Test Results on Computer Graphics Productivity for Aircraft Parts Design and Automated Machining

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Test results are presented comparing the productivity, with and without using computer graphics, in completing aircraft engineering analysis, drawings and numeric control programming tasks. Two computer graphics systems were tested with the following results: 1) A refresh CRT-IBM 370 system using Lockheed California Company's CADAM (Computer Augmented Design and Manufacturing) software. Productivity ratio was highest (17/1) for changes to a structural drawing and lowest (4/1) for mechanical drawings and numeric control functions, and 2) a lower cost Tektronix storage CRT-IBM 370 system. Productivity ratio was (2/1) in engineering analysis and master dimensions development. The following primary positive features resulted: feasibility of operating CADAM within the existing Northrop computer environment; the ability to create a 100% complete drawing. The following primary negative features were revealed: various programming "bugs" and "human engineering" deficiencies; and lack of compatible interface to various Northrop "hard copy" plotting devices and to Northrop's Direct Numeric Control System. Three drawings were made by Lockheed CADAM experts and eight drawings and one three-axis Numeric Control development were made by Northrop trainees. Productivity for the Northrop trainees were factored by an empirically derived learning curve. Although the productivity results derived herein apply to a controlled test defining potential computer graphics benefits realizable in an ideal environment and not in a hectic, day-to-day aircraft development and production program, positive cost-effective gains in an operational environment are expected.

I. Introduction

USING computer graphics for making engineering drawings and also for generating cutter path data for automated numerically controlled machines has been attempted in the aircraft industry with varying and uncertain degrees of success for the past ten years or so. Last year, Northrop management decided to investigate whether its aircraft development and production costs could be decreased by using computer graphics since the state-of-the-art of computer graphics possibly had developed to the extent that application of cost-effective, productive systems might be feasible. Toward that purpose, a Northrop study committee was formed in 1974 to recommend the best approach. However, conclusions from this committee's studies could not quantitatively substantiate a firm cost-effective recommendation. Quantitative productivity data to substantiate the economic viability of any cost savings conclusion are not avaialable in the literature; thus, study conclusions had to be based primarily on qualitative data and sales information from vendors. Furthermore, it could not be ascertained whether graphics systems could operate productively in the Northrop environment, or could interface effectively with Northrop systems, procedures and manual operations. However, the committee was able to recommend that two computer graphic systems be tested at Northrop to obtain controlled productivity data to compare with equivalent manual operations.

The Northrop Corporation, Aircraft Division, designs and manufactures low-cost fighter/trainer aircraft as exemplified by the T-38, F-5, F-17 and F-18 series. An element of the Northrop environment included the fact that all analyses and designs for these fighters were performed without using computer graphics. Numeric Control (NC) for automated machining of parts was performed by the Automated Programmed Tools (APT) noncomputer graphic programming method.

Four basic conclusions were reached by this committee:

1) Purchase of developed computer graphics software and associated hardware system is desirable because of the very costly, multiyear development required for a complex inhouse system. The purchased system, however, must be close to the capability required or development costs and time will still be large.

2) For Northrop applications in making engineering drawings, commericially available minicomputer systems seemed very promising for the future but currently were not of large enough capacity, efficient enough, nor capable of immediate benefit in a production design environment.

Development and risk areas include the following: a) Fast response time for multiple terminals. b) Limited thru-put capability to store and retrieve large complicated drawing models. The minicomputer must be efficiently matched to the IBM 370 so that optimum sharing of computer functions occur. c) Limited constuct capability; slow windowing and scissoring; limited drawing formatting capability. d) Inability to accomplish 100% complete Northrop drawing and (NC) tapes. e) Human engineering features which cause awkward, mistake-prone usage. f) Limited power and speed of the minicomputer system.

3) A storage CRT costs less than 1/5 that of a refresh CRT. For aircraft lofted surface-master dimension definition, and for open-ended, interative, engineering, structural or aerodynamic analysis, the two primary limitations of the storage CRT, namely, the longer time required to completely repaint the screen after any change command and the unavailability of light pen interactivity with the computer, are not significantly degrading. Changes and deletions are not as extensive for master dimensions definitions and for engineering analysis compared to engineering drawings. Thus, the storage Cathode Ray Tube (CRT) system suffices and is much more cost effective than using the IBM 2250 refresh system for these two specific applications.

4) The Lockheed developed software (CADAM-Computer Augmented Design and Manufacturing) and the IBM 2250 refresh CRT connected to a large mainframe computer (IBM 370) seemed the best availabe candidate for an evaluation of

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the use of computer graphics for engineering design and NC usage.

In this report the technical approach and productivity results of two months of controlled testing of these two potentially viable systems are presented. The following two systems were chosen for testing at Northrop:

1) Engineering Analysis and Lofting (Master Dimensions Definition) – 19-in. diagonal Tektronix storage CRT's, using software developed by Northrop and by Tektronix, to allow on-line display and on-line interactivity with inputs, outputs and program control for IBM 370 Time Sharing Operations (TSO) FORTRAN programs.

2) Engineering Drawings and Graphical Numeric Control – IBM 2250 refresh CRTs with CADAM software to allow all drawing constructions to be interactively developed on the CRT. The completed drawing is stored in the IBM 370 for recall and modification as required. These stored drawings are also accessed for programming numerically controlled parts from the CRTs.

This test was divided into two parts. Part I consisted of the CADAM system evaluation; Part II consisted of the graphical engineering analysis and lofted surfaces-master dimensions definitions.

II. (Part I) CADAM Test

This section discusses the expected productivity ratio obtained from using CADAM compared to manual methods. Answers to nonquantitative usage questions are presented in the next section.

The test setup is shown in Fig. 1. The Computer Graphics terminal consisted of an IBM 2250 Model I connected by coaxial cable to the IBM 370/165. A 150,000-byte partition was set aside in the computer. No attempt was made to run CADAM on any priority basis nor to reconfigure the computer from its normal operation. This included running background batch programs and TSO while CADAM was operating. The IBM 2250 was attached to a channel supporting a bank of 8 tape drives. The capability existed to switch CADAM between the two Northrop computers to provide backup operation when one of the computers was inoperative or overloaded.

Three important guidelines had to be rigorously observed to be sure of valid CADAM productivity data:

1) The Drawing and the NC programming process involved planning, thinking, sketching, division-wide coordination, as well as either the actual drafting or NC programming tasks. It was mandatory to compare only the drafting and programming functions performed nongraphically with those same functions performed on the CRT in order to make an "equal-basis" comparison. The functions, required to complete the total task, but not dependent on CADAM or manual methods, had to be factored out of the comparison.

2) Since many people involved in the test had strong pretest biases, it was mandatory to appoint an unbiased competent referee to make an impartial evaluation. This referee was furnished by Industrial Engineering.

3) There is some percentage of drawings and NC tapes for which CADAM is not at all applicable, and then there is some small percentage which is especially ideal for CADAM. Test samples had to be chosen that did not include these extremes, since one of the purposes of the test was to determine the type and characteristics of drawings and NC tapes that provided high CADAM productivity.

Since part of the test was to determine acceptability of CADAM at Northrop, some of the drawings and NC tapes had to be made by Northrop trainees. The efficiency of Northrop trainees was factored via the learning curve shown in Fig. 2. This learning curve is an empirical correlation built up over the years by Lockheed and is somewhat different from the standard learning curve. It was important that some experienced Lockheed CADAM operators also take part in the experiment to provide data in validating this learning

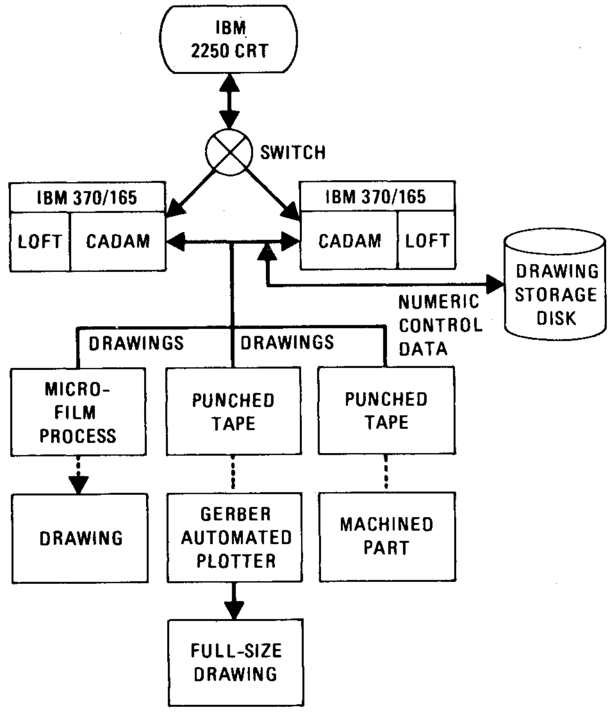


Fig. 1 Test setup for CADAM.

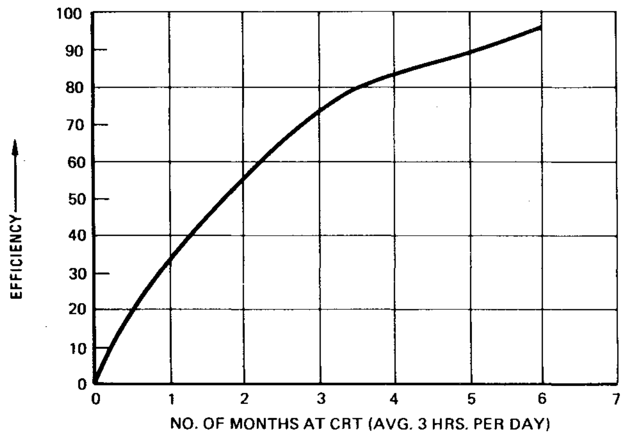


Fig. 2 Learning curve for "average" designer.

curve. Obviously, none of the personnel taking part in the test were allowed to have previously made the drawings or the NC tapes.

The time comparison technique was as follows: 1) Keep a carefully itemized log of all operator actions while using CADAM. 2) Factor out those tasks from the "manual" effort that make it possible to compare CADAM CRT time against only equivalent "manual" tasks. 3) Account for computer problems of variable time duration, such as "downtime," excessively slow response time, etc., by first factoring out these computer related items and then adding to each drawing time a consistent, conservative average time to account for these computer problems. 4) Factor CADAM elapsed CRT time for each drawing by a learning curve to account for operator capability level. 5) Compare the time to accomplish CADAM CRT tasks with the time to accomplish equivalent tasks during "manual" operations as shown in the following

$$\text{Productivity Ratio} = T_M / \bar{T}_{CRT}$$

where: T_M = time required for manual completion of task; $\bar{T}_{CRT}$ = normalized time to complete same task on CRT using CADAM

$$\bar{T}_{CRT} = \hat{T}_{CRT}(\text{L.C.E.})\ (1.15)$$

Table 1 Test results compare CADAM with manual method

Type	Drawing Description	Manual[a]			CRT[a] (Hours) Normalized	Productivity Ratio	Operator		Comments
		Hours Required	Method of Measurement: By Estimation	Method of Measurement: By Actual Elapsed Time			Northrop	Lockheed	
Advanced Design Layouts	Gun Install'tion	28		c	2.7	10.5/1	b		CADAM extended work alre
	Gun Installation (Layout/ Modification)	50		c	3.8	13/1	b		started manually. A critical dimension mistake was foun. Gun movement was visualiz
	Vane (Layout/ detailed drawing)	140	c		11.2	12.5/1	b		Some layout constructed entities were called forth fro computer for detailed drawi
Mechanical Installations	F-5 Rudder Pedal Mechanism	32	c		8.0	4/1	b		Multiple views showing the mechanism in different posit are useful in finding errors a understanding operation and limitation.
	F-5 Spring	16	c		1.9	8.5/1	b		
	F-5 Torque Tube – Rudder	12	c		2.4	5/1	b		Production drawing was rele
	F-5 Landing Gear – Geometry	50	c		8.0	6/1	b		Motion is accurately depicte during gear extension.
Structural Layouts	F-5 Chaff Dispenser	50		c	7.6	6.5/1		b	Showed that it was possible t perform layouts.
	F-5 Environmental Control System Compartment	80		c	10.7	7.5/1	b		
Details	F-5 Gun Gas Deflector Fitting	96		c	8.3	11.5/1	b		No symmetry or repetitive entities.
	F-5 Spin Chute Test Fairing	37		c	3.7	10/1		b	It took 2.5 hours to copy the drawing.
	F-5 Spin Chute Test Fairing (Modif.)	6	c		0.35	17/1		b	Mold line change was made.
Electrical Schematic	F-5 Electrical Wiring Diagram (VOR/ILS Radio)	8		c	1.2	6.5/1		b	
Numeric Control	747 3-Axis Frame	38		c	10.0	4/1	a		

a Only hours spent at CRT are compared with drafting board time for drawings and APT programming time for Numeric Control. Planning, coordinating, and tool proving are not included.

b Merely indicates whether the drawing was performed by a Northrop or Lockheed operator.

c Merely indicates whether the hours to complete the drawing manually were estimated or were obtained from actual project records.

where: $\hat{T}_{CRT}$ = actual elapsed CRT time to complete task; L.C.E. = Learning Curve Efficiency from Figure 2; and 1.15 = accounts for an average computer downtime and other operating inefficiencies that occurred during the test.

Quantitative Test Results

Table 1 depicts the results comparing manual with computer graphics operation for design and Numeric Control tape preparations. Twelve diverse specimens chosen ranged from Advanced Design concepts through F-5 fighter mechanical, structural layouts, electrical layouts, and detail drawings, to cutter path definition for three-axis machined parts. Specimens were chosen so as to have at least one drawing feature conducive to high CADAM productivity but yet be representative of typical drawings. Detail drawings were made on the CRT from manually prepared layouts and layouts were made on the CRT from sketches and from analytical data. Three CRT drawings were made by Lockheed CADAM operators. Eight CRT drawings and one three-axis NC-CRT development were made by Northrop trainees as the first effort after a three-week training course. All drawings and the NC development had been completed manually by Northrop personnel prior to this test program. Table 1 indicates whether the number of hours required to perform the task manually were by actual elapsed time (taken from project time records) or were estimated (hours were averaged from three designers' estimates).

Drawings

Drawing complexity varied from simple (eight hours to complete manually) to complex (96 hr required). CADAM productivity ratios varied from 4/1 to 17/1 compared to manual methods. The highest productivity occurred for the F-5 Spin Chute test structural fairing (17/1), (shown in Fig. 3) when moldline modifications were made to the completed drawing. The types of drawings for which the highest productivity occurred were structural detailed drawings, as expected. Mechanical installations had the lowest productivity, but would benefit the most from future usage of a stored library of entities, from visualization of mechanism motions and from capturing construction entities from installation layouts for use in detailing.

The electrical drawing was randomly chosen. Later drawings, completed on CADAM but not quantitatively measured, had more repetitive entities and less identifying typing and had higher productivity than that listed in Table 1.

There were six important reasons for this demonstrated high productivity compared to the manual method: 1) Using moldline data displayed on the CRT is considerably faster than tracing or manually drawing moldlines from coordinate points data. 2) Complex constructions (such as curves representing splines, conic or cubic equations or entities projected by analytical geometry through various views) if done manually are considerably slower than those same constructions performed by the computer. 3) Repetitive construction entities do not have to be redrawn but are instantaneously called forth from storage. 4) Any symmetry occuring on the drawing is immediately displayed rather than having to be redrawn. 5) Analytic geometry constructions are performed by the computer and do not have to be calculated and drawn manually. This capability is especially important if many views have to be constructed, and if section cuts have to be depicted. 6) Concentration by the operator on the CRT in the interactive mode is more intense than the designer is able to sustain on the drawing board.

Even higher productivity than measured in this test should be attained during operational usage primarily for four reasons: 1) A library of commonly used entities will be available. 2) A "family of drawings" planned from layouts through assembly and details and manufacturing are all made by CADAM, thus benefiting from the computer-stored geometric data base obtained during all these phases from previously derived constructions. 3) Design errors will be avoided because the computer will be able to accurately calculate motions of mechanisms and geometric clearances. 4) Division-wide data base information will be utilized.

Numeric Control

The three-axis part proved satisfactory on the first "tool try." The time-consuming steps of Numerical Control are the definition of the parts geometry, the programming and coding required to obtain the cutter motions and machine instructions, the steps involved in performing the original first tape trial, and then the checking and correcting of errors.

The test trials using CADAM for three-axis programming on the CRT showed a 4/1 productivity ratio over corresponding APT programming tasks to generate the machined part definition. These savings occurred for the following reasons: It is much faster and fewer mistakes are made by generating and checking the cutter motion and machine instructions on

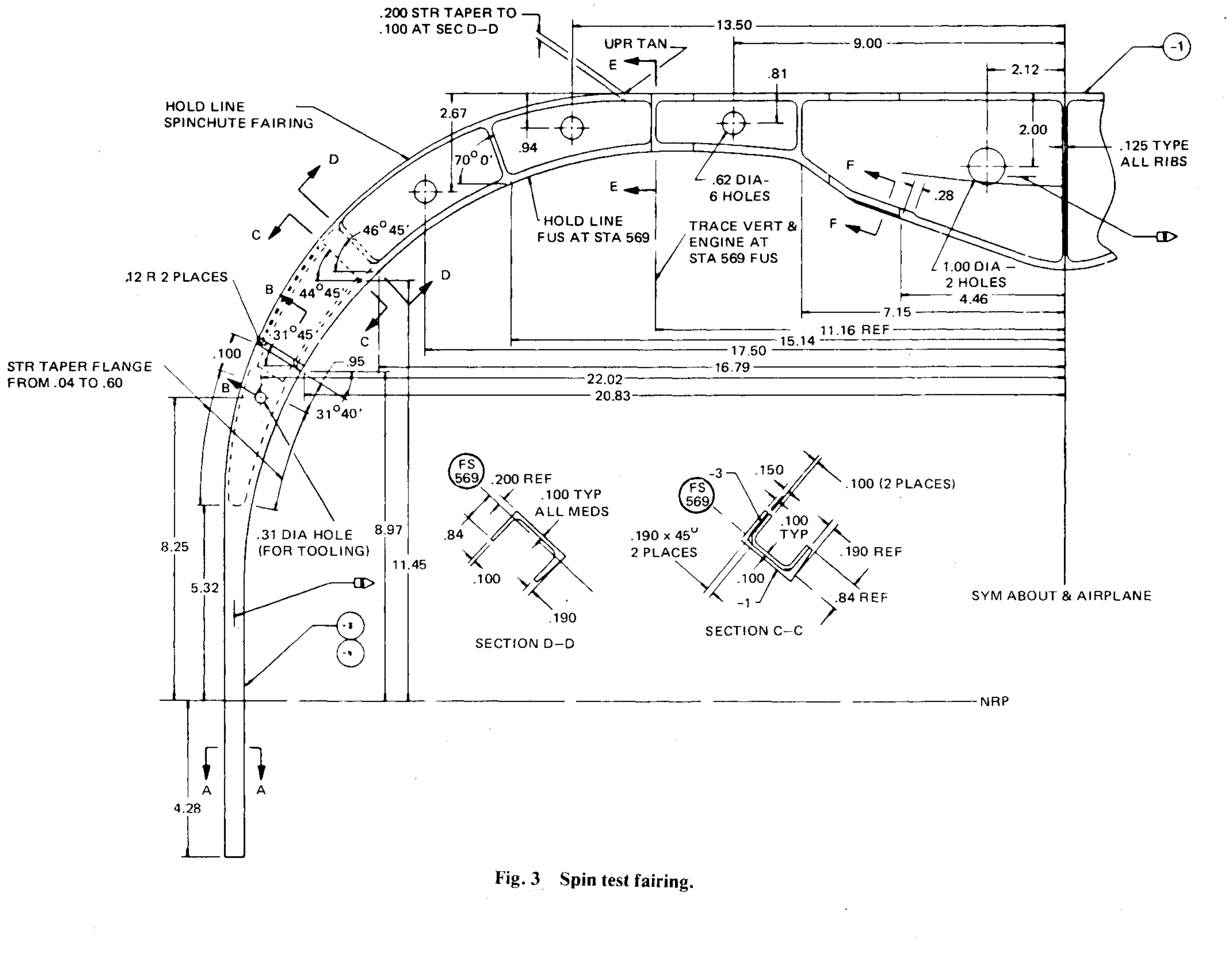


Fig. 3 Spin test fairing.

the CRT as compared to writing an APT program and checking it only on the Gerber flatbed plotter. By eliminating the computer card deck submittal and some of the Gerber plotter proving and by decreasing the number of times the program is recycled to obtain a valid tape (from three to one for this case), additional time savings result.

Additional time savings in the parts geometry definition phase may occur because the basic geometry is available on the CRT from the stored engineering data base. This eases the task of the NC parts programmer to mark up the engineering drawing and write geometric definitions.

Nonquantitative Test Results

The following nonquantitative questions were evaluated during the test:

1. Can CADAM operate within the existing Northrop computer environment? Yes, during the testing the impact of CADAM on other batch and interactive work has been minimal, with the most noticeable interference on the IBM 370/165 being computer operator-user interference caused by a lack of instruction to users and operators. During about 10% of the available CRT operating time, the computer was either inoperative or the slow response to input commands significantly disturbed the users. Overnight to two-day turnaround provided "hard copy" drawings from either the Gerber flatbed plotter or the microfilm process. For generating production drawings effectively, the designer will have to be provided with hard copy (higher resolution than that obtained with Polaroid camera shots) soon after his CRT construction, for his further study, planning and coordination. Thus, it will be necessary to automate some of the manual steps and to improve the current time consuming process of acquiring hard copy plots.

2) Can a 100% complete drawing or NC tape be created? Yes, as demonstrated by the fact that eleven drawings and a three-axis numerically controlled part of varying degrees of complexity were completely constructed using CADAM. However, improvements are required to correct cumbersome, error-prone or indirectly derived constructions.

3) Are design analysis aids of benefit to the designer? Yes, the following CADAM automatic calculations and displays were found to be useful design aids: (a) section properties, (b) beam analysis, (c) lug analysis, (d) weight and volume analysis, (e) torsion analysis, (f) crushing analysis, and (g) fluid flow analysis.

4) Can loft data be successfully accessed? Yes, during the test period CADAM accessible loft data as developed by Northrop computer programs was displayed on the IBM 2250 and subsequently used in the CADAM constructions.

5) Can CADAM be incorporated into the Northrop drawing release system? Yes, various drawings were successfully sent through the normal Northrop signature and release cycle.

6) Will CADAM be accepted by Northrop designers and managers? Yes, as demonstrated by active participation and willingness to pay proportionate system cost.

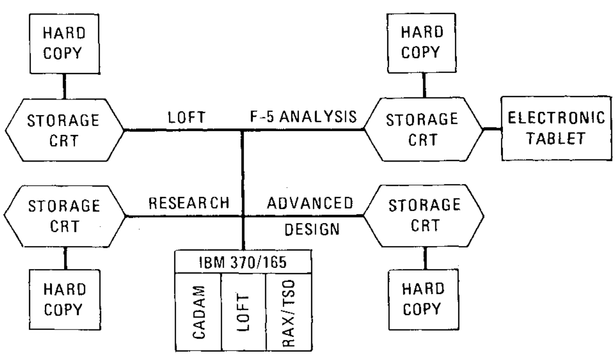


Fig. 4 Test setup for storage tube system.

III. (Part II) Engineering Analysis and Lofted Surface Definitions Using Computer Graphics

The low-cost, storage-CRT/TSO graphics system shown in Fig. 4 is being used now at Northrop to improve the speed, accuracy and visibility of engineering analysis and lofted surface developments. These graphical improvements are for computer programs currently operating in either batch mode or TSO.

The operating cost for this system is very low, approximately $10 per CRT hour compared to over $40 per CRT hour using the refresh system. The Tektronix CRT has on-line, low-cost hard copier capability ($0.05/print), in addition to large time savings in preparing graphical plots of calculated results, and in completing iterative analyses.

Specific applications examples are: Mission Analysis – airplane sizing; Stress Analysis – finite-element modeling; Dynamics Analysis – vibration mode shapes, vibration response; Flight Performance–drag data, stability and control parameters; and Engine Performance–thrust, bypass ratio and fuel flow parameters; Loft–longitudinal control lines and cross sections, area developments, and surface configurations.

In most analytical and lofted geometry applications, the analyst requires more evaluation time between each interaction with the computer than is required in design applications. There is also usually less change of the CRT display in these analysis programs than is the case when using a CRT to construct a drawing. For this reason, the low-cost storage CRT is more cost-effective than the refresh CRT system for most analytical applications.

The payoff in using Computer Graphics for engineering analysis arises from fewer mistakes in complex input of graphical data to a computer run, and from analyst interactivity in an iterative problem with the results displayed on the CRT. These benefits are most visible where very large amounts of time are required to prepare and correct input data, and where the input data are geometric in nature, as in stress analysis.

Storage CRT System Tests-Background/Method/Results

As examples of the productivity to be attained by using the storage CRT system, tests were conducted, and productivity measurements made for lofted surface developments and aircraft stress analyses. Test data obtained and a discussion thereof follow:

Master Dimensions (Loft)

Man-hour and span time savings resulted from using the storage CRT system to provide immediate visual display of

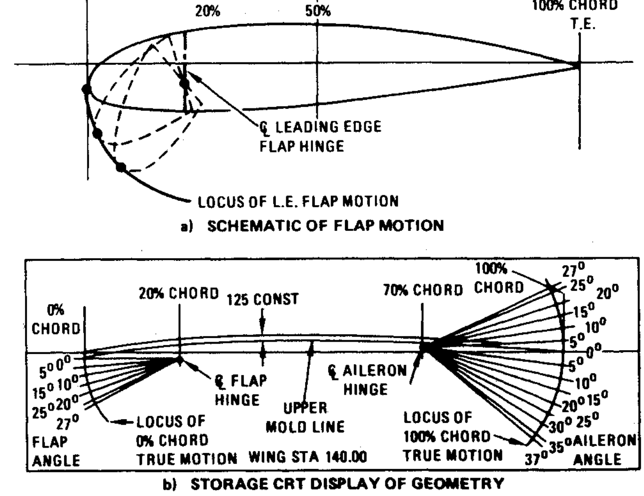


Fig. 5 Flap deflection analysis.

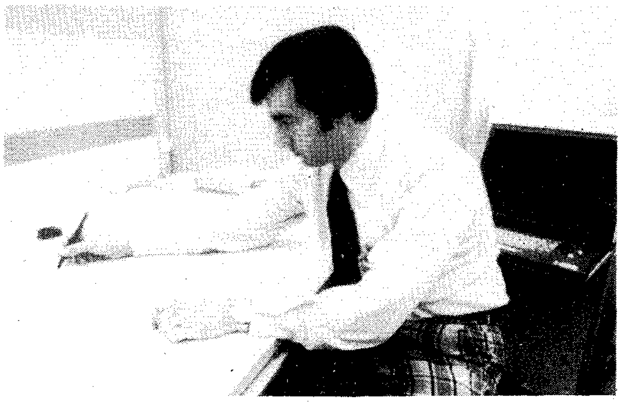


Fig. 6 Electronic tablet for geometry input.

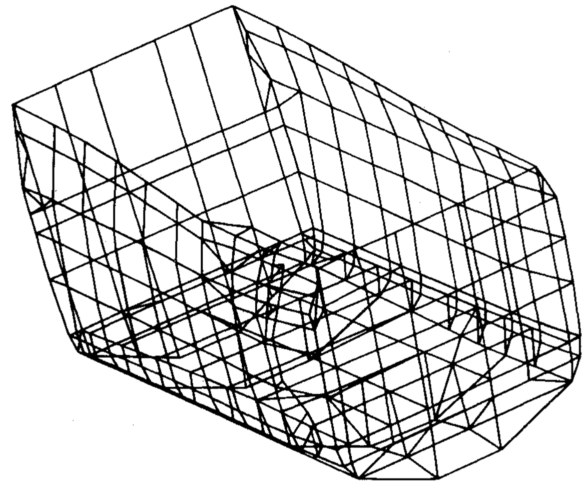


Fig. 7 Stress analysis input model example-cockpit section.

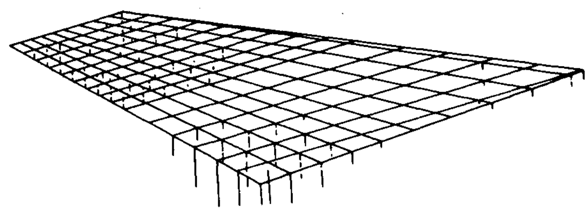


Fig. 8 Calculated load vectors (horizontal tail).

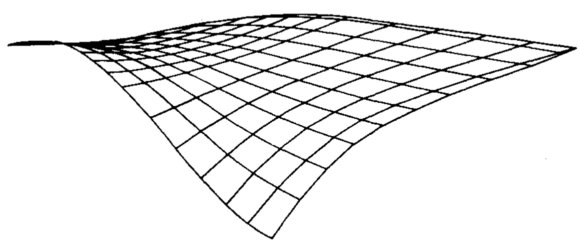


Fig. 9 Calculated deflection (horizontal tail).

calculated lofted surfaces and geometric control equations during the mathematical analysis phase of configuration development.

Immediate viewing of the iterative curve fitting process eliminates the time required for inputting the curve fitting program for a batch run and waiting for the punched tape to be produced so that the automated drawing machine can plot the result. When errors are found or changes made to the inputs in this iterative procedure, submittal of these revised inputs are made from the CRT terminal. Thus, the time required for coding, card punching and Gerber plotting is eliminated. The continuity of the interactive, iterative process also, of course, adds to the time savings. Thus many more trials are attained within a given time for surface change studies and tradeoffs.

Using the storage CRT system has the following benefits: 1) Capability for on-line visual display of aerodynamic shapes being developed and the ability to debug problem areas directly without recourse to: a) Keypunched card deck revisions, b) Tedious examination of printed data, c) Long flow-time due to queuing for batch mode computer runs to produce output tapes for Gerber plots of listed data. 2) Further savings result from the reduction in tape preparation and handling time and Gerber plotting time. 3) The developed lofted contours are stored on a computer file for recall by CADAM designers for immediate display on the IBM 2250 CRT.

To provide a quantitative example of these time savings the following typical test case was selected: A mathematical determination of the locus of the wing-flap leading edge (L.E.) and trailing edge (T.E.) true motion at various wing stations using Northrop loft computer programs. The schematic of the flap motion involved is shown in Fig. 5a.

Use of the storage CRT system for interactive visualization and debugging decreased the time required to provide all the geometry data from 40 hr for the noncomputer graphic method to 21 hr using the storage CRT system. An example of the CRT output result for one wing station is shown in Figure 5b.

Although no tests were conducted, task analysis indicates that for surface configuration definintions for new aircraft developments, man-hours will decrease by 80% and span time by 50% compared to noncomputer graphic methods. In these new aircraft surface developments, cross-section shapes and area graphs are stored in the graphics data base rather than having to be manually developed.

Stress Analysis

Aircraft analyses require the calculation of internal loads, stresses and deflections from a finite-element model which depicts the structural geometry involved. Manual generation of this model comprised 90% of the analyses effort and required transformation of structural geometric data from drawings into properly formatted input data cards. Prior to using computer graphics, the method of generating the data cards involved the following steps: 1) Scaling the geometry dimensional data off the drawings. 2) Time consuming manual transcribing of these data onto keypunch forms. 3) Manually coding and keypunching the input data cards. 4) Submitting the program, which contained these data as well as manually coded loft geometry dimensions and material data, to the computer to obtain analytical results. 5) Correcting mistakes in the complicated input data many times and rerunning the program until a valid representation is achieved. 6) Plotting the results. 7) Repeating steps 1 through 6 and interconnecting each model to build up an entire aircraft section.

Referring to the preceding steps, the storage CRT computer graphics method shortcuts this analysis in the following manner:

Steps 1-3

By placing the drawing on the electronic tablet shown in Fig. 6, a "cursor" "reads" the structural geometry directly into the computer program. Access to the lofted surface data base also allows "reading" this geometry directly into the computer. Thus, the time consuming manual steps 1 through 3 in the preceding are eliminated.

As an example, geometric input data for an F-5 cockpit structure as pictorially displayed on the CRT are shown in Fig. 7, enabling the analyst to immediately check data validity. Thus, most of the inputs errors are detected prior to submitting the computer run, eliminating most of the time consuming manual step 5.

Step 4-No Change

Step 5

Any result for any portion of the analysis is displayed on the CRT for interactive error correction or interactive input and program control modification.

Step 6

Figure 8 shows the load vector results calculated for a horizontal tail structural design. The deflections caused by these loads can also be shown on the CRT (Fig. 9). Numerical values for any of these load vectors and deflections can be displayed on the screen upon request, immediately following a batch run, thereby shortening time required to plot results.

A time comparison of the manual and CRT method summarized in Fig. 10 showed manhour savings of 58% and span time savings of 79%.The example used, a T-38 Aircraft Machined Part Former was a relatively simple analysis; higher savings would result from more complicated parts, such as for the cockpit structural analysis shown in Fig. 7.

An additional nonquantifiable but very important benefit is that more time is spent by the analyst in thinking about his technical problem rather than spending his time in mundane "measuring," coding and other routine data preparation tasks. Thus, in a given time, the analyst will be able to accomplish more iterations thoughtfully and derive a more accurate mathematical representation of the aircraft structure.

IV. Computer Graphics Payoff

It is characteristic of aircraft developement efforts that certain machined part structural elements are pacing items; the summation of manufacturing lead time and engineer flow time creates overall problems in meeting tight first-article schedules. The only resolution of these problems is to obtain significant reductions in engineering and manufacturing flow time on critical paths. Selective applications of computer graphics to critical path work will shorten design flow time for these tasks by more than 50%.

In addition to the flow-time advantages offered by computer graphics, an improvement in design quality can be expected; because design changes are so easy on graphics, many more alternate solutions can be tried in the available development time.

It has been demonstrated that computer graphics is a valuable and productive tool in the following functions:

Layout

A high-productivity ratio results due to the fact that layouts are subject to numerous changes, and changes are one of CADAM's biggest payoffs. Note that the highest computer graphics payoffs require the use of refresh (not storage) graphics for most of the functions. Changes are easily accomplished with CADAM features, such as instant selective erasure, bulk erasure, detail repetition, translation of display features and views, and accurate mechanism motion viewing to depict operation and to mathematically assure that no clearance problems occur with structure.

Master Dimension-Loft

In addition to time savings in definition development, additional savings in design and flow time will be realized in future applications because the computer stores existing loft data, thus eliminating the tasks of filling out request forms, obtaining signatures, transporting request forms and waiting for the Gerber-generated loft lines to be plotted based upon priority and work load, and then transported back to the designer who only then can start his drawing. This additional payoff is due to a data base formulation rather than to graphics visualization or interactivity benefits.

Analysis

Quicker, more accurate and error-free analysis using the storage CRT system increases the probability that these analyses will be completed correctly in a timely manner to support the design process. Inability of analysis to keep up with the design schedule, in the past has cost expensive "downstream" hardware modifications when late analysis indicated incorrect designs. This problem is especially acute with complicated stress analysis.

Drafting

CADAM has shown a potential capability to reduce the drafting time of the design process by a factor of 1/4 to 1/17 depending on the operator speed and proficiency and the type of drawing selected.

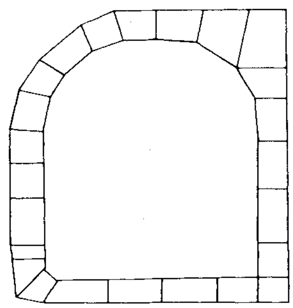
Numeric Control Programming

CADAM has shown the potential capability to reduce the programming time for three-axis parts to develop cutter motion by a factor of about 1/4. This saving is related only to CRT time compared to APT programming time. A time saving of about ½ is estimated for the total time to produce a part, which includes planning, coordination, and tool proving time.

General

It is emphasized that these data were obtained from a controlled test; thus, indicating only the potential payoff of computer graphics productivity. It remains to be seen whether necessary planning, discipline, training, managing and coordination can be achieved so that these productivities can be realized at Northrop in the hectic, real, day-to-day world of aircraft design and production. Furthermore, at other companies, a controlled test of this type would probably yield different though probably still positive productivity results because of a different operating environment.

It is beyond the scope of this paper to compare the potential productivity of computer graphics against the operating costs of hardware, computer and support personnel (most costly). It can be stated, however, that if over one-half of the potential productivity level could ever be attained, a very significant cost savings will occur, no matter what the differences in computer cost algorithms are at different companies. However, to achieve this potential, the problems listed in the following have to be solved.



TIME COMPARISON

	MANUAL	GRAPHICS	SAVINGS
MANHOURS	48	20	58%
SPANTIME IN DAYS	14	3	79% (11 DAYS)

Fig. 10 Structural modeling-T38 former.

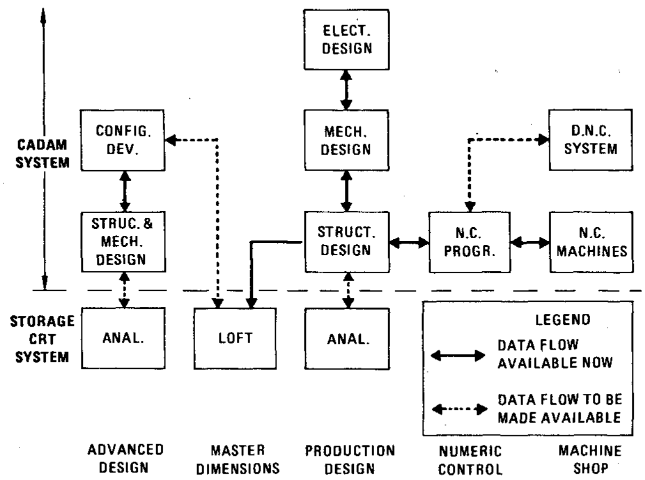


Fig. 11 CADAM storage CRT system.

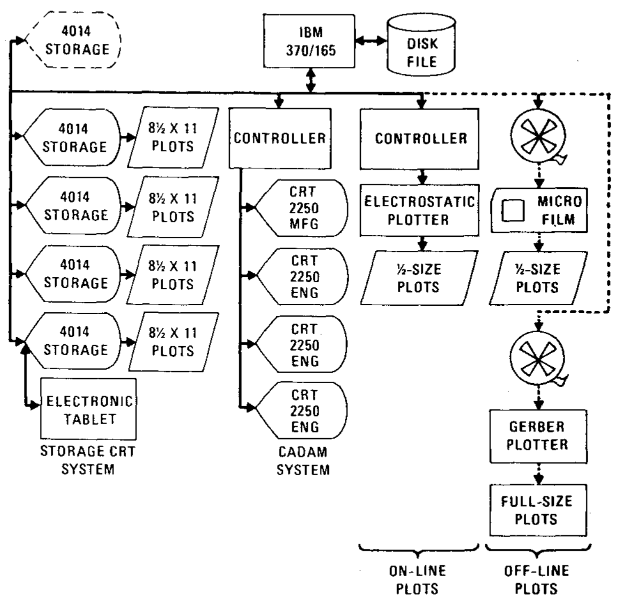


Fig. 12 CADAM storage CRT system schematic.

V. Problems

Problems encountered during the test fall into two categories: 1) programming "bugs" must be eliminated and "human engineering" capabilities need to be improved; and 2) "interface" programs to Northrop hardware and systems are lacking.

CADAM as it exists has some coding mistakes which must be eliminated. "human engineering" inadequacies have been discovered. These include not only the situation where the system interacts poorly with the user, leading to mistakes and misunderstandings, but the fact that certain constructions on the CRT cannot be done in a straightforward way but must be constructed in a complicated, cumbersome, "work-around" manner. Furthermore, the computer is not always functioning or functions inefficiently, thus at certain times slowing down the completion of work. These deficiencies form an important area of future CADAM and computer development to improve user acceptance and productivity.

Item 2 consists of the necessity to develop improved CADAM software capability to accomplish the following: 1) Interface to Northrop's Direct Numeric Control (D.N.C.) system. This interface must be bridged to use CADAM cost-effectively. Alpha-numeric CRT terminals located in the shop area will allow source language modification for tool proving, cutter motion optimization, and part changes. Thus CADAM must generate a source code, in which motion statements are directly associated with labeled parts geometry and motion commands. 2) Interface to an on-line quick "hard copy" within 1-2 hr or less after creation on CADAM. 3) Eliminate currently required manual steps to obtain finalized, full-size hard copy from the Gerber flatbed plotter or from the microfilm "hard copy" process.

VI. Future Improvements

The most significant future benefit is to interface the CADAM refresh CRT system to the storage CRT system through a common data base. The proposed system is shown in Fig. 11. Dotted lines indicate interfaces currently not available. Thus, with the improved system the capability would exist to use interactively the geometry created by CADAM as an input model for structural, aerodynamic, and other analyses.

Figure 12 shows a schematic of the proposed CADAM/storage CRT system. Hard copy for coordination and check prints would be obtained on-line from an electrostatic plotter. Released drawings would be made by the Gerber flatbed plotter initially with a planned switch-over to the microfilm plots when made cost-effective by a larger drawing volume. It will be a very long time at Northrop before hard copy masters will be replaced by computer data base stored geometry because of the perception by the designer and his management of his need to use conventional "blueprint" drawings.