometric language with which he is familiar and comfortable rather than having to understand the intricacies of the computer or programming languages.

The CADD system enables the engineer and computer to function as a problem-solving team. The significance of the team effort is that each member is free to do the part of a task for which he is best suited. The computer can perform the complex geometrical tasks, or the repetitive tasks, while the engineer can focus all of his creative talents to the problem rationale.

A CADD console was first used in a production environment for direct support of the F-15 project in July 1970. It was initially utilized for the purpose of synthesizing the three-dimensional spatial geometry and path of travel of the main landing gear mechanism (Fig. 4) to assure that the required precision of motion was obtained. It was later used to define many of the components of the fuselage and related structure (Fig. 5).

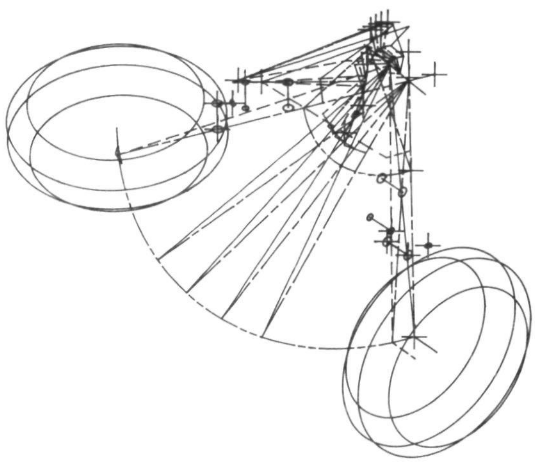

Fig. 4 F-15 Landing Gear Kinematics

Fig. 5 F-15 Fuselage Structural Component

Although some of the more general applications at MCAIR have been layouts and detail design of structural components and complex mechanisms not associated with the aircraft moldline, the ability to access lofted surface definitions of various aircraft via the CRT has been important to the designer. With lofted surface definitions available to the operator, he is capable of generating any section cut on the airplane to assist him in determining the best design approach for the configuration of a system component. Once the design approach is determined, the operator is able to offset from moldline a distance equal to the skin thickness and have the entire periphery of the structural component completely defined. The internal portion of the structure, including the flanges, pockets, and stiffeners are added in a 3-D wireframe format. The wireframe model is then converted to a surfaced model with each surface identified by a label. Labels are used as identifiers for accessing the geometric data of the surfaces from the computer.

CADD has also been used on several of our Advanced Design programs for defining vehicle configurations, landing gear mechanism geometry, external stores arrangements, and various vehicle system tradeoff studies.

Whenever a hardcopy drawing of the data displayed on the CRT is desired, the operator merely inputs pertinent drawing information into the computer, such as, scale, drawing size, type of drawing material, and any special instructions desired by the operator. These computer stored data are then queued for hardcopy, utilizing a computer driven automated plotter (Fig. 6) and, overnight, the completed hardcopy is delivered to the requestor.

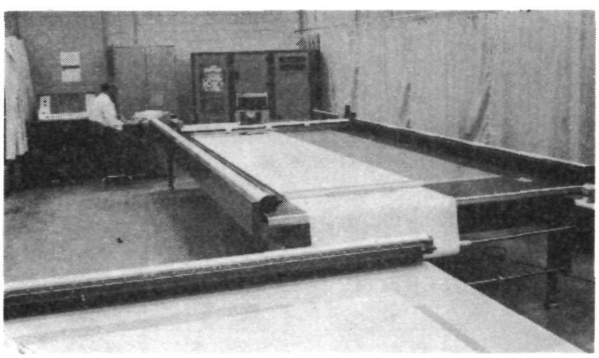

Fig. 6 Automated Plotter

Many disciplines are currently interfacing the CADD module, each accessing the single source geometric data created by the designer. They include Strength, Propulsion, Aerodynamics, Loads, Weights, Structural Dynamics, Thermodynamics, Operations Analysis, Wind Tunnel Design, Structural Dynamics Labs, Loft, Tool Design, Master Layout, Manufacturing Planning, and Quality Assurance. Each are accomplishing their required tasks in a more efficient and time saving manner than in the past as a result of this interface.

Interactive Computer Aided Design Evaluation (ICADE)

When an aircraft configuration has been synthesized on the CRT and stored in the computer, members of the design team responsible for performance analysis can access geometric data at the same console used to create the configuration, and apply an interactive parametric sizing analysis program called ICADE (pronounced eye'-kaydee), to determine if the flight performance requirements and vehicle size are compatible. He also has the capability of sizing the aircraft configuration to satisfy a specified set of flight performance requirements, i.e., size wing, engine, and/or fuel volumes to meet or exceed performance requirements and determine concommitant changes in the aircraft geometry, mass properties, aerodynamic characteristics, installed engine performance, and life cycle cost characteristics. The system is quite effective when used to conduct studies for determining the effect of parametric variations in aircraft design parameters, (e.g., wing geometry, wing loading, thrust to weight ratio, structural load factors, etc.) on the aircraft size while holding the performance constant, or determining the effect of parametric changes in performance parameters (e.g., mission radius, specific excess power, etc.) on aircraft size. In addition, ICADE can be used to evaluate specific design or performance tradeoffs; determine the sensitivity of aircraft size to incremental changes in engine size, fuel quantity, fixed weight, aerodynamic drag, specific fuel consumption, etc., while holding the performance constant; and generate data required for the Parametric Design Analysis Procedure, a separate batch analysis program, which is used to determine "optimum" design parameter values which maximize or minimize a measure of aircraft effectiveness (e.g., takeoff gross weight, life cycle cost, etc.) Figure 7 depicts the data flow of the program.

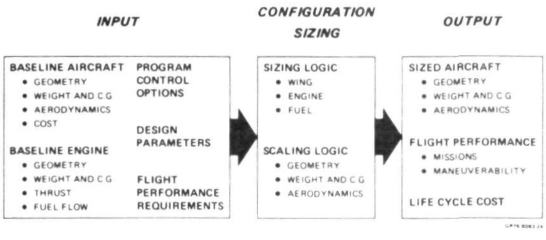

Fig. 7 ICADE Program Data Flow

All input data required by ICADE have been divided into thirteen categories to facilitate the editing process. These data categories are:

1. Design parameters
2. Program control indicators
3. Sensitivity parameters
4. Mission performance parameters
5. Maneuver performance parameters
6. Miscellaneous performance parameters
7. Geometric characteristics - baseline aircraft
8. Weight characteristics - baseline aircraft
9. CG characteristics - baseline aircraft
10. Aerodynamic characteristics - baseline aircraft
11. Propulsion system characteristics - reference engine
12. Cost characteristics - baseline aircraft
13. Payload characteristics

The analyst initiates the editing process by detecting with the light pen the data category to be edited from a menu display. The data from the selected category are then displayed in card image form identical to that used for the batch version of the program. A menu of commands is also displayed on the CRT.

During execution of the ICADE sizing iteration, the iteration number and current values of fundamental aircraft sizing parameters are displayed. These data provide the analyst with information on the convergence behavior of the sizing iteration, but do not allow him to interact with this phase of program execution.

After the sizing iteration has converged to a solution, and the cost and mission performance characteristics have been calculated, the following summary of the sized aircraft characteristics is displayed:

1. Geometric characteristics (comparison with baseline aircraft)
2. Weight characteristics (comparison with baseline aircraft)
3. CG characteristics (optional)
4. Mission performance
5. Maneuver performance
6. Cost characteristics (optional)
7. Aerodynamic characteristics

Computer Aided Loft Lines (CALL)

CALL is a module developed and utilized for the primary purpose of creating, modifying, and evaluating various surface geometry shapes interactively. Surface related geometry operations such as digitized data curve matching, continuous surface blending, creation of the CADD module entity types, and CADD drawing file system compatibility have been incorporated to provide the preliminary designer the ability to graphically define a surfaced vehicle in a format that is usable by other disciplines. Standard loft surface shapes, i.e., conic, ruled, parametric cubic, and general parametrics provide designers latitude in defining vehicle configurations and are helpful in determining fuel and equipment compartment volumes.

Computer Graphics Structural Analysis (CGSA)

CGSA is a module that has been developed to aid structural analysis and design. CGSA is used to provide internal loads, stresses, and strains for structural sizing, and documentation of structural integrity. This system functions in conjunction with the CADD system.

A special overlay is used on the function keyboard (Fig. 8) when the CGSA module is in operation. The function keyboard is the same as the one used for all of our modules, but the function of each button has been software-altered for each module.

CGSA is used to prepare three dimensional finite element model input data for either the CASD or NASTRAN structural analysis programs (Fig. 9). (CASD, an acronym for Computer Aided Structural Design, is a structural analysis program developed by Douglas Aircraft Company prior to the development of NASTRAN by NASA).

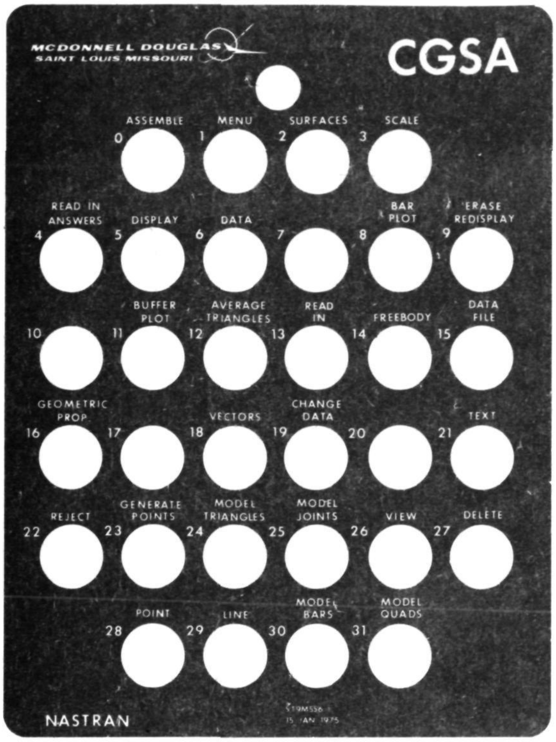

Fig. 8 CGSA Function Keyboard Overlay

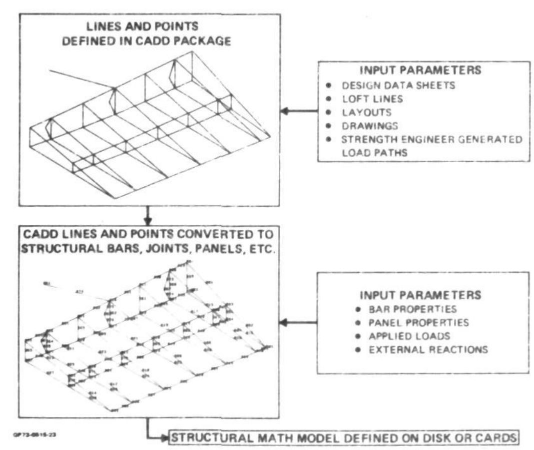

Fig 9 Structural Idealization

Basic geometry is developed from loft data, conventional engineering drawings, or the three dimensional geometry of the vehicle constructed and filed in the computer by the designer (Fig. 10).

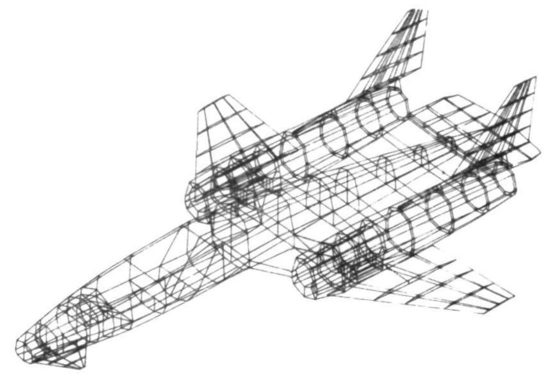

Fig. 10 Basic Structural Geometry in Point Line Format

This results in a point-line model which is converted to a finite element model by defining bar/ panel/membrane element properties, applied loads, and external boundary conditions. The model may be viewed, checked, and edited at the console for verification of the input data. Hardcopies are produced displaying input properties and element labels (Fig. 11 and 12) and the model is then stored in the CADD drawing files for future retrieval. The CASD or NASTRAN input card images are automatically created on a disk data set for submittal to the structural analysis program. The utilization of CGSA for model generation eliminates the need for manually creating the models, input sheets, and punched cards.

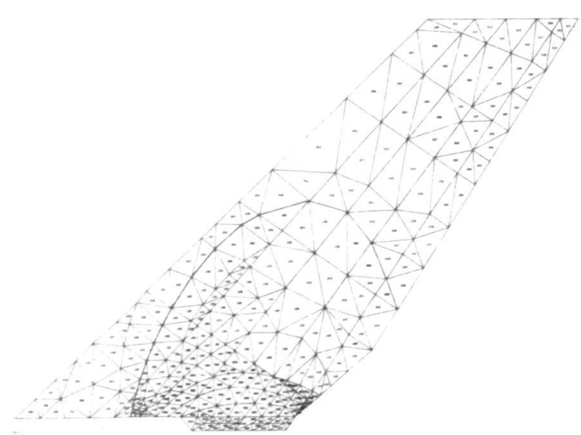

Fig. 11 Triangular Membrane Labels

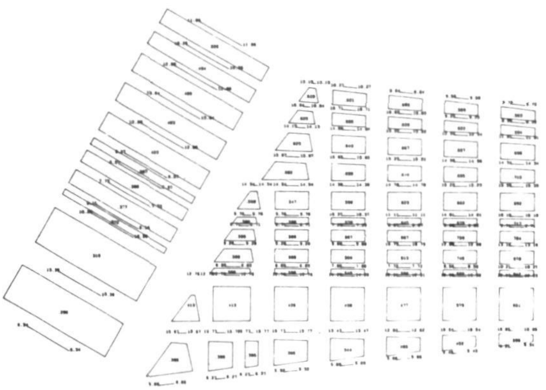

Fig. 12 Upper Cover Bar Areas and Panel Thicknesses

Upon completion of the CASD or NASTRAN structural analysis program (which performs a minimum strain energy solution), the results are stored with the model in the CADD drawing file and are also output in the more usual manner on an alphanumeric printer. The answers may be displayed at the console and hardcopied for all structural elements. The display options include magnitudes of bar load, bar stress, panel shear flow, panel shear stress, membrane stress, membrane strain, and membrane running loads, examples of which are shown in Fig. 13 and 14. Also the plotting of bar loads or stress, bending moments, and deflected shapes (Fig. 15) are available.

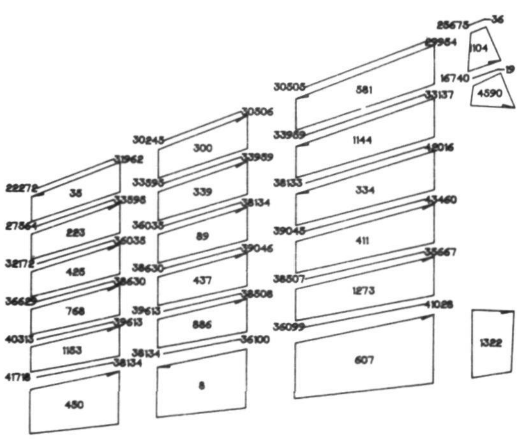

Fig. 13 Bar Stress and Panel Shear Flow

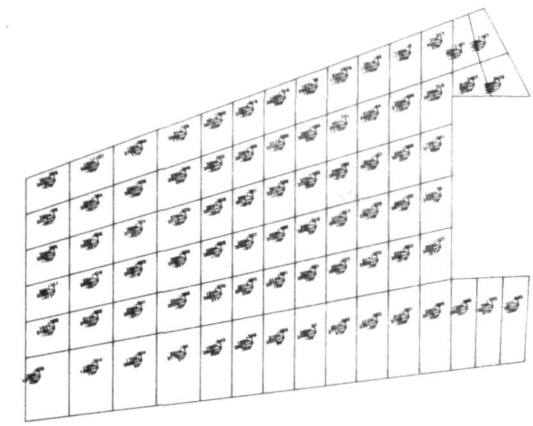

Fig. 14 Skin Strains - Micro-in./in.

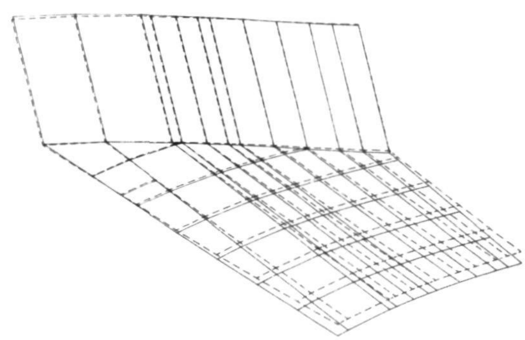

Fig. 15 DC-10 Upper Cover Deflected Shape

The displays and hardcopies in the form of load sheets are used by engineering supervision to gain an overall feel for the structural analysis, and also by the detail stress analyst as inputs for his computations. This type of graphical presentation eliminates the need to manually prepare load sheets. This was previously done by reading the printed output data and associating it with the pictures of the structural idealization.

CGSA is also used to transmit, within the computer, structural flexibility influence coefficients or a reduced stiffness matrix to the Loads and Structural Dynamics Departments. Additional geometric data is passed to the Loads Department who then generate panel point loads which are transmitted back to the CGSA module.

CGSA is effective when used in both Advanced Design and Project environments. Advanced Design requires smaller models, quick turnaround, and good visibility, and it adds to the technical credibility of technical proposals. In a Project environment, it is effective in handling large quantities of data (the F-15 Wing model has 10,000 card images) and in providing Design and Strength department personnel with essential data when responding to design changes and updates.

Graphic Numerical Control (GNC)

When work is scheduled to start on the manufacturing cycle of a part, a GNC programmer is assigned the task of creating an Automatically Programmed Tool (APT) program for machining the part. The programmer retrieves a copy of the engineering drawing of the part from the computer files and within seconds, the configuration appears on the CRT screen as shown in Fig. 16. This may be the first time he has seen the drawing; consequently, the dimensions and mathematical properties of the part are unknown to him. The part must be evaluated sectionally, and to achieve visual simplification, he will probably isolate one pocket at a time to work on. He may do this by typing in the label numbers of each surface comprising the pocket. The computer searches its files and displays the pocket on the CRT.

By depressing a specific function key, the programmer activates a routine which analyzes the connectivity of the part geometry, and extracts the geometric properties or mathematical description of the part and stores the data in the computer memory.

Another function key is then depressed and the programmer may then create the APT source statements. The setpoint of a cutting tool can be keyed-in using the alphanumeric keyboard, or can be lightpen detected. After the cutter setpoint location is established and accepted, various parameters necessary for defining the cutting operation are input: diameter of the cutter(s), spindle speed(s), check and drive surface(s), various tool axes, etc.

The APT program, created from the previous inputs, is then reviewed (Fig. 17). Using Data Set Edit, he can add, change, or delete APT statement from his program using the lightpen and alphanumeric keyboard, or by using a low cost VM 7000 terminal (Fig. 18). During the programmer's detects and inputs, APT source statements are simultaneously being generated.

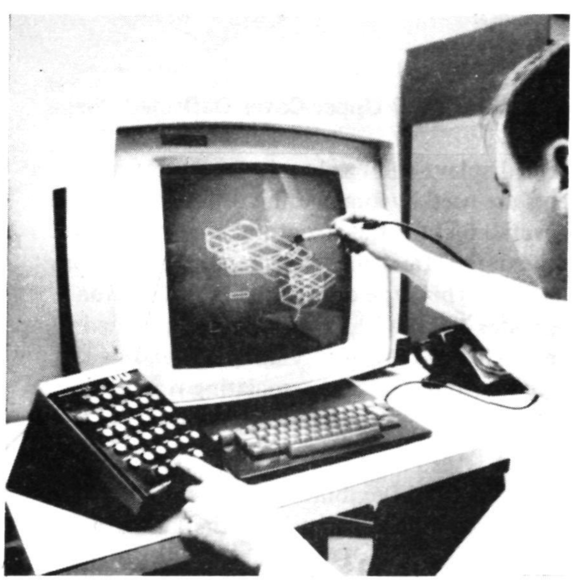

Fig. 16 Copy of Drawing Retrieved from Drawing Files

Fig. 17 Review of APT Source Program

Fig. 18 A Low-Cost VM7000 Can Be Used for Data Set Edit

A visual inspection of a cutting simulation then takes place. The programmer observes the motion of the cutter generated by the parts program. The path of travel of the center of the cutter is plotted and superimposed on the display of the part. The tool axes, tool end, and a representation of the tool itself can also be displayed to ensure that the parts program is correct (Fig. 19 and 20).

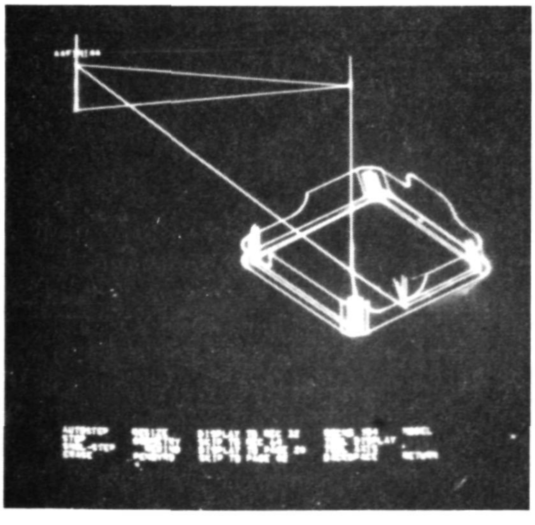

Fig. 19 Displaying the Path of the Center of the Cutter as Well as the Tool Axes

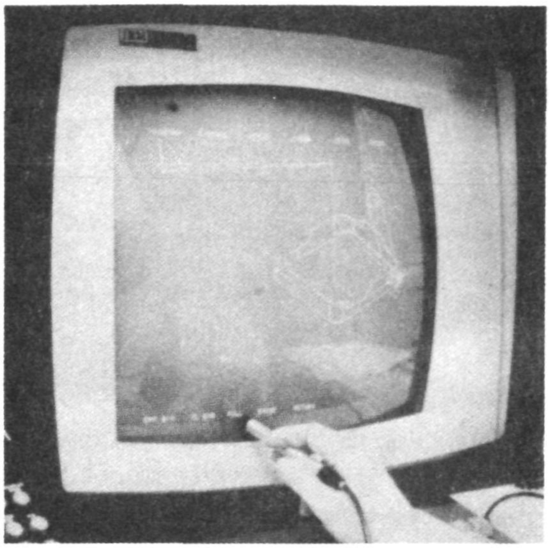

Fig. 20 Displaying the Tool at a Critical Position

If necessary, Data Set Edit is again used to correct errors. The program is then implemented to generate the machine tool data instructions for the actual machining of the part.

Computer Aided Quality Assurance (CAQA)

Upon completion of the machining operation, inspection of the part is necessary to determine if it accurately represents the design definition. A copy of the part definition that was defined by the designer is retrieved by the quality assurance programmer. Using the lightpen, he generates points on the surface of the part that the DNC inspection machine is to probe (Fig. 21). Vectors are displayed (Fig. 22) on the part at the points at which the probe is to make contact, and APT statements, which will guide the probe to these points on the actual part, are created as the vectors appear. He next reviews the program, using Data Set Edit if required, and then, as in the case of the centerline plot, it is visually verified (Fig. 23), edited if required, and finally sent to an IBM 1800 computer for the inspection operation.

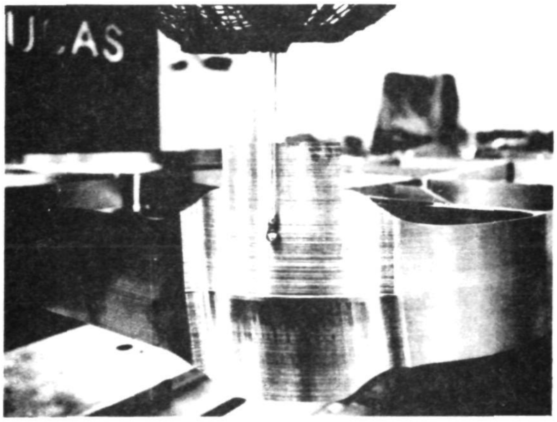

Fig. 21 DNC Inspection Machine Probing Points on the Surface of the Part

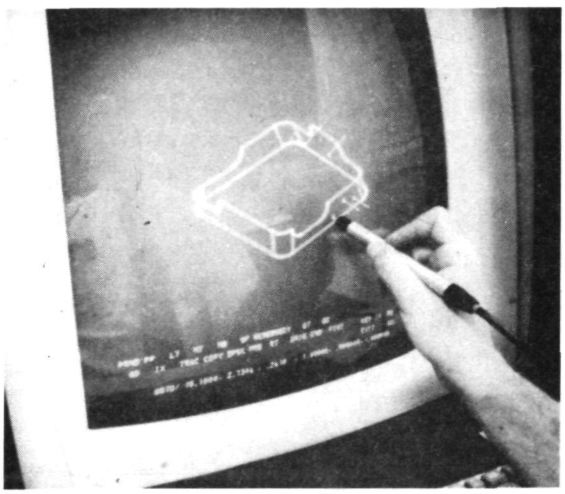

Fig. 22 "Blasting" Points on the Surface of the Part Where the Probe is to Make Contact

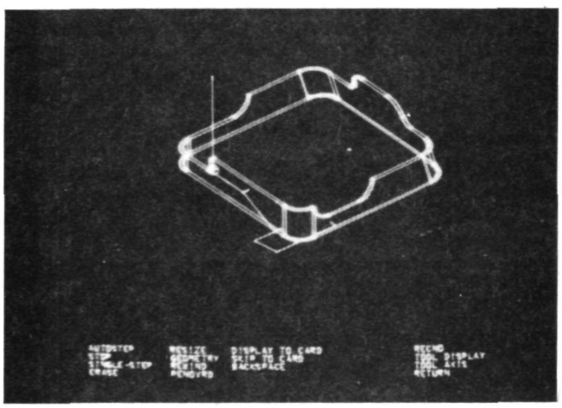

Fig. 23 Plotting the Path the Probe Traverses and the Points of Contact

During the actual inspection operation, the inspection probe is driven by DNC to each of the preprogrammed inspection points until contact of the part is made. When contact is made, the probe stops, and the actual surface coordinates, the programmed surface coordinates, the allowed tolerances, and out of tolerance conditions are automatically printed out on a high speed line printer. This process eliminates many hours of inspection set-up time and the human error that can result from more conventional inspection methods.

This inspection method is primarily used for first article inspections, for checking out modified GNC programs, or for checking parts to determine the effects of cutter tool wear.

For inspection of subsequent parts after a first article inspection, a Film Inspection Apply Template (FIAT) is sometimes used. It is made of a clear polyester plastic (Mylar) sheet 7.5 mills thick. When a FIAT is required a console operator in the Loft department will call up a copy of the engineering drawing, display it on the CRT, and input a request to the computer for a scribecoat hardcopy. When the hardcopy is completed, a photo-sensitive sheet of Mylar is overlaid on the hardcopy, exposed, and run through a development processor. Within a matter of minutes, an inspection template made of a dimensionally stable-base material is ready for use. These templates are used by Quality Assurance to check a finished machined part for proper machining of flanges, webs, and caps by overlaying the FIAT on the machined part. Any deviation from the intended configuration is readily detectable.

SYSTEM DESCRIPTION

MCAIR's software packages utilize a user-oriented programming language that is specifically tailored for the types of problems typically encountered in an aerospace engineering and manufacturing environment. They were developed to allow engineers to utilize the speed and accuracy of a large digital computer to assist in solving analytical and geometry-oriented problems and to present engineering data to other disciplines, both engineering and manufacturing, in the form of computer stored data or as a hardcopied engineering drawing. The output of the computer, which consists of geometric figures and relevant information relating to them, is visually displayed on a CRT.

The engineer can interact with the computer based on what he sees displayed on the CRT or by inputting specific instructions to the computer by means of the functional and alphanumeric keyboards. In essence, he has replaced his drawing board with the display console. Because of the immediate information feedback aspect of the designer's visual relationship with a computer, he is able to complete his tasks in a shorter period of time.

Each of our 15 CADD consoles is remotely connected to, and used in conjunction with, an IBM 360 Model 195 computer. Each console consists of a display CRT, a typewriter-like alphanumeric keyboard for typing in dimensional data or special instructions to the computer, a 32-button functional keyboard for ordering the creation and manipulation of geometric data (points, lines, arcs, conics, cubics, planes, surfaces, etc.) on the CRT, an electronic light pen for detecting specific displayed data to be manipulated, a closure hood with a Polaroid camera for quick-reference pictures, and a "hot-line" telephone to the CPU (Central Processing Unit) operator. Figure 24 shows a typical CADD console arrangement.

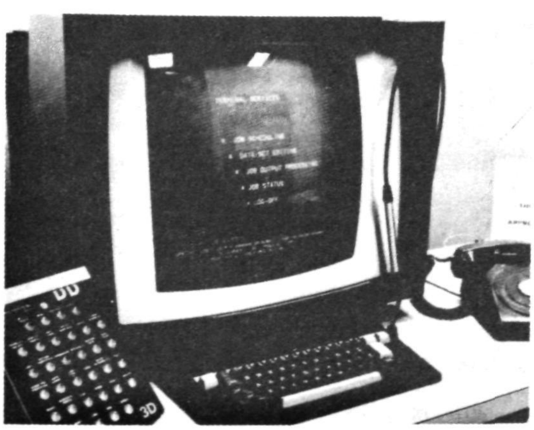

Fig. 24 CADD Console Arrangement

The console operator inputs information and orders to the computer, using the various input devices at the console. The output of the computer, which consists primarily of geometric entities, is displayed on the screen of the CRT. Some simple examples of functions which may be performed using the CADD system should illustrate the types of things that can be done.

For example, one of the ways in which an operator can generate a point is to hold the light pen in close proximity to the screen at the desired location and depress the function key labeled GENERATE POINTS. Figure 25 shows the function keyboard arrangement. A point will be generated and displayed in the vicinity of the location of the light pen tip. The position of the point, while mathematically precise, is only an approximation of the place or point where the light pen is held, however. If the designer wishes to generate a point at a mathematically precise location, he must depress the function key labeled POINT. A message (called a menu) will be displayed on the screen requesting the operator to input the desired 3-D coordinates of the point. With this accomplished using the alphanumeric keyboard, the computer generates and displays the point.

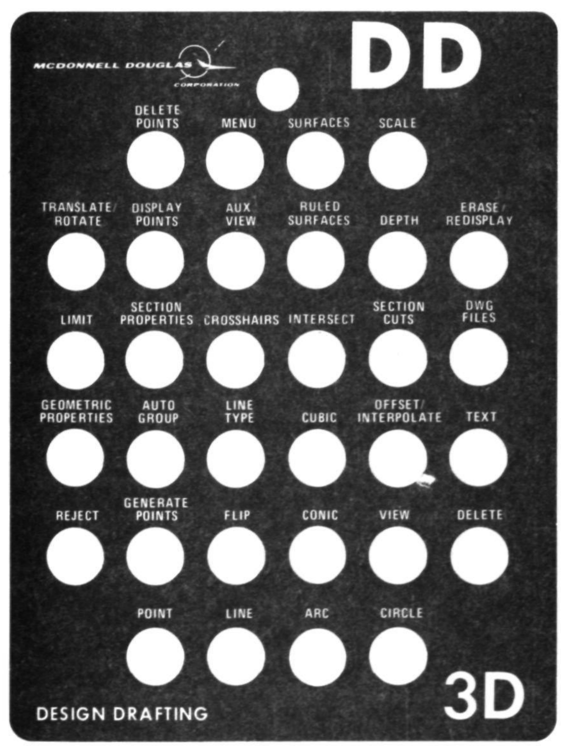

Fig. 25 CADD Function Keyboard Overlay

Although the light pen was used to indicate the approximate position of a point to be generated in the first example, its primary use is in detecting screen images of entities with which the operator wishes to work. Detection is accomplished by positioning the light pen over the image on the screen, then depressing its spring loaded tip against the screen. The light from the image registers on a photocell located within the pen and when detected, the image disappears, indicating that it has been detected. As soon as the operation on the detected element is completed, all detected entities are redisplayed, along with any new ones that have been created.

One way of generating a finite length line is for the operator to detect with the light pen two end points, having any x, y, z coordinates and depressing the function key labeled LINE. (Depression of a specific function key tells the computer what kind of entity it is to generate, i.e., line, circle, arc, etc.). The two detected points give the computer all of the information needed for it to generate the line. The result is a line between the two detected points. Should insufficient data be supplied to the computer for an entity generation, such as detecting one point with the light pen and depressing the function key labeled CIRCLE, a message will be displayed on the screen asking for a radius to be keyed in. Thus, the logic programmed into the system has been well planned in a natural engineering mode.

These examples illustrate how entities may be generated by using the function keyboard and the light pen (GENERATE POINTS and LINE) or the function keyboard and alphanumeric keyboard (POINT), but the more general case of generating geometric entities would utilize all the input devices in combination. For instance, to offset a line parallel to another line, the operator would detect the original line with the light pen and depress the LINE function key. The CRT would then display a menu requesting the distances from, and the side of, the detected line on which the parallel line is to be generated. When that information is supplied via the alphanumeric keyboard and the light pen, a parallel line is generated and displayed.

In addition to points and lines, our graphic system is capable of generating many other kinds of geometric elements. Separate function keys exist for POINT, GENERATE POINTS, LINE, ARC, CIRCLE, CONIC, ELLIPSE, SURFACES, and CUBIC entities, as shown in Fig. 25. Furthermore, since there are a number of different ways each element may be generated, virtually any figure can be defined by various combinations of the basic geometric elements.

The use of the computer in the design process has resulted in additional benefits and capabilities that enhance the basic attractiveness of the system. Admittedly, one of the chief attributes of computer graphics is its capability to geometrically define an object far more rapidly and accurately on the CRT, with the aid of the computer, than an engineer could on a drawing board. Once a computer is utilized and integrated into a graphic system, it lends itself well to a variety of tasks associated with generating, displaying, and manipulating geometric data. All of the geometric data displayed on the CRT are physical representations of what is modeled in the high speed core memory of the computer.

Once the computer has been programmed to deal with data in terms of a model, it is then possible for the computer to manipulate that model. Data manipulation functions such as SCALE (expand or contract the displayed drawing), FLIP (reflect a display about a line, i.e., mirror image), and TRANSLATE/ROTATE (translate and/or rotate a picture from one position to another) all make it easier for the console operator to work with the display. Beyond these, however, functions such as GEOMETRIC PROPERTIES (calculated geometric properties of selected figures), SECTION CUTS (display the cross-section of the displayed model when it is intersected by a plane), and VIEW (automatically view the displayed model from any desired vantage point) extend the utility of the system to a point where the computer is capable of accomplishing tasks easily which, if they were even possible on the drawing board, would normally be time consuming and often resulting in some degree of inaccuracy. This is one of the initial payoffs of computer graphics.

ADVANCED DESIGN: CONFIGURATION SYNTHESIS

The CADD system is effective as a design tool in Advanced Design. The aircraft configurationist is able to rapidly and accurately construct the vehicle, using time saving CADD capabilities such as the automated wing planform routine, the kinematics routine for defining the landing gear and controls spatial mechanism geometry, the vision plot routine for ascertaining the limits of the pilot's vision from the cockpit, the vision of the missile's seeker head when mounted as an external store, and the retrieval of engine and weapons geometry, previously created and stored in the computer files. This eliminates the need for recreating these common geometry data each time they are needed for a different vehicle configuration. The designer is also able to define the surfaced outline of the vehicle, the fuel tanks and other internal volumes. This provides him the capability to take section cuts of the vehicle to determine area distribution curves, fuel volumes, and other properties of the configuration that affect the vehicles's performance and mission adequacy.

The flow chart shown in Fig. 26 illustrates the sequence of events that occurs in advanced design activities. A more detailed description of these activities are discussed in the following paragraphs.

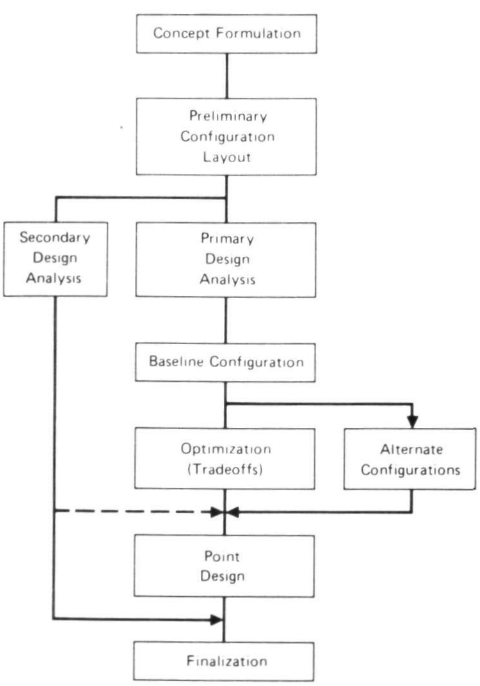

Fig. 26 Advanced Design Flow Chart

Concept Formulation

Concept formulation is the summation of all the vehicle study requirements and is comprised of such parameters as takeoff gross weight, thrust-to-weight ratio, wing loading, fineness ratio, fuel fraction, payload tradeoffs, general mission requirements, and specific ground rules. The ground rules are normally related to mission and customer specifications and generally pertain to equipment accessibility, materials to be used, design-to-cost requirements, takeoff and landing performance requirements, maintainability, reliability, etc. The other requirements noted are aerodynamic related parameters derived from statistical and theoretical data based on the projected technology of the study's time frame.

Preliminary Configuration Layout

The aircraft configurationist must graphically establish a moldline definition of the vehicle and locate the various system components and equipment. He must establish a large matrix of vehicles defined by many combinations of the vehicle component variations: high wing versus low wing, side versus bottom inlets, podded engines versus fuselage mounted engines, etc. This is normally time consuming and requires extensive analysis before an optimum configuration can be established. Figure 27 shows a few of the vehicle permutations configured and evaluated (without the use of CADD) in the process of establishing a final point design of the F-15 air superiority fighter.

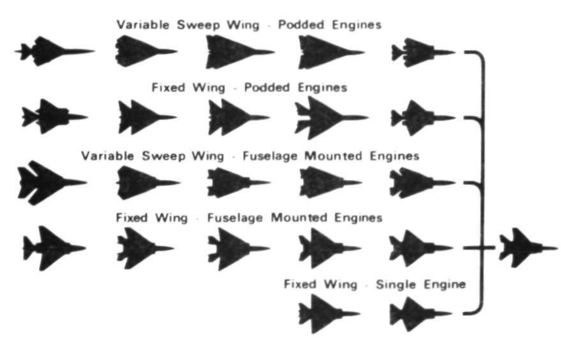

Fig. 27 Configuration Evolution
Studies and Tests

With the use of the CADD system in the configuration process, the time span for establishing the matrix of study vehicles has been reduced, resulting in an earlier decision on a final point design.

A typical sequence of design events, illustrated in Fig. 28, is discussed in the following paragraphs to show in more detail how CADD is currently being used in this process.

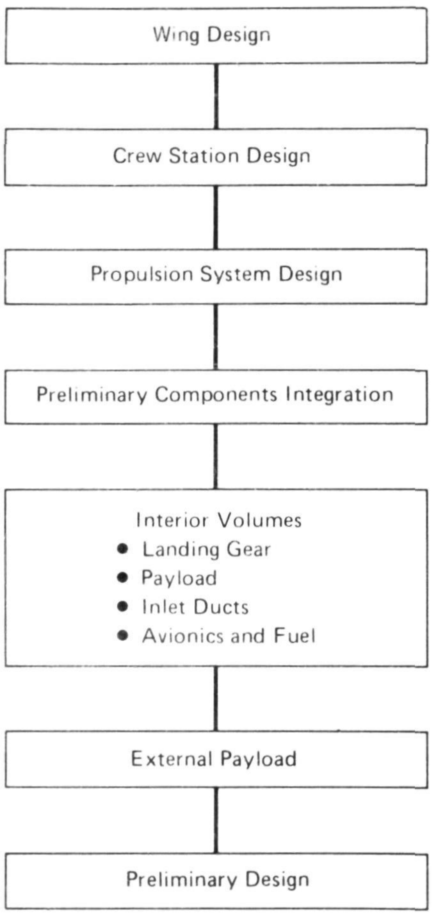

Fig. 28 Preliminary Configuration Layout Flow Chart

Wing Design

The optimization of a vehicle configuration requires that many different wings be considered and evaluated for performance adequacy. The study analysis, and test of various combinations of geometric considerations such as wing area, aspect ratio, leading edge sweep angle, taper ratio, and variations of wing twist, camber, and sweep are necessary to assure the best geometric and aerodynamic wing design is selected. For example, Fig. 29 shows but a few of the wing planforms considered for the F-15 Air Superiority Fighter.

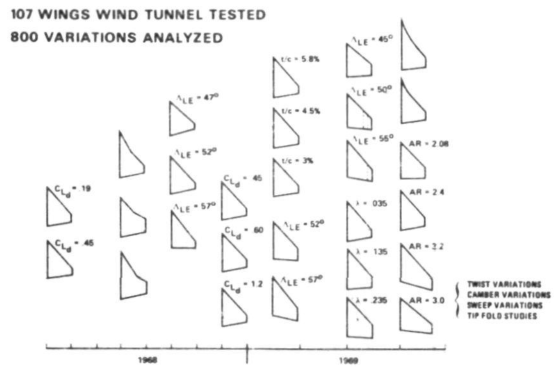

Fig. 29 Wing Development

Today, with the use of CADD, this design and selection process provides a compression of the study's time frame at less cost. To establish a wing planform, the designer needs only to light pen detect TAPERED WING from the menu displayed on the CRT, and type in values for wing area, aspect ratio, taper ratio, sweep angle, and apex origin. The wing planform, mean aerodynamic chord, and quarter chord are immediately created and displayed as shown in Fig. 30.

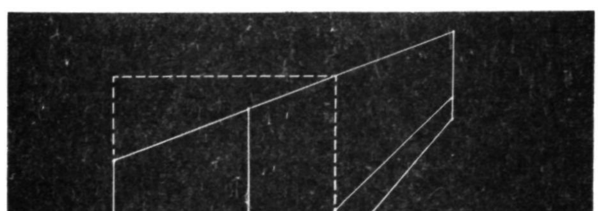

Fig. 30 Wing Layout

Different types of airfoils, previously created and stored in the computer, are available to the designer for merging with the wing planform to give it a three-dimensional definition in a wireframe form. After selecting the desired airfoil, he scales it to the proper chord lengths for the root and tip chords and translates them to their respective positions on the wing (Fig. 31). By detecting the two airfoils with the light pen and depressing the RULED SURFACE function key, the wing becomes fully surface-defined with a parametric ruled surface (PRS).

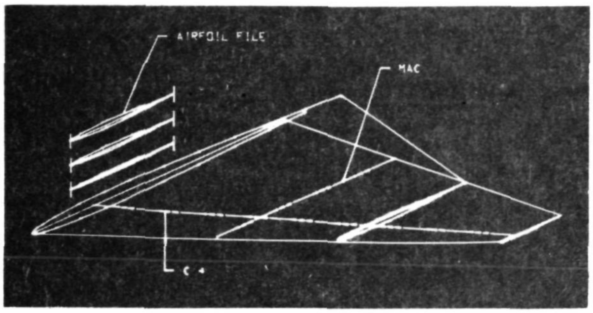

Fig. 31 Wing with Airfoils

Should he desire to define the wing with parametric cubic (PC) patches, he converts the airfoils to PC entities, light pen detects them, and depresses the SURFACE function key. Either of these routines provides the designer the capability to determine the volume of the wing, accomplished by light pen detecting the surface of the wing and depressing the GEOMETRIC PROPERTY function key. Internal volumes, such as fuel tanks, can be determined in the same manner, after defining the tanks with surfaces.

This automated and interactive routine allows the designer to consider many different wings in this phase of the design activities and assures him that he has adequately defined a wing that meets all design and performance requirements.

Crew Station Design

The cockpit layout is generally based on specifications, number of crew, method of crew egress, etc. The specification requirements include pilot vision limits, percentile man, instruments required, and cockpit clearance. The methods of egress could be with ejection seat or escape module, with the selection normally resulting from trade-offs between survivability requirements and minimum weight of the system.

By positioning the pilot's eye at the desired location, the designer is able to construct the canopy and establish the fore, aft, and over-the-side vision constraints as shown in Fig. 32. With this established, he can then construct the sill width, console width, and sidewall thickness. The forward fuselage can then be completed by constructing the fuselage half breadth line, the upper and lower moldline, several fuselage station cuts, then transforming the wireframe geometry into a fully surfaced definition in a manner similar to that previously discussed for the wing design.

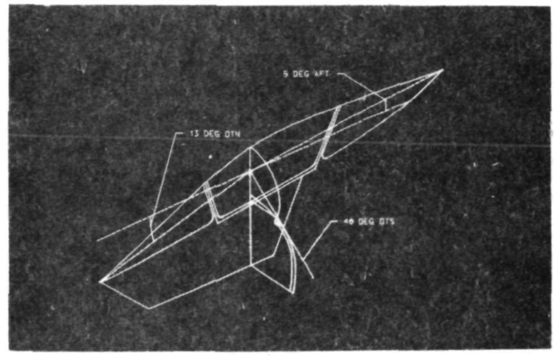

Fig. 32 Cockpit Layout

Systems and Structural Component Integration

The remainder of the fuselage structure and other structural and system components comprising the airplane are then constructed and integrated into a complete definition of the airframe. These components include the tail surface, inlet and propulsion system, landing gear system, fuel tanks, avionics bays, and weapons systems. The tail surfaces are constructed in the same manner used for constructing the wing. Figure 33 shows the wing and tail surfaces. For the propulsion system design, the designer must first size the engine based on aerodynamic inputs (T/W versus TOGW) using propulsion scaling curves as shown in Fig. 34. The base engine configuration, defined and stored in the computer, is retrieved from the computer files, displayed on the CRT, and translated to a position established by Weights department personnel in their preliminary balance of the vehicle. The inlet system is then constructed and merged with the engine as shown in Fig. 35.

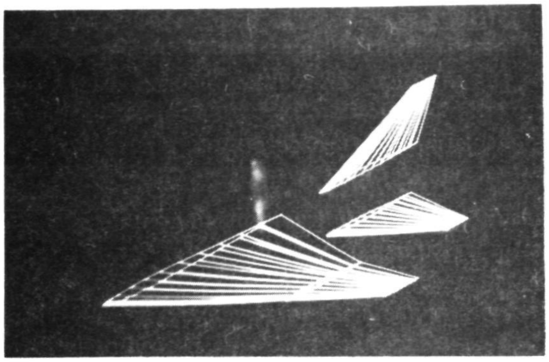

Fig. 33 Ruled Surface of Wing and Tails

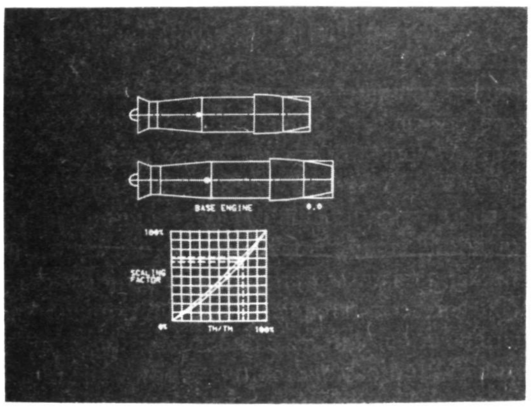

Fig. 34 Engine and Sizing Curves

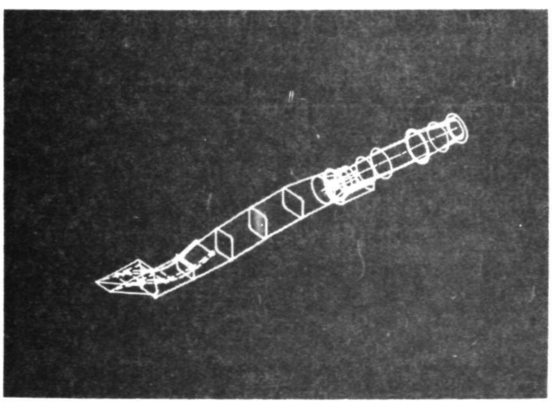

Fig. 35 Propulsion System

The kinematics routine in the CADD system is ideally suited for solving landing gear mechanism problems. The location of a skewed axis landing gear trunnion can be determined readily by establishing the extended and retracted positions of the landing gear wheel. In addition, the path of the gear during retraction is displayed in as many increments as desired, allowing the designer to determine landing gear door opening requirements and minimum clearances with aircraft structure and external stores in the landing gear retraction/extension cycle. It is also beneficial for solving spatial four bar linkage problems (Fig. 36) that are time consuming and fraught with tolerance errors when solved manually. This routine provides a graphic display of the positions of the driver, coupler, and driven bellcrank of a spatial mechanism with its intermediate positions displayed, thus providing the designer mechanical advantages and load/stroke data for the mechanism throughout its motion, merely by interrogating the computer.

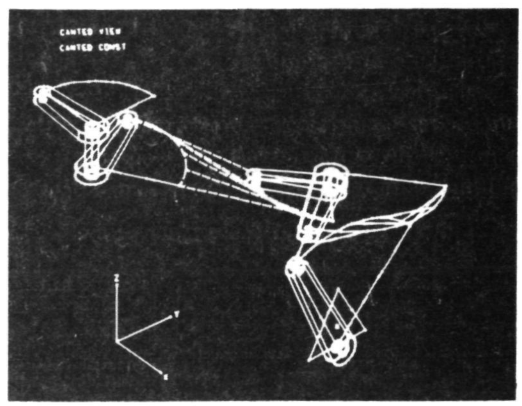

Fig. 36 Mechanisms

Several types of external and internal weapons are always considered when defining combat mission scenarios for military aircraft. In the past, it was necessary to trace or redraw the weapons at various locations on the wing and fuselage for each of the various tradeoff configurations, which was a time consuming and non-creative task. Currently, the designer can retrieve from the computer the weapons file (Fig. 37) that contains various military inventory weapon geometric descriptions, and merge the selected weapons with the vehicle description displayed on the CRT at any location he desires. Figure 38 shows a missile that has been placed at the airplane's wing tip. This capability saves countless hours of prosaic drafting that would be required if computers were not used.

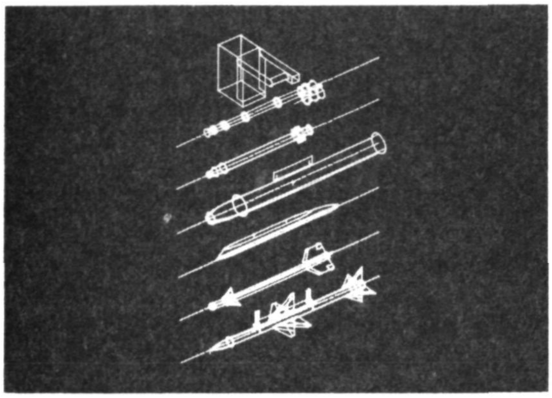

Fig. 37 Weapons File

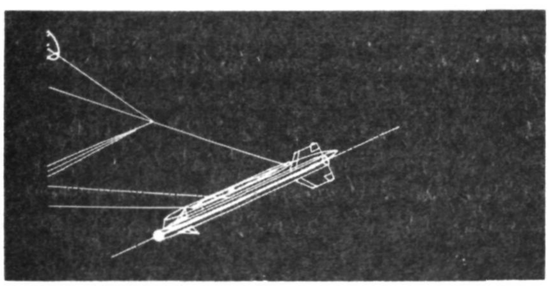

Fig. 38 Missile Placement

When the "preliminary design" (Fig. 39) configuration is completed, it is ready for aerodynamic analysis to determine if its mission and performance requirements can be met. If analysis shows that these requirements have not been met, ICADE may be used to size the vehicle and determine the sensitivity of the aircraft size to incremental changes in the various vehicle components.

With the rapid output of these data from the computer to the advanced design team, a more thorough evaluation of the study vehicle can be made, attributed largely to the increased number of design iterations possible in a given time frame, and due to increased visibility and recognition of convergence to the desired performance results.

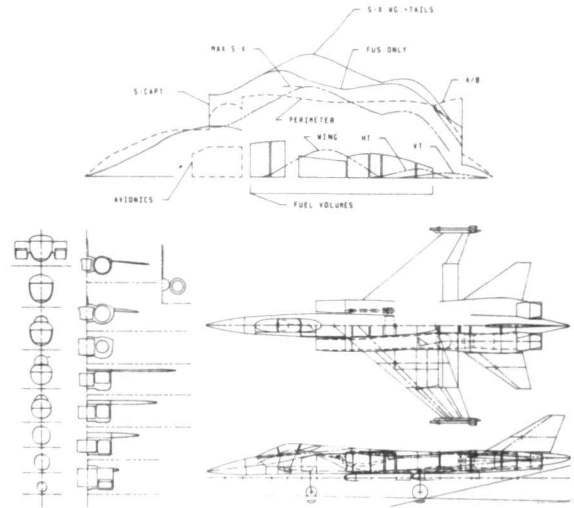

Fig. 39 Preliminary Configuration and Area Distribution

Wave Drag Analysis

The IBM 2250 graphics console has been adapted to provide the geometric input data deck for the NASA Wave Drag Program where these input data are coordinates of surface points, surface chordal lengths, surface thickness ratios, etc., for a particular aircraft configuration that has been created by the designer and filed in the computer. The CADD module is used to make section cuts through the surfaced configuration of the vehicle (Fig. 40) and to create boundary points on those section cuts (Fig. 41). The points are then connected with straight lines, labeled, and filed in the CADD drawing files (Fig. 42). The aerodynamics analyst then accesses the section-cut/point data from the CADD files and determines and stores x, y, z coordinates of the points on an on-line disk pack in a card image form (Fig. 43). In order to complete the procedure for obtaining the geometric input data deck for the NASA Wave Drag Program, it is necessary to utilize an auxiliary computer program on the IBM 360 computer to access the on-line disk pack geometric data, reorient them, and calculate the geometric data in the format required by the NASA Wave Drag Program. It should be noted that this data deck can also be used for the Subsonic Potential Flow Program, the Subsonic-Supersonic Linear Theory Program, and the

Supersonic-Hypersonic Arbitrary Body Program, all of which are active, analytical computer programs used at MCAIR. Figure 44 shows a schematic of the data flow for the NASA Wave Drag Program.

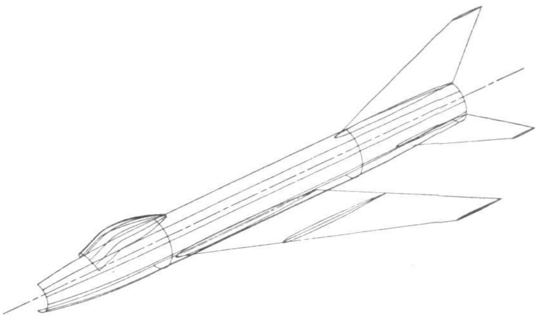

Fig. 40 Surfaced Vehicle Configuration

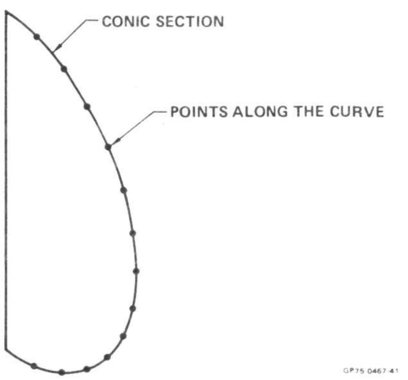

Fig. 41 Section Cut with Boundary Points

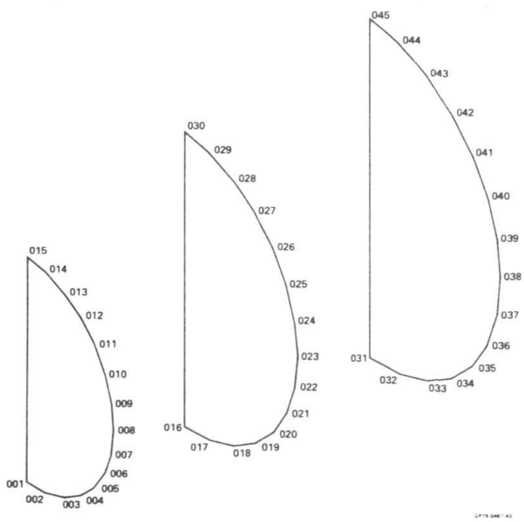

Fig. 42 Points Connected with Straight Lines and Labeled

POINT	X	Y	Z
10001	.00000	.00000	12.0000
10002	.00000	19.36246	6.40355
10003	1.39400	19.36246	6.52022
10004	2.75050	19.36246	6.86749
10005	4.02853	19.36246	7.43716
10006	5.19116	19.36246	8.21519
10007	6.20235	19.36246	9.18134
10008	7.02898	19.36246	10.3088
10009	7.64245	19.36246	11.5640
10010	8.02052	19.36246	12.9063
10011	8.15028	19.36246	14.3119
10012	8.03072	19.36246	15.7667
10013	7.67538	19.36246	17.1793
10014	7.09197	19.36246	18.5128
10015	6.29330	19.36246	19.7288
10016	5.29835	19.36246	20.7895
10017	4.13314	19.36246	21.6592
10018	2.83122	19.36246	22.3058
10019	1.43337	19.36246	22.7038
10020	.00000	19.36246	22.8366
10021	.00000	38.72492	3.57100
10022	2.29010	38.72492	3.76551
10023	4.51441	38.72492	4.34410
10024	6.60814	38.72492	5.29188
10025	8.50875	38.72492	6.58376
10026	10.15756	38.72492	8.18422
10027	11.50173	38.72492	10.0473
10028	12.49655	38.72492	12.1174
10029	13.10793	38.72492	14.3293
10030	13.31527	38.72492	16.6238
10031	13.11953	38.72492	18.9777
10032	12.53657	38.72492	21.2667
10033	11.57942	38.72492	23.4263
10034	10.27068	38.72492	25.3928
10035	8.64338	38.72492	27.1049
10036	6.74177	38.72492	28.5058
10037	4.62148	38.72492	29.5459
10038	2.34855	38.72492	30.1864
10039	.00000	38.72492	30.4024
10040	.00000	67.00000	1.44415
10041	2.98750	67.00000	1.68090
10042	5.90019	67.00000	2.38556
10043	8.66482	67.00000	3.54149
10044	11.21101	67.00000	5.12110
10045	13.47289	67.00000	7.08602

Fig. 43 Card Image Form of Point Coordinates

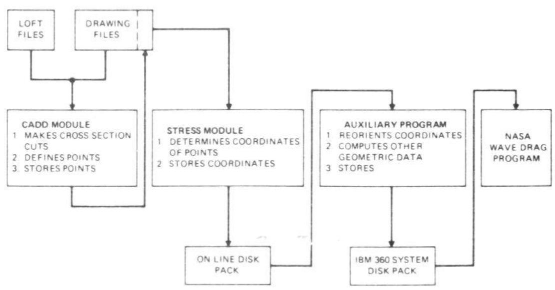

Fig. 44 Schematic of the Procedure for Obtaining the Data Deck for the NASA Wave Drag Program Using the IBM 2250 Graphics System

Field of Vision Plots

Investigation of the pilot's field of vision is a customer requirement. In the past, the results were illustrated on two-dimensional diagrams culminating from geometry data generated by conventional drawing board techniques. With the construct capabilities and the three-dimensional aspects of the CADD package, however, the vision limitation angles can be determined directly (Fig. 45). Geometric diagrams made on the CRT can then be merged with a standard vision plot format retrieved from the files in the computer (Fig. 46). Hardcopies of the completed vision plot can then be made for the final report.

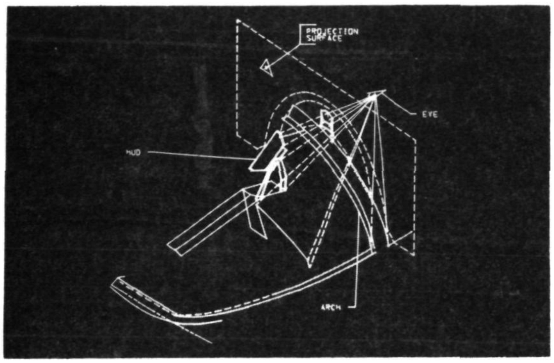

Fig. 45 Vision Plot Construction

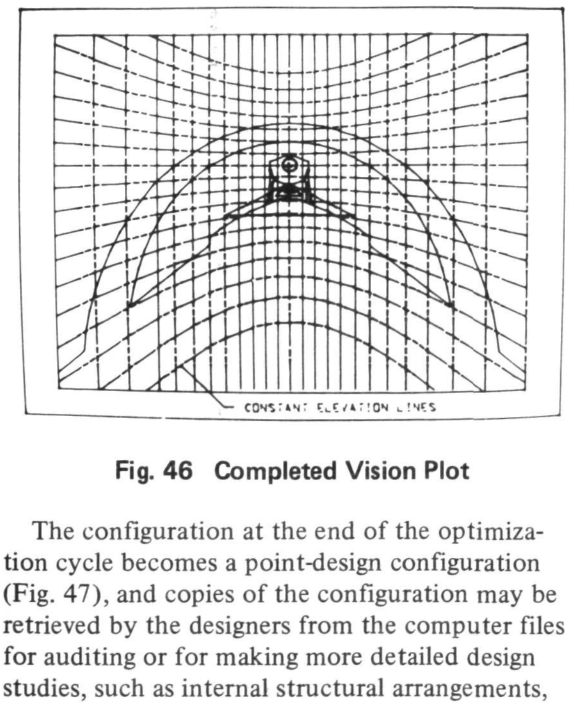

Fig. 46 Completed Vision Plot

The configuration at the end of the optimization cycle becomes a point-design configuration (Fig. 47), and copies of the configuration may be retrieved by the designers from the computer files for auditing or for making more detailed design studies, such as internal structural arrangements, landing gear mechanism geometry synthesis, field of vision variations, etc. The point designs are representative of established mission areas in the study matrices There are as many baseline designs generated and optimized as are practical to obtain a comprehensive cross section for point design selection. The baseline designs are investigations of tradeoffs of such things as variations of wing sweep and aspect ratio (Fig. 48), and fixed versus variable sweep wing geometry (Fig. 49).

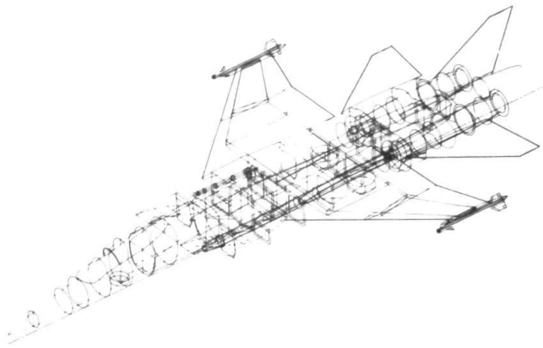

Fig. 47 Trimetric of Point Design Configuration

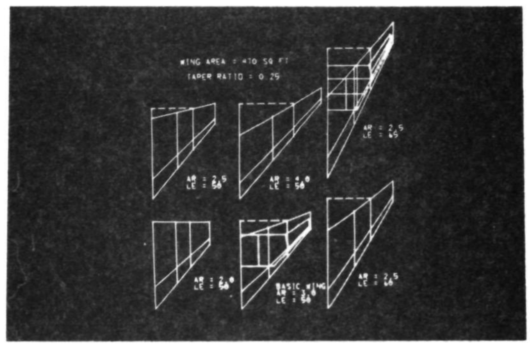

Fig. 48 Wing Geometry Tradeoff Study

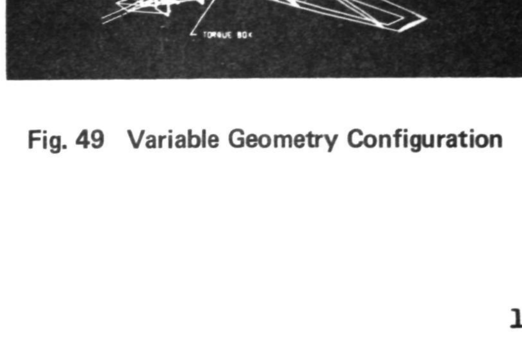

Fig. 49 Variable Geometry Configuration

Some points in a study matrix may be completely different design approaches to preclude the omission of any configuration possibility. In the end, the program manager must select the vehicle configuration that best meets the mission requirements stipulated by the customer and establish it as the "point design".

Design Aids

Design aid models can be made from layouts constructed on the CRT using the filed configuration, with the resultant drawings being transferred from the CADD system to paper by an automated plotter (Fig. 50). The paper patterns can then be glued to a material, such as plywood, cut out, and assembled (Fig. 51).

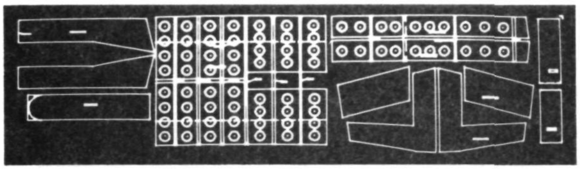

Fig. 50 Pattern Layout for Cockpit Design Aid

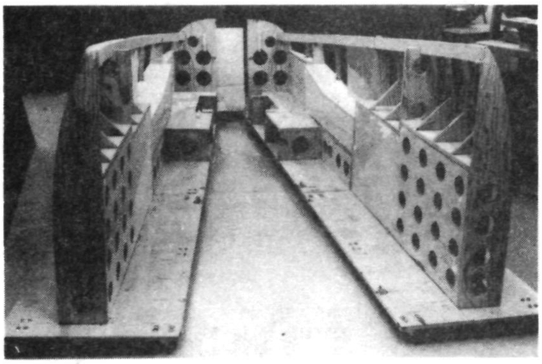

Fig. 51 Plywood Design Aid of Cockpit Area

PRODUCT DESIGN APPLICATIONS

When the designer has the desired lofted surface contour displayed on the CRT, he is ready to start the detailed design of his loft surface related part. For example, in the case of a fuselage-station cut at a bulkhead or frame location, the designer accesses the loft files, types in the pertinent loft surface identification information, and momentarily, the desired moldline contour of the fuselage-station cut is displayed on the CRT. He may then create a line, offset from the moldline contour, distance equivalent to the thickness of the fuselage sheet metal skin, resulting in having displayed a complete outside definition of the part to be designed. This saves hours of drafting time and eliminates the need for conventional splining techniques which often result in deviations from the desired part outline. After the periphery of the part has been displayed, a finite element model may be created by the strength engineer utilizing the CGSA module. Figure 52 shows a merged hardcopy of a typical fuselage bulkhead including a finite element model and its completed design configuration. This activity is accomplished after having coordinated with the designer during the layout of the part (either on the drawing board or at the console), thus establishing various design constraints that might dictate the locations of the major load paths.

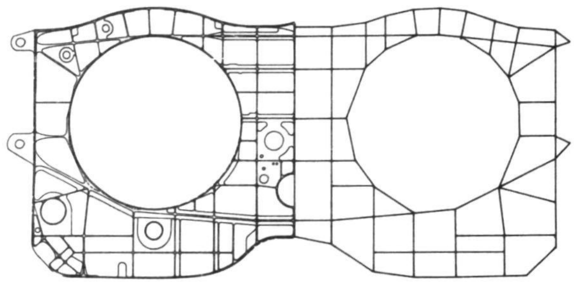

Fig. 52 Finite Element Model (Right) Merged with Final Design Configuration (Left) of a Typical Fuselage Bulkhead

Constraints such as holes and openings for engine ducts, lines for fuel, ECS, and hydraulics, and mounting provisions for various pieces of equipment that are to be installed are examples. After the load paths are established, the finite element model established, and the member loads and stresses displayed, the designer is ready to size the thicknesses of the flanges, caps, and webs of the part. With these items properly sized, he creates a three-dimensional wireframe model of the part, surfaces it with parametric ruled surfaces or parametric cubic patches, automatically creating unique labels for each surface, and takes appropriate section cuts of the part. Figure 53 shows a surfaced and labeled part. The labels are identifiers used for accessing specific portions of a model stored in the computer. This provides manufacturing planners a quick method of accessing data when they are creating the APT program for machining the part. Certain portions of these section cuts are then dimensioned, using the automated dimensioning routine, to aid in the final stress analysis of the part. This dimensioning routine, which creates and displays dimensions to areas of the part that have been light pen picked, eliminates the errors that might occur if the operator manually keyed-in the dimensions via the alpha-numeric keyboard. Even though certain section cuts have dimensional data displayed, a major portion of the geometry of the part will not have displayed dimensions, since the entire part is completely defined mathematically in the computer, providing all the numerical data necessary to machine the part using numerically controlled milling machines.

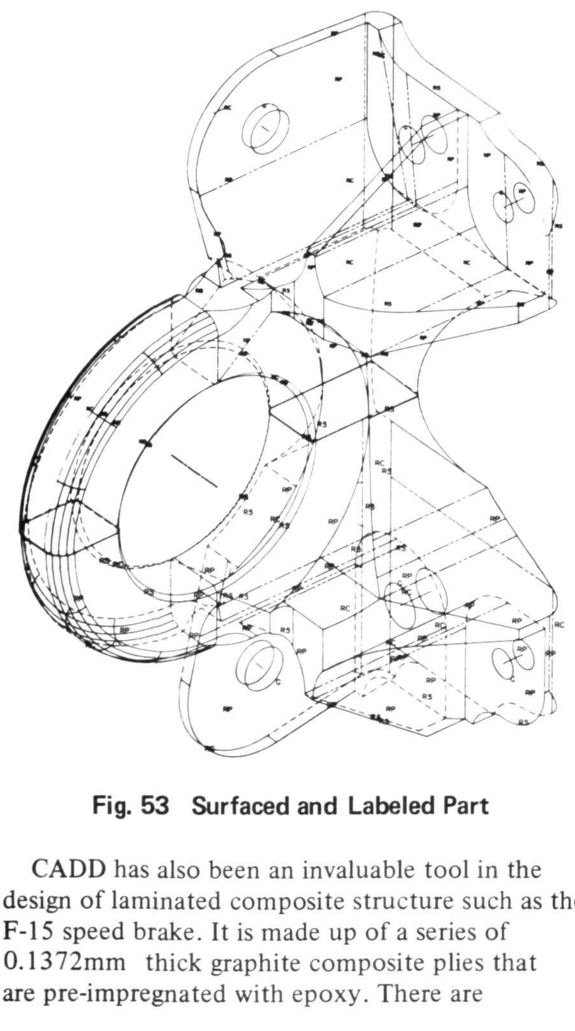

Fig. 53 Surfaced and Labeled Part

CADD has also been an invaluable tool in the design of laminated composite structure such as the F-15 speed brake. It is made up of a series of 0.1372mm thick graphite composite plies that are pre-impregnated with epoxy. There are seventy-six plies at one section of the speed brake, each of which is moldline related. In the past, it was necessary for the designer to describe each ply in the installed configuration, but he was unable to define the flat pattern dimensions required by manufacturing to cut out the plies from raw stock. Personnel from the Master Layout section of the Loft department would have to manually lay out each ply, which was costly and time consuming. With the Triangulated Flat Pattern routine in the CADD system, our designers now define the installed, curved configuration of each ply, then instruct the computer to unroll them into a flat pattern. In an instant the flat pattern of the ply is displayed on the CRT screen. Each of the flat patterned plies is then hardcopied at full scale and input to manufacturing as a template for cutting out the material. Thus, manual layout errors are eliminated and the design/fabricate cycle time is reduced. Figure 54 shows a typical example of a flat pattern that has been rolled out from its curved installation position.

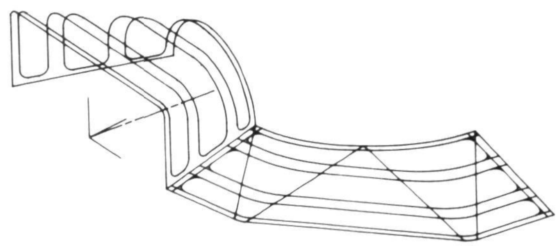

Fig. 54 Triangulated Flat Pattern

Conventional sheet metal parts are easily defined with CADD. By light pen detection, a CADD operator can input the contour and flange limits of the part. In turn the computer asks tutorial questions that may be answered by selecting menu items displayed on the CRT screen or by the alpha-numeric keyboard. The variables requiring answers are flange width, material thickness, flange bend radius, and rivet size and spacing. From these inputs, the program develops a completed flat pattern of the part showing joggles, developed flanges, rivet locations, bend angles, form block lines, and bend tangent lines. This routine compresses the design time required for sheet metal parts. Figure 55 shows a typical flat pattern sheet metal part designed with this routine.

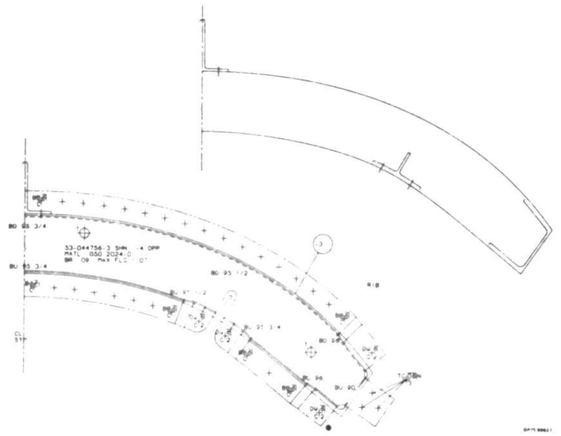

Fig. 55 CADD Sheet Metal Design

Many other types of design tasks are accomplished daily using the CADD system, including complex spatial kinematics synthesis problems, the routing of hydraulic and fuel lines, general equipment installations, determination of clearance problems of moving elements with respect to structure, and generally, any type of layout work conceivable. All of these tasks are accomplished faster and with more fidelity than was ever possible prior to the advent of interactive graphics.

Manufacturing

After parts have been designed utilizing the CADD and CGSA modules and released by engineering, manufacturing must concern themselves with the task of using the stored geometric data to provide computerized instructions for driving the N/C milling machines to cut the parts. These tasks are accomplished with the Graphical Numerical Control system, using the same type console used by design engineering to define the parts. Using GNC, Automatically Programmed Tool (APT) source statements are created for operating five-axis machines as well as a Direct Numerical Control (DNC) precision measuring and inspection machine.

In the production process, the program for the part to be machined is fed from the IBM 360-195 computer into an IBM 1800 process computer, which uses a high speed disk file for program storage and is capable of driving 10 DNC machine tools simultaneously. The machine tools are different configurations and can cut different parts at the same time.

On each DNC machine, there is a machine control unit made by Actron, a McDonnell Douglas subsidiary, to receive data from the 1800 computer. Each machine control unit has in it a mini-computer, a General Automation SPC 12. It is used for auxiliary functions to turn the spindle on and off, or to provide liquid coolant functions that are not contained in the program for the part.

Another significant benefit of this graphic system is for the design of part holding fixtures. The geometry of a part to be machined and the cutting tool path are displayed on the CRT and the locators, supports, and clamps are added. This simple procedure replaces the task of drawing the part and fixture on paper.

SUMMARY

The use of CADD, CGSA, GNC, CALL, CAQA, ICADE, and all of the other programs and systems comprising Computer Aided Technology at MCAIR, has effected many changes in traditional work methods of our various interfacing disciplines. We have streamlined our tasks by utilizing the various cost/time saving techniques afforded by these systems and plan additional development efforts which will further improve it. One might argue whether these activities are evolutionary or revolutionary, but in either case, it must be recognized that there is never an "optimum" method of operation in the design/manufacture cycle. We are never satisfied with the tools for accomplishing the required tasks and are always seeking improvements.

Our final objectives or goals cannot accurately be defined since they are in a constant state of change, but we are confident that the enhancements afforded by Computer Aided Technology will continue to provide increased productivity in the years to come.