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DECEMBER 1973 J. AIRCRAFT VOL. 10, NO. 12

Computer Aided Design-Drafting (CADD)—Engineering/Manufacturing Tool

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A description is given of a powerful computer-operated graphic system, used from design through manufacture at McDonnell Aircraft Company (MCAIR). This system has made designers many times more productive than when they are using conventional drawing board methods. High engineering productivity, however, is only an initial benefit. When fully developed, the system will allow Manufacturing to machine parts, utilizing the programmed data created by the designer at the console, without writing additional programmed instructions to drive the milling machines. In addition, Tool Design and Quality Assurance have direct access to the original three-dimensional geometric data, thus eliminating misinterpretation of design intentions. With lofted surfaces developed, defined mathematically, and stored in a shared-computer file, a designer is able to indicate the plane in which a lofted contour is desired, and in a matter of seconds, he can have the contour displayed on the CRT. This enables the designer to create a design almost as fast as he can think. Further, his designs are defined mathematically at a degree of accuracy never before known. Other disciplines which interface with design are strength, aerodynamics, thermodynamics, and propulsion. With continued use and development of this system, even greater time and cost-saving techniques will be realized.

Introduction

ANY business firm, and especially a company oriented to the aerospace industry, must continually seek methods for improving its varied functions if it is to retain its competitive position. Such improvements are normally measured in terms of reduced costs, reduced manhours, reduced lead time, and better products.

The design of an aerospace vehicle, by necessity, is dictated by the many parametric requirements of each of the systems and technical disciplines comprising the total design effort. In order that each discipline may be properly interfaced with the other disciplines, and the integrity of the vehicle performance and specification requirements maintained, very close intergroup coordination is required. During any program, several design iterations to system components are usually required as the result of loads analyses, weight and balance requirements, aerodynamic considerations, and other design ramifications. As a result of these necessary design iterations, there is often some degree of difficulty encountered in effecting a smooth and orderly response to the required realignment of the specific designs to meet the new requirements. Reaction time by all affected parties must be coordinated closely so that the major milestones are not jeopardized. Although many design changes are minor in nature, some can be very complex. Changes of this type can be extremely disruptive and require that every available technique, talent, and design tool at our disposal be directed toward a common goal of producing the necessary changes on a timely basis to assure a good design on schedule. Computer Aided Design-Drafting, or CADD (pronounced caddy) as it is commonly called at MCAIR, is a tool that we are presently using to help us meet that goal.

The term, CADD, denotes various computer techniques and applications where data are either presented or accepted by a computer in the form of line drawings or graphs, as opposed to alphanumerics only. CADD is "interactive," which implies that there is an efficient and 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 geo-

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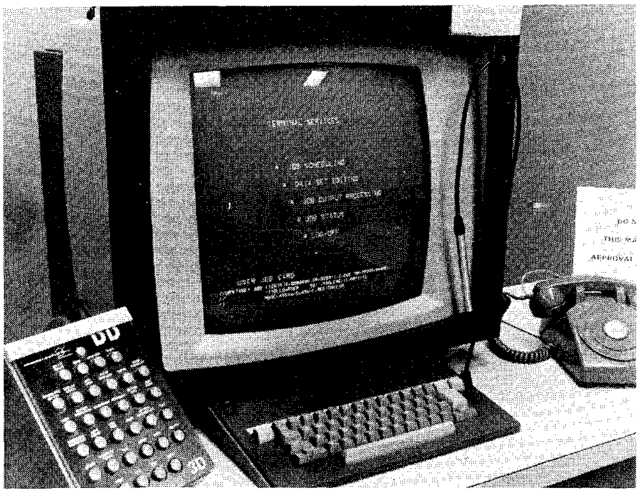

Fig. 1 CADD console arrangement.

metric representation of a physical object. In the drawing board mode, these are lines on paper or mylar. This representation, when the CADD package is used, is in terms of an exact mathematical description in the computer's memory. In addition, the graphic representation is displayed on the cathode ray tube (CRT). Hardware and software system features enable the operator to converse with the computer by detecting, with a light pen, elements displayed on the CRT screen. 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 language and by methods with which he is familiar and comfortable (in terms of graphics and numerics) rather than by having to become a programmer and deal with punched cards and printed listings. The CADD system enables the engineer and computer to function in concert as a problem-solving team. The significance of the team effect is that each member is free to do that for which he is best suited. The computer can perform the more routine and repetitive tasks, while the engineer, being freed from these tasks, can focus all of his creative talents on the solution to the problem. This environment greatly enhances the creative potential of the design engineer.

A CADD console was first used for direct support of the F-15 project in July 1970. It was utilized for the purpose of synthesizing the three-dimensional spatial geometry and path of travel of the main landing gear mechanism to assure that the required precision of motion was obtained. There are now nine consoles at MCAIR, four of which are being used by Engineering. The other five are being used by Loft, Tool Design, Master Layout, Quality Assurance, Manufacturing Planning, and CADD Development.

MCAIR has approximately 155 trained CADD operators from varied technical disciplines, with more scheduled to be trained in the future as the need arises.

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 mold line, the ability to access lofted surface definitions of various aircraft on the CRT has been extremely important to the designer. With the lofted surface definitions immediately 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.

The sophistication of present-day aircraft systems and components requires a different design philosophy from those used in the past. One-piece sculptured bulkheads, composite structures, and complex weight-saving techniques can cause serious problems when design changes occur, unless the design team is system-oriented and recognizes the need to respond to the team needs in effecting the necessary design changes in a coordinated manner. We have experienced major design changes of this type and have learned to cope with them by recognizing them as such, and by responding with the necessary emphasis, manpower, and design tools, such as CADD, to accomplish these changes.

System Description

MCAIR's CADD software package utilizes a user-oriented programming language that was specifically tailored for the types of problems typically encountered in a design-engineering environment. It was developed to allow a designer to utilize the speed and accuracy of a large digital computer to assist in producing engineering drawings. The output from the computer, which consists of geometric figures and information relating to them, is displayed visually on a CRT. The engineer can interact with the computer on the basis of what he sees displayed on the CRT by the computer. In effect, he has replaced his drawing board with the display console. Because of the immediate-feedback aspect of the designer's visual relationship with a computer, CADD is not only dynamic, but also interactive.

Each CADD console is remotely connected to and used in conjunction with an IBM 360 Model 195 computer. Each console consists of a display CRT, a typewriterlike alphanumeric keyboard for typing-in dimensional data or special instructions to the computer, a 32-button functional keyboard for ordering the creation or manipulation of geometric data (points, lines, arcs, conics, cubics, etc.) on the CRT, an electronic light pen for detecting specific displayed data to be operated-on, a closure hood with a Polaroid camera for quick-reference pictures, and a "hotline" telephone to the computer operator. Figure 1 shows a typical CADD console arrangement.

How it Works

The operator inputs information and orders to the computer by using the light pen, function keyboard, or alphanumeric keyboard. The output of the computer, which consists primarily of geometric figures, is displayed on the screen of the CRT. Some simple examples of functions which may be performed using the CADD package 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 on the screen at the desired location and then press the key labeled GENERATE POINTS. A point will be generated and displayed in the vicinity of the tip of the light pen. The position of the point is only an approximation of the place or point where the light pen is held, however. If the designer wishes to generate a mathematically precise point, he needs to press the function key labeled POINT. The computer will then display a message (called a menu) on the screen, requesting the engineer to input the desired 3D coordinates of the point. After the engineer keys in the desired coordinates by means of the alphanumeric keyboard, the computer generates and displays the point.

Although the light pen was used to indicate the position of a point to be generated in the first example, its main use is in "detecting" screen images of entities with which the designer wishes to work. Detection is accomplished by positioning the light pen over the image on the screen, and then depressing its springloaded tip against the screen. The light from the image registers on a photocell and when detected, it disappears, indicating that it has been detected. As soon as a function is completed, all detected elements are redisplayed, along with the new element.

One way of generating a line is for the operator to detect with the light pen two end points for the line and depress 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 that a line between the two detected points is generated and displayed.

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 the alphanumeric keyboard (POINT), but the general case for generating geometric entities would utilize many of the elements of CADD 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 on the function keyboard. The CRT would then display a menu requesting the distance 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 the points and lines discussed in the preceding examples, the CADD package is capable of generating many other kinds of geometric elements. Separate function keys exist for POINT, GENERATE POINTS, LINE, ARC, CIRCLE, CONIC, ELLIPSE, and CUBIC entities, as shown in Fig. 2. Furthermore, since there are a number of different ways with which to generate each element, virtually any figure can be defined by various combinations of the basic geometric elements.

The use of a computer in the design process has resulted in additional benefits and capabilities that enhance the basic attractiveness of the system. Admittedly, the chief attribute of CADD is its capability to "draw" a picture far more rapidly and accurately on the tube, with the aid of the computer, than an engineer could on a drawing board. Once a computer is utilized and integrated into a graphics system, it lends itself very well to a variety of tasks not strictly associated with generating and displaying geometric data. It is essentially the same mechanism which is responsible for the capability of the computer to generate and display data that allows it to also manipulate these data. All of the geometric data displayed on the CRT are a physical representation of what is "modeled" with 10^{-12} mathematical precision in the highspeed core memory of the computer.

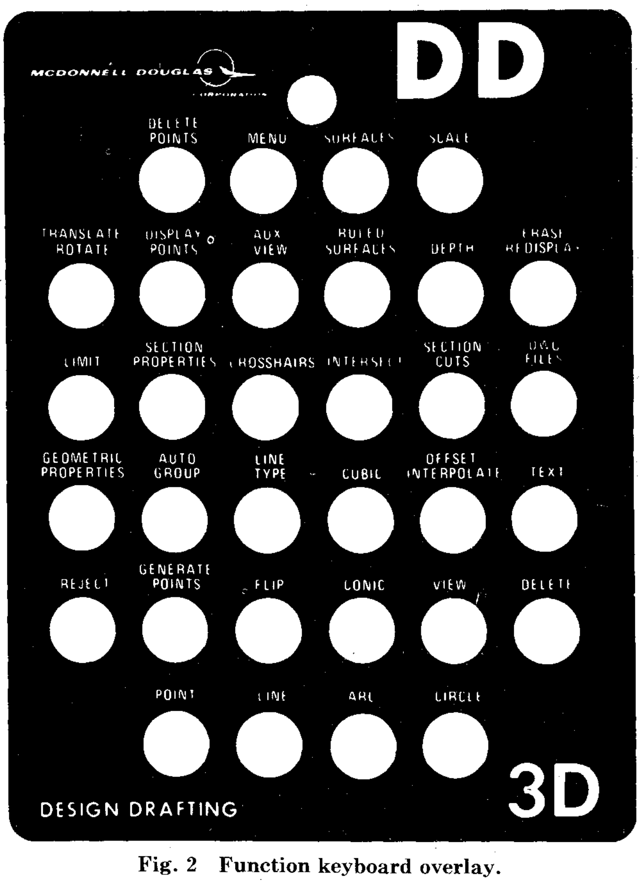

Fig. 2 Function keyboard overlay.

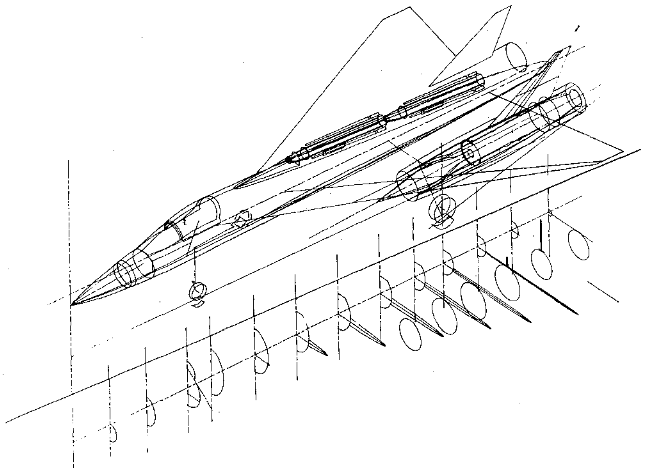

Fig. 3 Three-dimension view of an advanced aircraft configuration produced by CADD.

The "model" is a programming term that refers to the computer's memory matrix which stores the information pertaining to the display necessary for the computer to mathematically define the displayed picture. 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), and TRANSLATE/ROTATE (translate and/or rotate a picture) all make it easier for the operator to work with the display. Beyond these, however, functions such as TRIMETRIC VIEW (automatically view the display in perspective), GEOMETRIC PROPERTIES (calculated geometric properties of selected figures), and SECTION CUTS 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 drafting board, would normally be very time-consuming. This is one of the initial payoffs of CADD.

Advanced Design: Where It All Starts

The final configuration of an aircraft is generally the culmination of a multitude of design iterations requiring the inputs of many technical disciplines. The use of CADD in this activity greatly enhances the orderly interface and integration of the various technical requirements, and in turn, provides the visibility and perspective of the vehicle. With a configuration defined mathematically in three dimensions, the console operator may view it from any vantage point merely by rotating the display to the desired position, as shown in Fig. 3.

Parametric wing studies are facilitated by utilizing an automated wing planform program that gives an immediate planview display of the wing after values for aspect ratio, taper ratio, sweep angle, wing area, and location of the wing apex are typed in. This planform, coupled with one of many preprogrammed and filed airfoil sections, results in an immediate three-dimensionally defined wing which may be examined perspectively from any view. Fuel volumes can then be quickly determined by light-pen de-

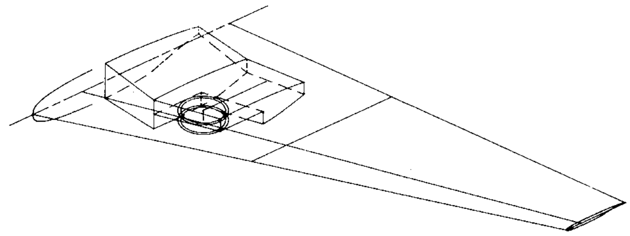

Fig. 4 Typical wing fuel volume configuration.

tecting the appropriate cross-sectional areas, depressing the function key labeled SECTION PROPERTIES for area readouts, and integrating them into a final volume plot on the CRT screen. Wing designs can be optimized with this method much more quickly and accurately than was previously possible. Figure 4 shows a typical wing fuel volume configuration.

Another advanced design application is that of making vision-blockage studies. A pilot's vision, a missile seeker head's "vision," or a transmitting/receiving antenna's "vision" are limited by certain portions of the aircraft structure and external stores. With CADD, an engineer may "position" himself relative to a displayed aircraft configuration at any three-dimensional coordinate he desires, view and cut the vehicle with a cutting plane in any azimuth and elevation, and read out the blockage angle. After all desired blockage angles are determined, an Aitoff's polar vision plot may be drawn to show the degree of vision blockage in all directions from the point of origin.

CADD has also been used effectively in studies of infrared signature, aerodynamic drag, and cockpit arrangements.

Definition of Lofted Surfaces

Once an authority to proceed has been given for the design of a new vehicle, the Loft Department mathematically defines the entire external surface of the aircraft and stores the data in a shared-computer file, making the data immediately accessible to the designer at the console. In the past, if a designer needed accurate loft data upon which to base his design of an aircraft structure or mechanism, he had to send a request to the Loft Department where the request was interpreted, the contours developed, and a hard copy sent back to him. The average turnaround time was two weeks; the absolute minimum in a rush situation was two days.

Today, the designer sits at a CADD console in his work area and defines the plane in which he wants a contour. The system directly accesses the lofted surface files in the computer, intersects the pertinent loft surfaces with the defined plane, and displays the resultant contour, all in a matter of seconds, even if the plane is double-canted. Moreover, it is displayed and either immediately recognized as the contour he wants, or is rejected without undue loss of time. Whenever the desired contour is needed again, it will be exactly the same, without degradation of accuracy. When he desires a hard copy of his displayed drawing, the engineer keys in the required information concerning the drawing size, desired scale, drawing material, and other special instructions relating to the drawing format. The Loft Department then loads these data into their computer-driven Orthomat plotter, and in minutes an accurate drawing is made exactly to the specifications provided by the designer at the console The drawing is then delivered to the designer the following morning. In a rush situation, the drawing can be made available the same day. Figure 5 shows several nested fuselage contour segments of the F-4 aircraft that have been accessed from the Loft files.

When the designer has the desired lofted surface contour displayed, he is ready to start the detailed design of his part. For example, in the case of a fuselage-station cut at a bulkhead or frame location, the designer displays the moldline contour at the desired fuselage station, types in the skin thickness dimension, and almost immediately has a new contour displayed defining the outside edge of the part to be designed. This saves countless hours of tedious drafting time and eliminates the need of conventional splining techniques. After the edge of the part has been displayed and the structural model and internal load paths are established, the thicknesses of the bulkhead flanges, caps, and webs may be determined and the part analyzed for adequate strength. When the part definition is finalized, it is stored in the computer files, making it

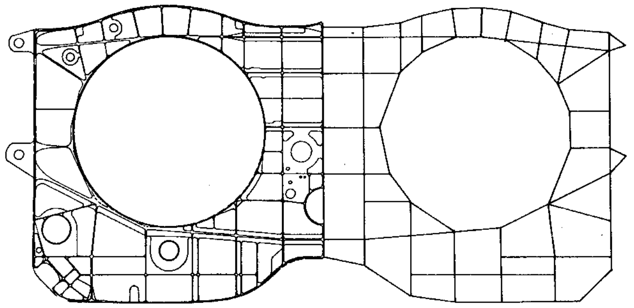

Fig. 6 Finite element model (right) merged with final design configuration (left) of a typical fuselage bulkhead.

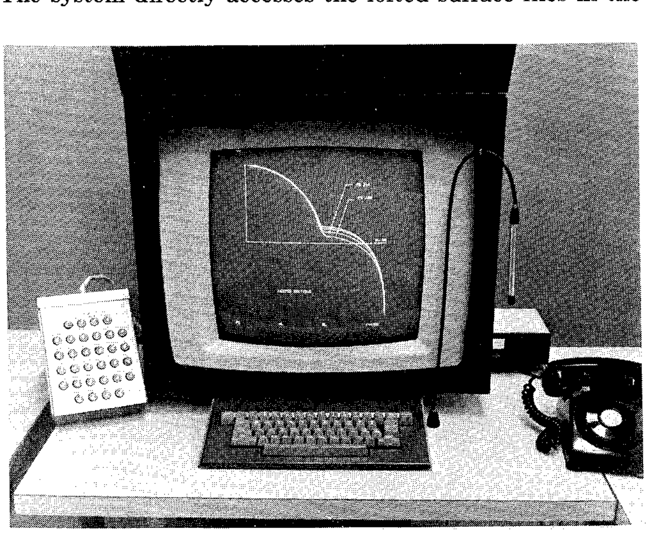

Fig. 5 CADD display of nested fuselage contour segments.

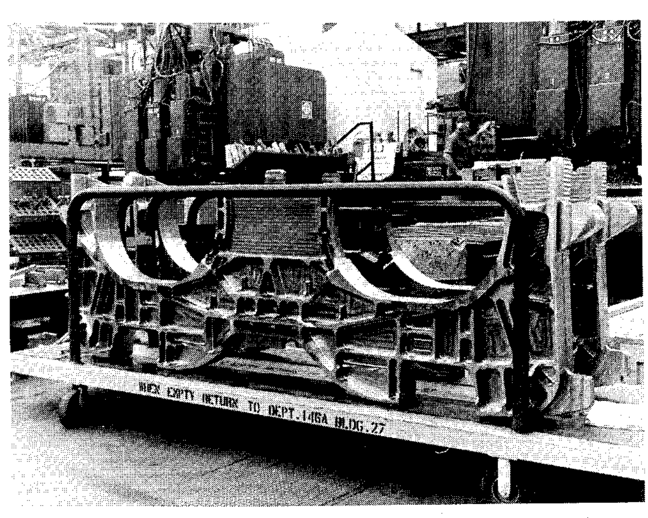

Fig. 7 F-15 titanium bulkhead rough-machined using a CADD/NC interfacing system.

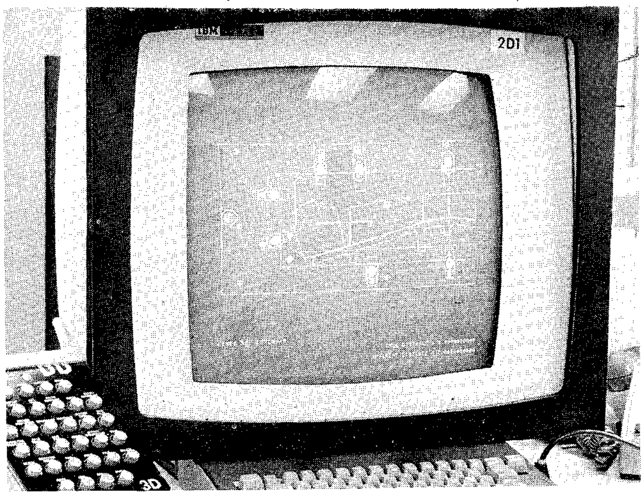

Fig. 8 CADD display of holding fixture required for part machining.

immediately available to Tool Design, Manufacturing Planning, or Master Layout personnel to start the manufacturing sequence. In addition, the designer may retrieve the stored drawing from the computer files for making modifications or for merging a detail part into an assembly. Figure 6 shows a merged hard copy of a typical fuselage bulkhead including a finite element model of the part and its final design configuration.

Manufacturing Cycle

The production planner may call-up the designed part by part number, display it on the CRT, and with his light pen, develop instructions for the numerical control machine indicating the size, speed, and travel path of the machine cutter necessary for producing the part.

The computer automatically post-processes these data into the language of the numerical control machine tool and stores them on the disc of one of our IBM 1800 data acquisition and control computers. The 1800 accesses the data and communicates them to the machine which produces the part. This eliminates magnetic and punched tapes and gives us a total system whereby the designer defines the part, the production planner tells the machine the cutter path to follow to make it, and the numerical control machine cuts the part, all working in conjunction with the computers. A by-product is a program deck output that allows single operation statements to be subsequently changed to meet revised manufacturing require-

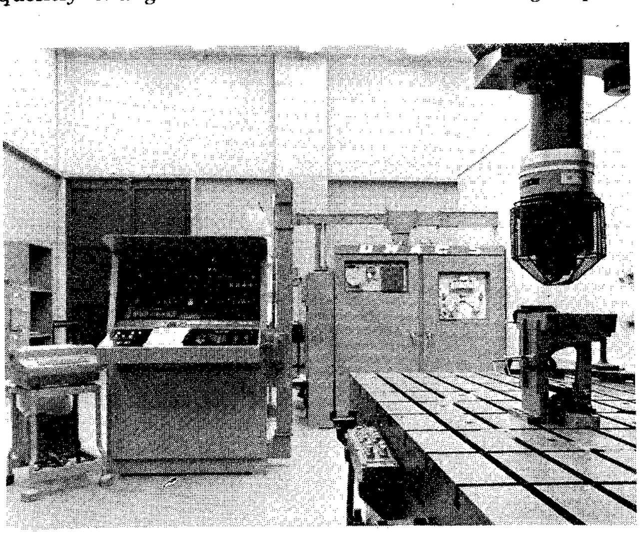

Fig. 9 Lucas numerical control measuring machine.

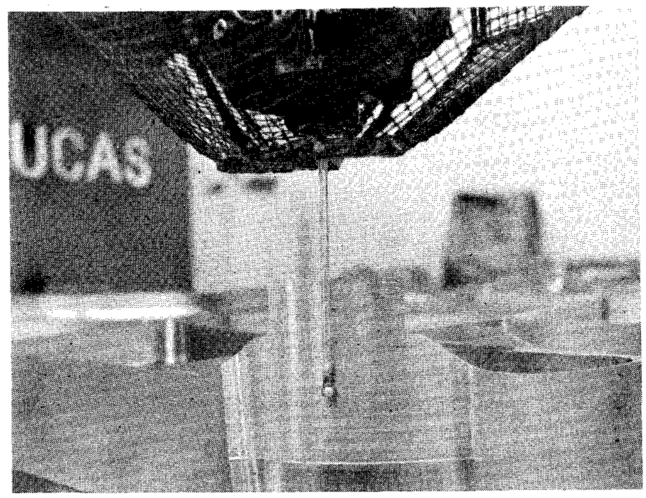

Fig. 10 Lucas inspection probe measuring a bulkhead flange.

ments. Figure 7 shows an F-15 titanium bulkhead that has been rough-machined by this process.

Tool Design

Before a part can be actually machined, hold-down fixtures or jigs must be designed, planned, and constructed. The tool designer calls up a display of the part to be machined, by part number, and can immediately start his hold-down fixture design activity. By displaying the entire outer portion of the part to be machined, he is able to accurately locate standard hold-down clamps, or design new ones and locate them very rapidly. Should new clamps be needed, a numerical control programmer will display the details of the clamp and issue instructions to the computer for the cutter size, speed, and path of travel necessary for producing the part. This computerized method of tool designing has greatly reduced the number of manhours required for tasks and has compressed the time span for overall tasks by approximately 50%. Figure 8 depicts a typical tool design task accomplished with CADD.

Quality Assurance

When first-article inspection of a machined part is required, Quality Assurance creates a punched tape, programmed to drive a Lucas Numerical Control Measuring Machine depicted in Fig. 9. This punched tape is generated by the console operator's calling up a CRT display of the part to be inspected, and he in turn creates inspection points on the surface representation of the part. These points, mathematically defined by the computer and coded in the tape, may then be compared with surface locations of the actual part. The tape drives an inspection probe, shown in Fig. 10, to each of the inspection points until contact with 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 teletype machine. This eliminates many hours of inspection set-up time and the human error that can result from more conventional inspection methods.

For inspection of subsequent parts after first-article inspection, a Film Inspection Apply Template (FIAT) is used which is made of a clear polyester plastic (Mylar) sheet 7.5 mils thick. When a FIAT is required, a console operator in the Loft Department will callup an engineering drawing, display it on the CRT, and input a request to the computer for a scribe-coat hard copy; when the hard copy is complete, a photo-sensitive sheet of Mylar is overlaid on the hard copy, exposed, and run through a development processor. Within a matter of minutes, an inspection template made of a 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 immediately detectable.

Future Development

The use of CADD has effected many changes in traditional work methods of the various interfacing disciplines at MCAIR. We have streamlined our tasks by utilizing the cost/time saving techniques presently afforded by this system, and plan to continue additional development efforts which will further improve it. As we discover more and more practical applications for CADD, new or modified software routines will be formulated to make the system as responsive and reliable as possible. Since the potential for substantial dollar savings exists, particularly in the area of manufacturing, we are consciously attempting to align our techniques to make engineering data as usable as possible by manufacturing personnel in its existing form, thus eliminating as many intermediate manual processes as possible. Our final objectives, however, cannot now be defined. CADD's utility will increase as we continue to conceive new ideas for its application. Its ultimate benefits can only be determined by the limits of our creative imagination.

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Rapid Scanning, Three-Dimensional Hot-Wire Anemometer Surveys of Wing-Tip Vortices

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A rapid-rotation arm traversing mechanism with a three-wire, hot-wire anemometer at the tip was developed for surveying trailing vortices whose paths were distorted over long distances by wind-tunnel turbulence. Measurements were obtained behind two geometrically similar rectangular wings up to 31 span lengths in the Ames 40- by 80-Foot Wind Tunnel. Peak tangential velocities normalized by free-stream velocity and lift coefficient decreased from 0.8 at the trailing edge to 0.6 at 31 span lengths downstream while the circulation within the core remained constant. Measured tangential velocity distributions had the same functional form as that determined by Hoffmann and Joubert.

Nomenclature

A,B,C,D,E	= experimentally determined coefficients of Eqs. (4) to (6)
b	= wing span
c	= wing chord
C_L	= lift coefficient
r	= radial coordinate from vortex center
R_e	= Reynolds number based on c, V_∞
r_0	= outer radius where $\Gamma = 0.99\Gamma_0$
u	= velocity
V_∞	= wind-tunnel mainstream velocity
x	= streamwise ordinate aft from trailing edge
α	= angle of attack, deg
Γ	= circulation around a contour of radius r
Γ_0	= value of circulation shed from one side of wing = $(1/2)C_L V_\infty c$

Subscripts

1	= radius where u_θ is a maximum
max	= maximum value
x	= axial component parallel to vortex axis
θ	= tangential component

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Introduction

THERE has been considerable interest in wing-tip trailing vortices from large aircraft because of their danger to smaller following aircraft in the vicinity of airports. Studies that have used wind tunnels have been limited by the relatively short test-section length available since axial distances greater than about 3-span lengths cannot be achieved with a reasonable model scale. The authors have reported previously on the velocity distributions in the wake of a rectangular wing and a CV-990 aircraft model[1,2] at axial distances up to 1.7- and 2.2-span lengths, respectively. Similar measurements have been reported by Mason and Marchman,[3] and Poppleton.[4] El-Ramly[5] has recently compiled a comprehensive survey of the subject.

All previous measurements of velocity distributions in trailing vortices which have been made in wind tunnels were conducted with fixed probes. Generally, the investigators found that trailing vortices were not stationary and that the amplitude of the disturbance increased with distance downstream of the trailing edge. Probes were fixed at a single position, and time mean average values of ve-