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CADAM® Data Handling from Conceptual Design through Product Support

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The use of interactive computer graphics for data handling in aircraft design, manufacturing, and product support is discussed. The software used is the Lockheed-California Company Computer-graphics Augmented Design and Manufacturing (CADAM®) system and the Independent Research and Development program CADATA. Starting with the conceptual design three view on CADAM, configuration geometry is then available through CADATA for use by the analytic users for developing the design to achieve the desired performance and cost. CADAM provides a common data base of the selected vehicle design for all user disciplines: preliminary design, loft, production design, tool design, numerical control part programming, quality control, and product support. Examples of the use of CADAM and CADATA are given to illustrate the cost savings and reduced time spans achieved.

Introduction

THE requirement for ever increasing performance in vehicle design leads to increased complexity and costs. One way to reduce costs, reduce man-hours, and shorten the time span in design, manufacturing, and product support is through the use of interactive computer graphics.

The development of interactive graphics technology at the Lockheed-California Company began in early 1965. By March 1966, an initial software program for engineering design applications had been developed and made operational at the company. This program ultimately evolved into the Lockheed-California Company Computer-graphics Augmented Design and Manufacturing (CADAM®) system.

The computer-aided design portion of this system is a high-function general purpose design drafting package containing a number of embedded analytical and configurational design aides. The functional architecture of the design/drafting portion of the system is based on classical descriptive geometry. CADAM is a set of computer programs that comprise both interactive on-line functions and batch operations, which together permit the construction of geometry for drawing production, certain steps of design analysis, and data base management. Numerical control tapes are also produced with the system.

Using a refresh-type graphic display terminal, a wide range of desired functional options may be done by using the combinations of a light pen, an alphanumeric keyboard, a functional keyboard, or a free cursor (digitizer input). Figure 1 shows a typical CADAM terminal. Geometry (namely, data other than text or alphanumerics) information developed by the user is stored in the computer in the form of mathematical models that may be concatenated. All input data (text, alphanumerical, and geometrical) are retrievable via the graphics display terminal for various uses in the system.

Output is obtainable in various hardcopy forms including that obtained from plotters, computer output microfilm, numerical control (NC) tapes, and various types of printed reports, lists, etc. Figure 2 shows an Orthomat *X-Y* plotter producing a finished drawing with ink on mylar.

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Lockheed's efforts in computer-aided design and computer-aided manufacturing have culminated in the utilization of the CADAM system for advanced design, production design, manufacturing, and product support. CADAM was used for the loft development of the L-1011 TriStar, the S-3A Viking, and the lofting for a number of research and development aerospace vehicles. More than half of the total NC production parts for the TriStar and the Viking aircraft were produced with CADAM.

More than half the configuration designs produced in the Commercial and Military Advanced Design departments use CADAM. They include subsonic, supersonic, and hypersonic transports, military V/STOL, and advanced structural concepts. Production design is also heavily involved in the use of CADAM for structural design, interior arrangements, and galley design.

The Lockheed-California Company now has over 90 CADAM scopes operating from four main frame computers. They are located in at least six buildings, usually near the users. The scopes include IBM 2250's, IBM 3250's, Adages, and Vector Generals.

The Lockheed-Georgia Company and the Lockheed Missiles and Space Company also use CADAM. The structural design layouts and production drawings for the stretched C-141B Starlifter were produced at the scope for a big saving in man-hours, time span, and dollars.

The rapid growth and wide application of CADAM has been made possible because the system was designed with the user's point of view being of paramount importance. However, programming efficiency and maintainability have not been sacrificed in meeting the objectives of the user. Another important consideration in the creation of the CADAM system was the ability to interface with non-CADAM programs and data bases.

A major feature of the CADAM system is its common data base and data management system for various user disciplines. As an integral part of the CADAM system, Lockheed has developed data base and file management software especially designed to handle geometric data (both two dimensional and quasi-three dimensional), the requirements of which differ from data base or file management systems intended for use only with alphanumeric data.

In 1975, Lockheed made CADAM available for licensing,[1] and more recently IBM has offered the system for licensing. Among the 50 companies using CADAM are Beech, General Dynamics, Grumman, Martin-Marietta, Northrop, Augusta of Italy, Aerospatiale, and Dassault of France, Fuji and

Mitsubishi of Japan, and Messerschmitt-Boelkow-Blohm of Germany.

The Lockheed-California Company is continually updating and improving CADAM. In addition, they are adding other computer graphics software programs, developed under Independent Research and Development (IRAD), to enhance the use of CADAM and its data base in the process of designing and manufacturing new aerospace vehicles. These include SURFACE DESIGN, NETWORKS, and KINEMATICS. NETWORKS includes MESH, interactive vortex lattice (VORLAX) modeling, NASTRAN OUTPUT DISPLAY, and CADATA.

The paper will discuss the many uses and applications of CADAM and the benefits derived by generating and using a common data base.

Conceptual Design

The conceptual design phase must evaluate configuration alternatives to determine the best aircraft to perform the required mission. The designer creates a large matrix of vehicles that considers many combinations of aircraft components. These include wing planform, located high or low on the fuselage, number of engines, podded or fuselage mounted, type of inlets and location, payload arrangement, etc. The designer must make layouts of a number of these to determine which configurations to pursue.

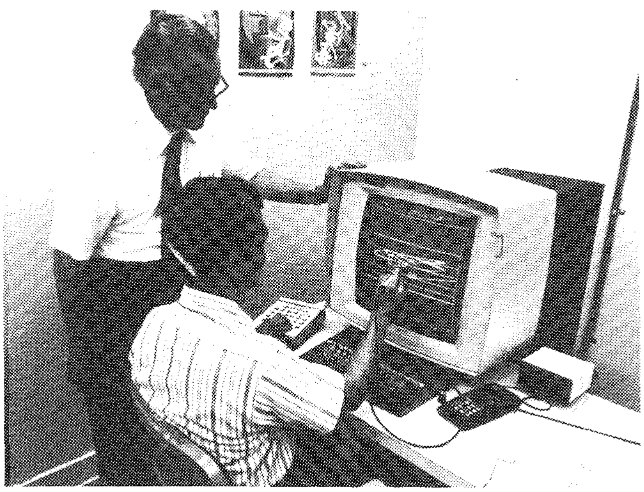

Fig. 1 CADAM terminal.

The conceptual design phase provides the opportunity to start a CADAM data base that will grow and benefit each succeeding phase of the program. The designer requires the same information to start the configuration at the cathode ray tube (CRT) terminal that he would use on the drawing board. These include wing planform, inlet type, wing, tail, engine, inlet, payload, and cockpit size, etc. The designer using CADAM has the advantage that once components are drawn and filed in the computer, they can be called up, combined in different arrangements, and filed each under a new drawing number. This can be done very quickly as compared to tracing the components on the board. Using the CADAM function TRANSLATE, the designer can move a wing, engine, or tail in seconds.

When the initial configuration is completed, it goes to the Advanced Systems Synthesis and Evaluation Technique (ASSET) program to determine its ability to meet the desired performance and cost. ASSET iterates the configuration to size it for the mission requirements and to obtain a preselected result, such as minimum direct operating cost (DOC), minimum gross weight, or maximum range. ASSET is a batch program that has modules for determining weight, drag, performance,[2] noise, and cost to do the required mission, given the configuration and installed engine performance.

CADATA, an IRAD program nearing completion, permits the designer to extract configuration geometry from the CADAM general arrangement drawing while sitting at the terminal. An accompanying batch program will draw off this aircraft geometry data base and insert it in ASSET and other analytic computer programs. The designer uses the light pen to select a line or two points; the computer recording the length of the fuselage, a wing chord, etc. Data which does not appear as geometry on the screen, such as gross weight, thrust, aspect ratio, etc., are entered on the alphanumeric keyboard. Figure 3 shows the CADATA output tables on the CRT.

Upon completion of the ASSET runs, the designer revises the CADAM drawing, working from a computer printout. If the wing requires resizing, it is accomplished by using the CADAM function TRANSLATE. The square root of the ratio of the new wing area to the existing area is entered on the keyboard and, in seconds, the wing is resized including flaps, spoilers, and leading edge devices. All other changes are as

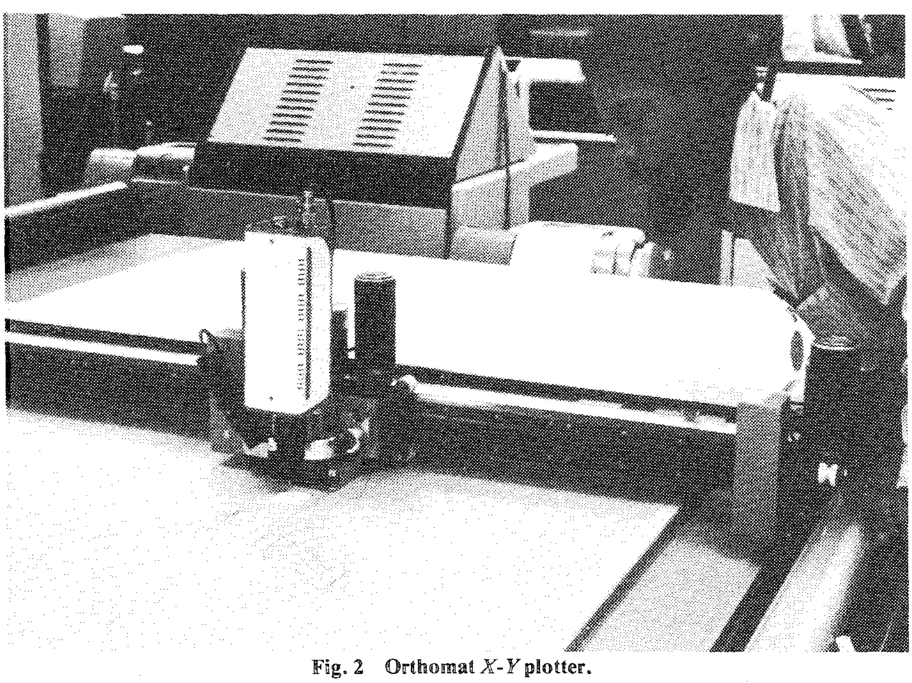

Fig. 2 Orthomat X-Y plotter.

easily accomplished, and while this would take from several days to a week on the drawing board, it takes only one to six hours on CADAM. Figure 4 is a three view of a Supersonic Cruise Vehicle for a NASA study which was drawn on CADAM.

As the configuration develops, designers can start developing the structural arrangement, propulsion installation, landing gear, subsystem requirements, etc. Having the configuration in the computer means that each designer can call up the same picture and data base, give CADAM a new drawing identity, and proceed with his design problem without spending a lot of time tracing as on the board.

An IRAD program which has improved the productivity of CADAM immensely is SURFACE DESIGN. This program permits the development of a surface or surfaces or the complete contours of the vehicle in three dimensions.

SURFACE DESIGN requires the designer to specify to the computer through the CRT which CADAM lines will be part of the surface and how they are connected. This may take from a few minutes to an hour or two depending on the model size, but once this is complete, there is no limit to the surface information that can be obtained.

The program generates cross-sectional cuts of fuselage stations, buttock lines (BL), water lines (WL), or canted cuts by the designer simply keying in the station, BL, WL, or z value. The cut is displayed on the scope in less than 15 seconds, while on the board it might take half a day or longer to develop. The designer may generate any required view or rotate the vehicle in pitch, roll, and yaw interactively, again in less than 15 seconds. Figure 5 shows a SURFACE DESIGN model being rotated at the terminal. Under development is the capability to measure wetted areas, volumes, and determine the *x,y*, and *z* values of a line piercing the surface.

Where a mass of geometric data has been calculated in a computer program, it is unnecessary for the designer to key this data into CADAM point by point sitting at the terminal. A NETWORKS interface exists that allows a computer analysis program data to be converted into a CADAM element model and stored in a specified CADAM file and model number. An example is the NASA Twist and Camber program combined with the airfoil shape for a supersonic wing. There are 48 points with *x, y,* and *z* values per wing section and 12 or more sections. The points appear in the CADAM model where they can be connected using the function key SPLINE. They can easily be converted to SURFACE DESIGN if desired.

In addition to CADATA, SURFACE DESIGN, and the addition of data points from a batch program, the aerodynamicist, propulsion engineer, weight engineer, and structures engineer have other software programs that interface with CADAM. These include the NETWORKS programs, MESH and VORLAX modeling. MESH is an interactive finite element modeling program interfacing with CADAM and SURFACE DESIGN. MESH permits the generation, modification, and display of a finite element model at the terminal using the CADAM geometry data base. This data can be used as the input data for NASTRAN. Figure 6 shows a finite element model as displayed on the screen. VORLAX model generation is also possible using the CADAM geometry and is used by loads and aerodynamics.

An area progression program is also available that permits the designer to extract cross-sectional areas at the terminal that are tabulated with a display of the area progression curve. These data are used by the aerodynamicist in the NASA Wave Drag program.

A KINEMATICS program has been developing for several years. This program permits the designer to use the CADAM geometry of a mechanism to determine the path followed, the velocity, the acceleration of each link, and the load in each link at each position. The program, when complete, will aid in the design of control systems, landing gears, and door mechanisms.

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 MACH NO =2.200       WTANK2   =.900
 ALT     =59000.000  FVFB
 CREW    =12.000     VFB
 PASS    =234.000                              PROPULSN
 PAYLOAD =49000.000                        * EL       =180.883
 FUEL    =96286.000                          ED       =63.635
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*S-H     =287.200    *S-V      =191.500
 AR-H    =10.000      AR-V     =10.000      XINLET   =1500.000
 TR-H    =10.000      TR-V     =10.000      LINLET   =132.683
 SWPL-H  =56.640      SWPL-V   =70.201      SWETIN   =19439.523
 SWPQ-H  =56.640      SWPQ-V   =66.109     *SCAPT    =2827.400
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TOC-H                TOC-V                 SPWET
 X-H     =192.015    *X-V      =200.611    VPOD
 Y-H     =91.475     *Y-V      =140.000    TOCPOD
 XCP-H   =319.990    *XCP-V    =300.552     PFB      =132.683
*SEXP-H  =185.860    *SEXP-V   =191.500    *PAB      =180.883
SWET-H               SWET-V                *SCAPT    =2827.400
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Fig. 3 CADATA output tables.

With the conceptual design general arrangement in CADAM, an accurate description of the contours exist for building wind tunnel models and wood mockups. Full-size templates can be made on mylar or metal using an *X-Y* plotter. NC tapes can be produced for some machining and a program is well along which will produce an NC tape using CADAM and SURFACE DESIGN to machine the complete wind tunnel model. The configuration data base in the computer also permits the wind tunnel model designer to use CADAM to make layouts and detail drawings without a lot of tracing or redrawing.

Preliminary Design

The preliminary design phase will take the configuration selected in the conceptual design phase and design it in sufficient detail to determine that it can be built for the weight, cost, and performance required to make it a successful project. This will require design layouts of many areas that were only superficially examined in the earlier phase. With the

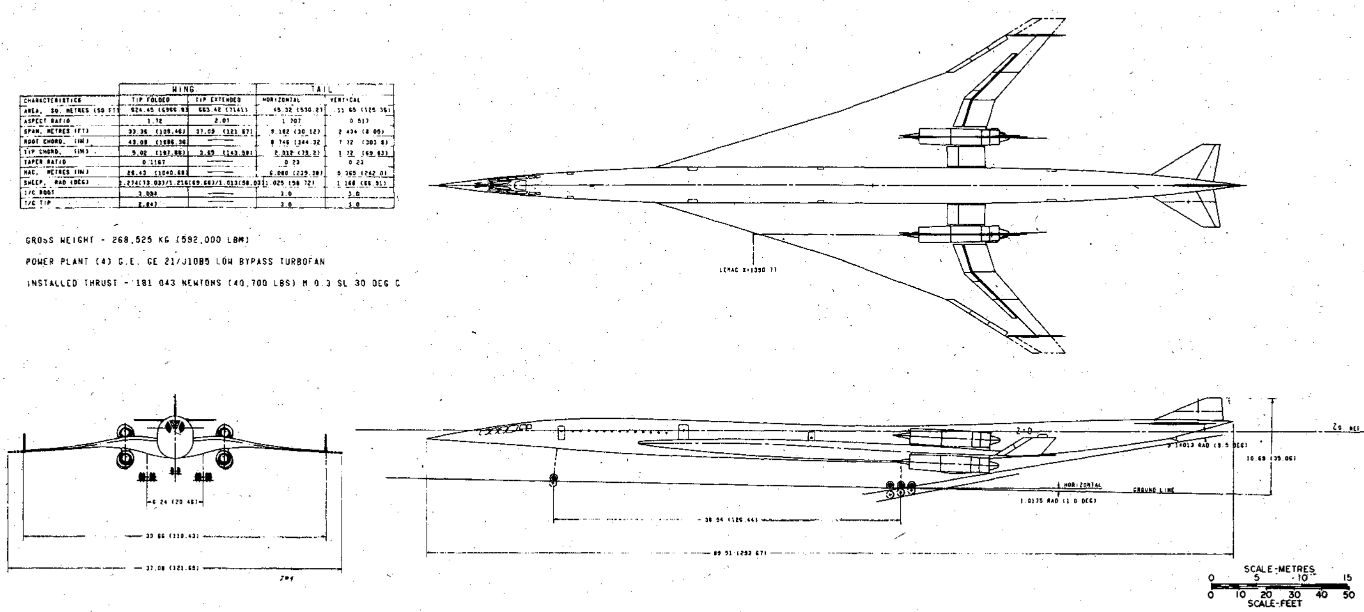

Fig. 4 NASA supersonic cruise vehicle CADAM drawing.

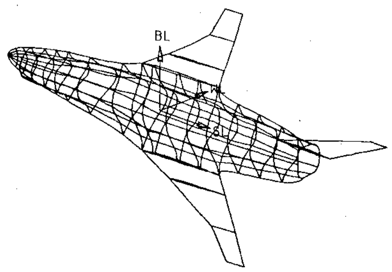

Fig. 5 SURFACE DESIGN model being rotated at the terminal.

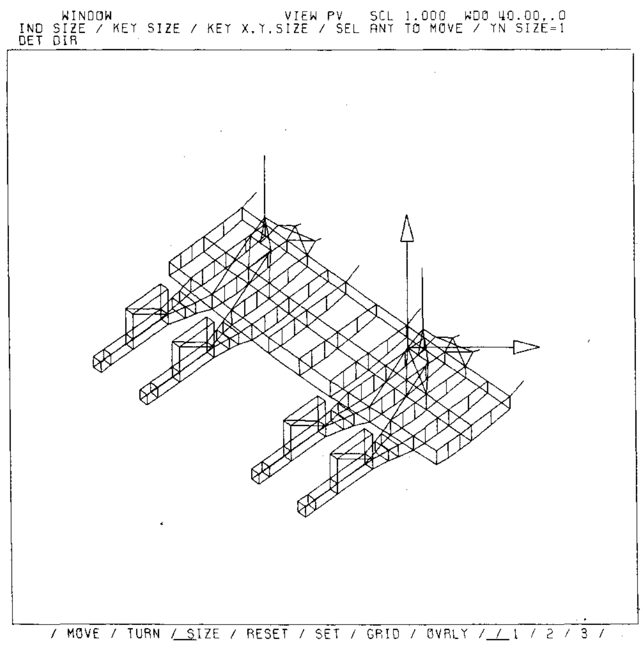

Fig. 6 Finite element model of a Navy V/STOL wing box, engine nacelle, and landing gear.

conceptual design phase in the CADAM file, the preliminary design engineer has an accurate geometric data base of the selected configuration.

Starting with the general arrangement, inboard profile, structural arrangement, propulsion installation, landing gear, and any subsystems on the terminal, designers can begin to refine the design and add more detail. Each major component of the aircraft can be separated from the rest of the drawing in the computer by the CADAM functions TRAP and TRANSFER, by designers working at the terminal. The CADAM wing geometry, for example, can be used to create a basic dimensions drawing and a wing structural arrangement drawing. Utilizing the contours already developed on the scope, the wing surfaces, the front and rear beams, typical wing ribs, the landing gear support structure, if located in the wing, and the wing tank arrangement can be designed on the scope using CADAM.

The weight engineer can obtain more accurate volumes from the CADAM analysis function, and the structures engineer can develop a more refined finite element model using MESH and the more detailed preliminary design drawings. All of the structure and subsystems can be developed in preliminary design in the same manner.

An extremely useful function of CADAM is DETAIL. It permits drawing one component on the scope, filing it as a detail, and then using it as often as required by merely selecting points on the scope. This function is particularly adapted to interior arrangements on both military and commercial aircraft. With the many payloads to be arranged efficiently in limited space and within tight center-of-gravity limits, CADAM and DETAIL become an important tool. For example, for the cabin arrangement on a commercial transport, first class and economy seats, lavatories, galleys, serving carts, and coat closets can be filed in a standard library. They can then be called up quickly to try many combinations. Because only one of any unit has to be drawn on CADAM, more detail can be added without any additional time; for instance, all the seats can have arm rests and backs; if done on the board, seats will probably be represented as rectangles because of the time required to draw each individual seat. Figure 7 shows a NASA Energy Efficient Engine Study 400 passenger seating arrangement drawn on CADAM.

When the preliminary design phase starts, the loft group develops the final contours for the complete aircraft. They begin with the conceptual design contours developed by the designers at the terminal. They do the complete loft on the scope using CADAM and SURFACE DESIGN. The designers obtain their loft data at the terminal instead of receiving inked contours on mylar.

The aerodynamics, propulsion, and structures departments, as well as other specialists continue the analysis of the design and evaluate alternate solutions. They will use all of the interface programs already mentioned in the conceptual design phase.

At the completion of the preliminary design phase, the aircraft configuration is well defined with drawings of the structure and subsystems in CADAM files stored in the computer. These drawings coupled with the interface data and analysis developed by the analytic groups provide a massive data base describing the geometry and design of the aircraft.

Production Engineering

Production engineering must provide the shop with complete information to fabricate and assemble the aircraft. This requires a vast number of pictures and dimensional data. With the computer's capability to remember and CADAM's ability to call up quickly any drawing in its data base, add information or remove it, file it as a new number and revise it, designers can turn out a vast number of drawings very quickly.

The preliminary design CADAM drawing file becomes the foundation for the production design phase. Wing designers will use the typical wing rib drawings already in the file as a guide. Rib details which are typical at many locations will be designed at the terminal and filed as CADAM details in the standard library. These include wing surface stiffener attachment to the ribs, spar cap design, rib attachment to the spars, rib web cutouts, and rib web stiffeners.

The designer starts a rib layout using the rib loft moldline contour already in the file. The designer uses the CADAM function OFFSET to draw lines parallel to the moldline and the thickness of the rib flange. Using CADAM function POINT-SPACE, points are spaced on the upper and lower surface of the wing at the location of each stiffener. Selecting the function DETAIL, the designer selects the typical upper surface stiffener with its rib attachment. Each time a stiffener point on the surface is touched, CADAM draws the complete detail at that point. The designer does the same on the lower surface, adds spar caps, spar web attachments, continuing until the rib layout is completed. The layout will be reiden-

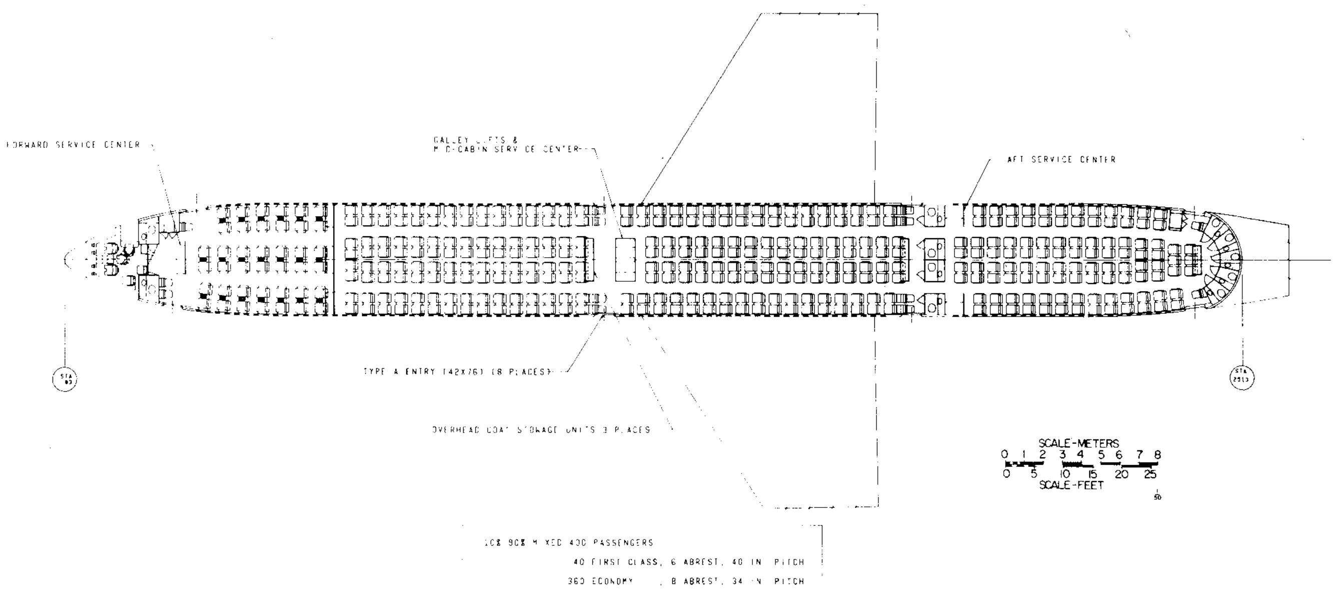

Fig. 7 NASA energy efficient engine study 400 passenger seating arrangement on CADAM.

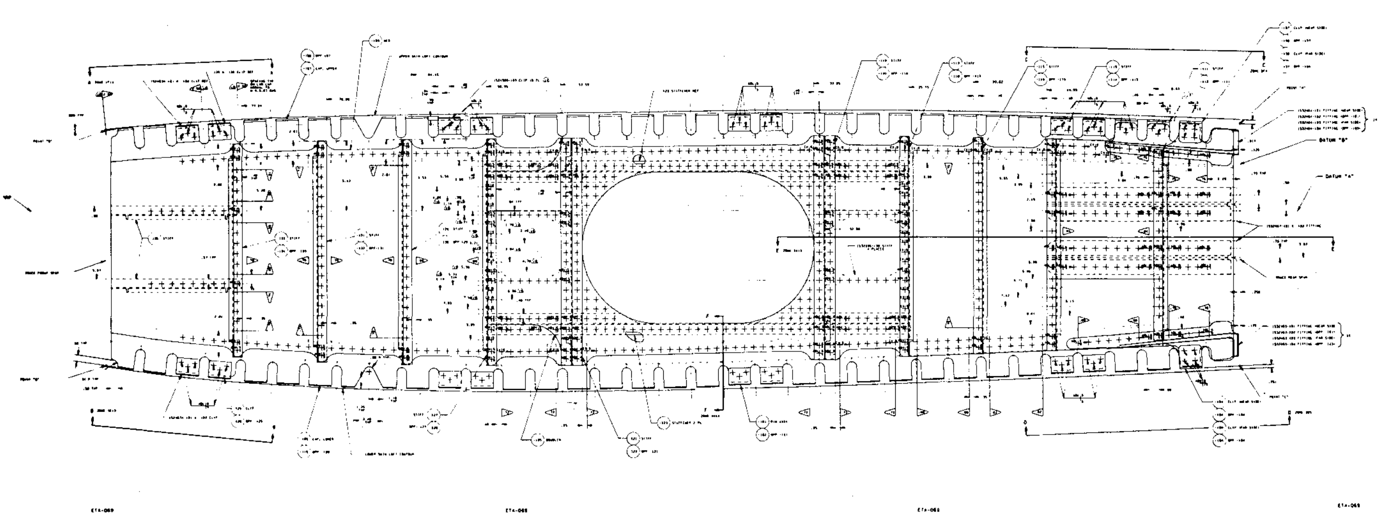

Fig. 8 L-1011 horizontal tail rib assembly drawn on CADAM.

tified to provide an assembly and an installation drawing. Figure 8 is an L-1011 horizontal tail rib assembly drawn on CADAM. These drawings are nearly complete except for assembly and installation information and callouts. Rib details that must be made as separate drawings are taken from the rib layout by the CADAM function TRAP and then transferred to the new drawing. The same techniques used for the ribs can be used to produce wing spars, fuselage frames, floor beams, etc.

Forgings and machined parts are completely defined in CADAM, providing a data base for manufacturing. These computer models will later be called up by the tool designer and NC programmer to locate hold down fixtures and produce NC tapes.

Equipment installations start with the equipment designer calling up the CADAM drawings that show the structure in the area that the unet will be added. The designer may change the type of line representing the structure from solid and dash to phantom, and then add equipment that was developed in another CADAM model. This eliminates interference because the structure is just as it will be built including the location of fasteners to be used in the installation.

When floor structure and floor panels are drawn on the scope, the designers may use the CADAM function OVERLAY to see both drawings on the scope at the same time. Interferences and mismatching fastener locations show up very clearly allowing corrections before the drawings and tooling are released and not after the parts are made.

As mentioned previously, interiors may be rapidly evaluated by using the standard library of seats, galleys, lavatories, etc. When an airline requests a seating change on the L-1011, Lockheed engineers use outlines of floor panels and over 70 various seat assemblies stored in the data base. Working at the terminal with the airline representative, they achieve new plans in as little as two or three hours, instead of several weeks.

Manufacturing

With the geometric definition and other pertinent attributes of a new aircraft defined and stored in a CADAM data base, then a large variety of manufacturing operations benefit directly from this shared use of the common data base. They include process planning, scheduling, tool design, quality assurance, template layout and computer-assisted NC operations. By providing manufacturing with this CADAM data base, production engineering has not only saved man-hours, time span, and dollars for engineering, but has significantly contributed to the early phase in manufacturing. If manufacturing uses CADAM without any computer data base available from engineering, the productivity achieved will still make it very cost effective. The NC programmer will take the drawing produced on the board and quickly draw it on CADAM.

When manufacturing people begin their work at the terminal, they can call up a listing by part or drawing number of all of the related drawings that are filed within the computer's storage system. The engineering drawings thus displayed may be quickly modified for the tool design, template, or NC programmer by a mass erasure of notes, dimensions, and other irrelevant information, leaving only the basic geometry of the part on the screen. The tool designer will then design jigs, fixtures, clamps, or hold-down blocks as required. The CADAM function, line TYPE, can be used to make the lines of the part phantom. Optionally, a SPLIT FILE may be used to file part geometry separately from the specialized manufacturing data.

Upon completing the preliminary planning, the NC programmer begins the development of the cutter path by selecting the functional subroutine on CADAM called NC. The programmer will supply the desired cutter diameter and radius of the cutter. Cutter speeds, feed rates, and auxiliary functions, such as turning on coolants and turret control, are also entered during cutter path selection. The part geometry is then used for automatically constructing cutter centerline paths by offsetting the amount of the cutter radius plus any thick amount. The programmer verifies the cutter path by selecting the REPLAY option from the menu. The cutter will be displayed dynamically in animation as it moves along its path on the screen, see Fig. 9. This is highly effective in detecting the possible existence of programming errors. When that part program has been completed, the programmer requests that the geometry path information and related instructions be transferred to the post processor section of the computer program. The parts programmer's responsibility at Lockheed extends through the actual tool tryout in production. The programmer takes the control tape out to the NC machine, working with the machine operator throughout tool tryout.

The major benefit of computer graphics in NC parts programming is the improvement in the quality of machine instructions on the NC control tape.[3] Tool metal-cutting time on machines that are very expensive to operate can therefore be reduced.

Prior to the use of computer graphics, an average of four tool tryouts was required to achieve an acceptable NC machined part. Since all NC machines are heavily loaded with production work, it was often a week or more between tool tryouts on a new part, therefore it might require a month to produce an acceptable tape. With CADAM, the average number of tool tryouts has been reduced to two.

CADAM provides a useful tool for plant layouts. Plant facilities can be stored in the computer model with the location of doors, windows, posts, electrical, air, and water supplies, and safety and clearance requirements. A standard library of machine tools, large fixtures, work benches, storage cabinets, and wheeled vehicles can be available. The aircraft to be produced is also in the library, stored as individual components, wing, fuselage, tails, and power plant, and complete. The facilities engineer calls up a building from the file, gives it a new drawing number and proceeds to arrange the pieces until satisfied that the most efficient arrangement has been achieved.

A small but useful role of CADAM can be the drawing of the production breakdown. Using the isometric of the aircraft already produced by engineering, it can easily be rearranged into all the assembly segments.

Product Support

By the time a new aircraft is designed using CADAM, a large data base exists. This data base can be used to produce the information and manuals required for product support.

An important requirement in the delivery of a new commercial transport is that the aircraft manufacturer provide the

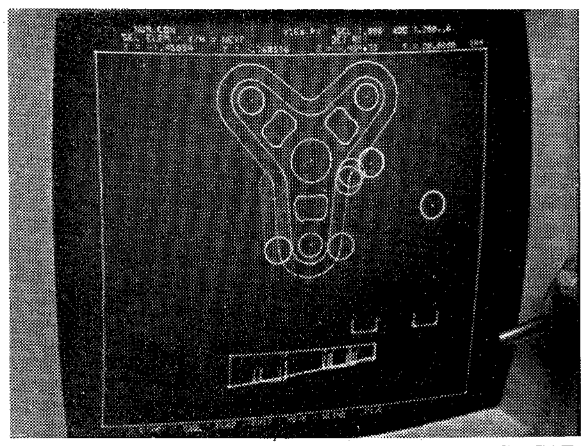

Fig. 9 Cutter displayed in animation during NC CADAM programming.

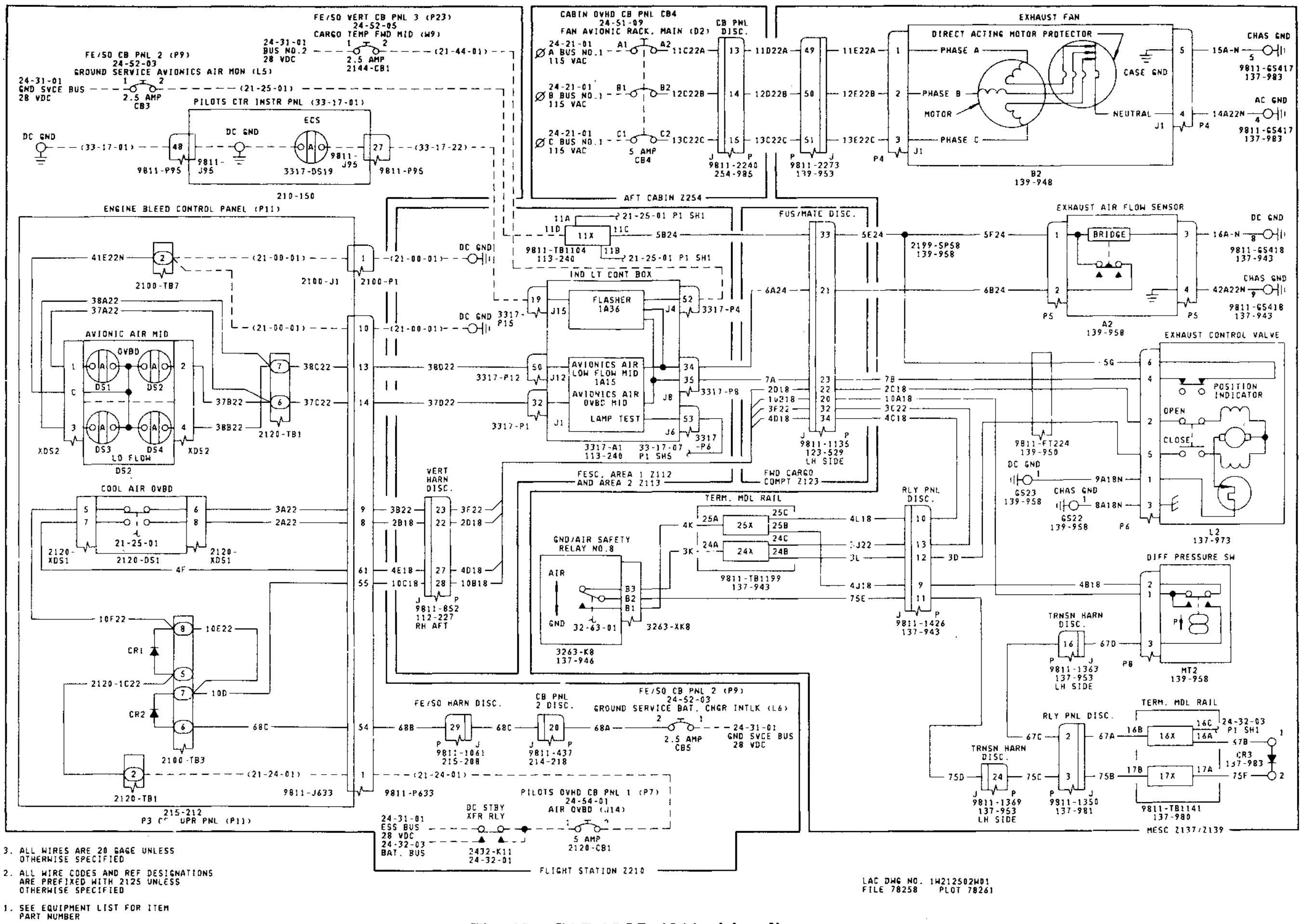

Fig. 10 CADAM L-1011 wiring diagram.

airlines with wiring diagrams to permit maintenance of these systems. Each airline has differences in their electrical and avionic systems, and the wiring diagram manual for one airliner configuration contains 1200-1500 sheets of drawings. The wiring diagrams for a new customer are visually similar enough to a previous design, that the earlier CADAM model can be called up at the terminal, reidentified, modified, and refiled. In addition, the standard library contains all the useful symbols required for additions and revisions. Figure 10 shows a wiring diagram drawn on CADAM.

The L-1011 TriStar wiring diagrams department issues up to 6000 new drawings each quarter for the L-1011 fleet. With the CADAM system, six people at four terminals keep the entire set of 250,000 TriStar aircraft wiring drawings up to date.

Both commercial and military aircraft require maintenance manuals and illustrated parts lists that through words and pictures describe how to service the aircraft. The pictures include both orthograph views and isometrics. These are easily obtained from the CADAM data base. Isometrics can be made from details and assemblies and exploded views easily created.

Conclusions

The use of CADAM by engineering and manufacturing during the development of a new vehicle provides all users with a common geometry data base. The result is reduced costs, reduced man-hours, a shorter time span, fewer errors, greater accuracy, and the capability to perform more design iterations in the development of a new product.

If on a given projet only one or two departments use CADAM independently, they will still benefit greatly, but the program will not achieve the full cost savings possible.

The productivity ratio, the time spent at the interactive computer graphics terminal compared to the time spent at the drawing board or manual programming of NC, is an impressive measure of the cost effectiveness of CADAM. In a study of computer graphics productivity at Northrop,[4] CADAM ranged from 4:1 to 17:1 over the old way. The 4:1 was for making mechanical installation drawings and NC tapes and the 17:1 was for changes to structural detail drawings on CADAM. Lockheed-California Company productivity ratios are very similar. In one example using SURFACE DESIGN a ratio of 40:1 was achieved.

The use of interactive computer graphics is relatively new in industry and will require many changes in the way we think. As older experienced people retire, there will be a shortage in the work force as is being experienced now in the shortage of designers in aerospace. Companies will have to invest capital for computer graphics equipment to make up the difference.

There has been a tendency in some areas for the designer to make the layout on the drawing board, and then a CADAM operator does the production drawings at the terminal. This reduces the effectiveness of using computer graphics and must be avoided.

Engineering and manufacturing organizations will have to keep transition at pace with their management's enthusiasm, their people's ability to learn, and the company's capability in investing capital in computer graphics.

In the 1980's and 1990's, interactive computer graphics will grow in importance to the designer, analyst, and management. Its capabilities will reach far beyond our expectations. Efforts at developing new and improved software and hardware are increasing rapidly. The number of companies using a computer graphics system is increasing daily.

Software improvements will include new analytic programs to help the designer solve graphical design problems, improved three-dimensional systems and conversion programs to permit the transfer of drawings made by different computer systems between companies by computer tapes. Hardware improvements will include larger graphical display terminals for some jobs, more usage of color terminals for specialized functions, and more consideration to human engineering in the design of the work station. Voice communication between the designer and the computer, reduced response time, and reduced computer graphics hardware costs are all under development.

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