M 1/3*

SOME ORGANIZATIONAL ASPECTS OF NASTRAN

R.H. MacNEAL
The MacNeal-Schwendler Corporation, Los Angeles, California 90041, U.S.A.

SUMMARY

NASTRAN is a large digital computer program for static and dynamic structural analysis by the finite element approach, which has been in public use since 1970. Development under NASA sponsorship began in 1965 and continues to the present. NASTRAN was initially conceived as, and to a degree has become, an integrated, general purpose structures program with a wide spectrum of users, but with primary emphasis on aerospace applications. The paper reviews two aspects of the organization of NASTRAN: first, the objectives and specifications initially set for the program and the technical functions performed internally to achieve them; and, second, the relationships between the groups of people involved in the planning, development and distribution of NASTRAN.

The development of NASTRAN began with the activities of a NASA committee which decided, in 1964, that a new computer program should be written to satisfy NASA's needs for structural analysis. We are indebted to Mr. T.G. Butler, the government leader of the original NASTRAN development team, for his recent publication of the considerations underlying the initial specifications for NASTRAN (T.G. Butler, "Considerations for the Design of a General Purpose Structural Analysis Program," presented at the Winter Annual Meeting of the ASME, Washington, D.C., November 30, 1971, and published in the colloquium report, *Synthesis of Vibrating Systems*).

The present paper reviews the original objectives for NASTRAN with respect to types of analysis, methods of analysis, problem size, computer types, user conveniences, maintainability, etc., and discussed how specific features of the program relate to the objectives. Particular attention is paid to the executive system, which is the main instrument of program organization in NASTRAN and which controls the sequence of operations, manages the secondary storage files, and maintains a restart capability. Problem solution functions are performed by independent subprograms, called functional modules, which may be entered only from the executive system.

Since NASTRAN is sponsored by a government agency, its development is open to public scrutiny, and an examination of the history of its development should be of value to those engaged in, or planning, similar projects. The paper reviews the history of NASTRAN in terms of the functions and achievements of the participating government and industrial agencies. Additions and improvements subsequent to the initial development, and plans for future developments, are described. The present organizational structure for planning, developing and distributing NASTRAN is outlined, and its effectiveness is evaluated in terms of the initial objectives and in terms of the present needs of various user groups.

1. Introduction

The finite element computer program for structural analysis known as NASTRAN was released for public use in December 1970 and it is currently in the libraries of over one hundred organizations. Thus, it cannot be considered a new or little known development and, in fact, the technical aspects of NASTRAN have been very generously documented. The basic documentation supplied by the official distribution agency, COSMIC*, includes a Theoretical Manual [2], a User's Manual [3], a Programmer's Manual [4], and a Demonstration Problem Manual [5], which total some 4000 pages. A short summary of NASTRAN's capabilities has been published in an international technical journal, [6]. The proceedings of the NASTRAN User's Colloquia [7][8], held annually at Langley Research Center, are excellent sources of information on applications and current developments.

The author of the present paper has been continuously involved with NASTRAN since 1965, both as a technical contributor and as a manager, and has achieved some perspectives which may be of value to others in their assessment of NASTRAN. Too often in recent times the chronologies of research projects and engineering developments are omitted from the printed accounts and the reader is left to guess what struggles occured in their accomplishment. Since the development of NASTRAN was carried out under NASA sponsorship and management, the public record of contract awards and other formal announcements provides a good deal of historically useful information. A most valuable source of information, with particular emphasis on management problems, is T. G. Butler's account [1] of the development of NASTRAN from the viewpoint of the responsible government project manager. The emphasis in the present paper is on the evaluation of NASTRAN content and management relative to original intentions and current needs.

2. Technical Features of NASTRAN

2.1 Review of the Original Specifications

The original specifications for the program were worked out by the members of a NASA committee which had been formed, in 1964, to find a structural analysis computer program which could be used as a standard by all NASA centers. At the time the best structural analysis programs in the United States had been developed by aircraft companies on a proprietary basis, and the distribution of these private programs was, as it is today, highly restricted. The committee interviewed several aircraft companies, found many very useful features, not all of which, unfortunately, were contained in any single program, and decided that NASA should develop a new program.

The news that NASA would issue a competetive procurement for the new program spread quickly and there was much speculation regarding the forthcoming specifications. The most widely held belief was that the budget would be small, so that austere economies would be evident in every detail. When the Request for Proposal actually was issued in July 1965, we in industry were overwhelmed by the breadth of its scope. There were fifty pages of detailed specifications, covering every aspect of structural analysis, and whenever a choice of method was indicated, the instructions called for "both" or "all" or "several." It was as if the committee had resolved every issue by adopting the proposals of each of its members.

---

[*] Information Services Computer Center, Barrow Hall, University of Georgia, Athens, GA 30601

It is difficult, at this distance in time, to judge the motivation of NASA from remembered impressions and it is perhaps best to quote directly from the specification (revised version December 13, 1965, [9]):

"It is the intent that this procurement will provide NASA with the most modern and efficient program that can be developed within the state-of-the-art. The purpose of this specification is to incorporate the most desirable features into a general purpose program, which would be acceptable as a NASA-wide standard."

"2.1 Scope. The purpose of this program is to analyze large linear structures of complex geometry under diverse loading conditions. This will be a digital computer program capable of continuous and step-by-step analysis from the assembly of the mathematical model of the geometry and elasticity, through a determination of static and dynamic properties, to a solution of the response to static and time dependent loads and onto either a structural control-feedback stability analysis and/or a spectral density analysis of random loading. Solution is to follow matrix methods. In order to have as modern and efficient a program as possible without the risk of early obsolescence, the source language is specified as Fortran IV, subject to conditions in article 2.8.* The input and output information is to be standardized to allow easy communication between different NASA digital installations of varying manufacture."

Analysis of these quotations shows the following general goals for the program:

-- general purpose
-- NASA-wide standard
-- solution of the largest, most complex *linear* problems
-- static capability and several forms of dynamic capability
-- longevity
-- implementation on several different computers

The further implication that output data should be automatically transferrable from one type of computer to another was never taken seriously, until quite recently.

Due to their large number, it is not practical to list all of the detailed specifications here. Table 1 summarizes some of the most important ones, particularly those that relate to engineering content. Some curiosities will be noted which reveal the march of progress in the intervening years. These include the very modest requirements for problem size, the absence of a requirement for three-dimensional structural elements, and the requirement that *both* force and displacement methods be used. On the other hand the requirements for elastic stability analysis, structure-control system interaction, and the input of substructure properties (experimental measurements were mentioned as a possible source) were innovative, at least for a large general purpose program.

The specifications also gave instruction with regard to user conveniences, efficiency and other important matters not covered by Table 1. For example, with regard to input data: "All input data shall be basic, requiring no prior calculation by the analyst. The analyst shall not be required to perform any task that can be done efficiently by the computer."

"Provision shall be made to revise input by resubmitting only items of change....."

---

*which provides for source assembly language in places where it is *necessary*.

"Repetition of input data should be held to a minimum."

And with regard to automatic checks:

"These checks shall include:

a. Checks for compatibility of input data
b. Checks on the matrix size, sparseness and bandwidth to insure that the more efficient matrix operations are chosen
c. Positive definiteness
d. Accuracy of the inverse
e. Equilibrium and compatibility."

In summary, the salient features of the NASTRAN specification were the large number of required analysis types, concern for both generality and convenience, and a penchant for multiplicity with regard to approaches and methods. The latter quality is evident in the specifications for computer hardware, methods of user control, the methods to be used in both static and dynamic analysis, in matrix operations and in real eigenvalue extraction.

The specifications do not reveal any intent that the program should be distributed any more widely than just to NASA centers. This is an interesting omission in view of the present widespread public distribution of NASTRAN, and more will be said later about the evolution of a distribution policy.

2.2 Internal Organization of NASTRAN

Most large computer programs evolve from modest beginnings with the result that the internal organizational structure which handles scheduling and filing is often badly overloaded. This is not the case for NASTRAN because the specifications made it abundantly clear that a flexible organization structure with many sophisticated capabilities was necessary. The specification said little about how this was to be accomplished. It did, however, identify the need for modular design, and it defined an Executive Routine which would "contain the management logic of the entire General Purpose Program."

The design of the internal organizational structure which emerged in response to the specifications will now be described briefly. The program itself consists of machine language instructions obtained by normal compilation procedures from source code written chiefly in machine-independent FØRTRAN IV but with some instructions written in machine-dependent source assembly language, mainly to enhance efficiency. Three levels of modularity are distinguishable in the code: subroutines (or decks); modules; and links. The most important level is that of the modules, because they are the entities which are called in sequence by the NASTRAN executive system to solve problems. Different sequences of module calls produce different solution *types*. Subroutines are interior to modules (sometimes a single subroutine will appear in several modules), and the links are entities which interface with the resident computer operating system for the purpose of assembling the executable program, etc. To give some idea of the size of the NASTRAN code, it contains approximately 200,000 source statements, one thousand subroutines, more than one hundred modules, and fourteen links.

The management of such a large amount of code is not an easy task. As conceived in NASTRAN, the essential functions of the executive system are:

1. To establish and control the sequence of module executions according to options specified by the user.
2. To allocate files for all data blocks generated during program execution and to perform input/output to auxiliary files for each module.
3. To establish and communicate to the modules the values of parameters required to select options.
4. To maintain a full restart capability for restoring a program execution after either a scheduled or unscheduled interruption.

Each of these functions is essentially independent of any particular feature of structural analysis and applies to the operational control of any complex multimodule, multifile application program. The executive system is open-ended in the sense that it can accommodate an essentially unlimited number of functional modules, files, and parameters. Modification of the executive system necessary for modification or extension of functional modules is restricted to changes in entries in control tables stored within the executive routine.

Since the executive system performs all of the functions of file management and communication to and from functional modules, the modules themselves operate as independent subprograms which can only be called by the executive system and not by each other. As far as input and output are concerned, each module is supplied with input data blocks by the executive system and returns computed output data blocks to the executive system. The allocation of auxiliary file storage for data blocks is controlled by an executive subroutine called GIN0 (General Input Output) which interfaces with the operating system of the computer. An important consequence of this treatment of communications was that it greatly simplified the programming task. Each programmer assigned to a functional module only concerned himself with the task at hand and did not require knowledge of the remainder of the system. This was an important consideration in the development of NASTRAN since as many as fifteen programmers worked simultaneously.

At the beginning of each NASTRAN run the sequence of required module calls is assembled and placed in an executive table called the OSCAR (Operational Sequence Control Array). At present thirteen basic sequences, called Rigid Formats, have been compiled and stored. Each Rigid Format corresponds to a distinct type of analysis which roughly corresponds to one of the types listed in Table 1. In addition, the user can construct his own sequence of module calls by a macro instruction language called DMAP (Direct Matrix Abstraction Program). Figure 1, which is a simplified flow diagram for dynamic analysis within NASTRAN, contains seven distinct paths each of which corresponds to one of the seven Rigid Formats for structural dynamics. Several of the more important dynamic modules are indicated in Figure 1 by their mnemonics.

Restarts with new data are handled quite efficiently in NASTRAN, since all that is required is to ascertain the earliest point in the sequence of module calls where the new data will be used first. A set of restart tables assists in selecting the entry point. The tables even permit a change of Rigid Format at restart, and will allow restarts on restarts, although these features are not infallible and should be used cautiously.

2.3 Evolution of NASTRAN Functional Capabilities

The chronology of significant NASTRAN events in Table 2 shows that the program was completed in February 1970 after 3 ½ years of development and that it was released to the public in November 1970. Since then development has continued at a more modest pace. It is instructive to compare the features of the program as first delivered and at various later stages with the original specifications. This is done in Table 1. The dates selected correspond to the first publicly released version, to the most recent version currently available, and to a not-too-distant future date when all current developments will be completed.

Comparison of the specification with the first public release (Level 12), in the category labeled A. GENERAL FEATURES, reveals that three specified capabilities were not provided, namely static analysis by the force method, structural partitioning, and restart within modules. The force method was deleted for the reasons that it was farther behind schedule than the displacement method and that there were insufficient funds to finish both. There is, however, little prospect that the force method will ever be completed in NASTRAN due to almost universal acceptance of the fact that it cannot compete efficiently with the displacement method. The omission of substructuring was a consequence of the omission of the force method, for which substructuring is virtually a requirement, since it was felt that substructuring offered only a small gain in efficiency over the "bandwidth plus active column" method of matrix decomposition used with the displacement method. This is certainly true up to the core storage capacity of the computer and it was not until the advent of much larger problems (which also have logistic reasons that favor substructuring) that substructuring was implemented in NASTRAN. Ironically the current development of highly automated substructuring in NASTRAN will be completed at about the same time as a new matrix decomposition method which largely eliminates inefficiencies associated with out-of-core operations.

The requirement for restart within modules was eliminated when it was shown that the penalty in running time associated with providing access to emergency procedures at each step in the calculation outweighed the potential savings for any statistically reasonable failure rate of the computer hardware.

An overall comparison of the specification with the first public release shows that in all other matters the delivery exceeded the specification. This was particularly true with respect to structural elements where, admittedly, the specification was rather nonspecific. In other cases, such as problem size, number of computers, and the inclusion of a method of dynamic reduction, the increases were mainly due to progress in the relevant technical fields.

By comparison with the initial development, the number of increases in NASTRAN capability that have occured since 1970 appear to be much fewer in number. This is only partly true because many improvements have occured in existing categories and in areas not included in Table 1. For example, the overall speed of Level 15.5 is about three times that of Level 12, and current developments will further increase the speed by a similar factor. Nevertheless, it can only be expected that the accretion of new basic features has proceeded and will proceed rather slowly, due in part to a less intensive development effort, and in part to the limitations imposed by the original design concept. In a sense, it may be said that a computer program cannot proceed very far beyond its initial specifications, mainly for reasons of internal organization. In the case of NASTRAN this is not bad, and it augers a long life, because the initial concept was very bold indeed.

3. The Development and Distribution of NASTRAN

3.1 Organization of the Initial Development

Figure 2 outlines the relationships between the government agencies and the private companies which participated in the initial development of NASTRAN. The development was managed on the government side by the NASTRAN Project Office at Goddard Space Flight Center near Washington, D. C. Computer Sciences Corporation, a large Los Angeles-based software firm, was the prime contractor. The development team also included two major subcontractors, which were The Baltimore Division of Martin Marietta and The MacNeal-Schwendler Corporation of Los Angeles. In addition, Bell Aerospace of Buffalo, New York, developed three of the four NASTRAN axisymmetric elements under a small subcontract.

Butler has written a fairly detailed analysis [1] of the management problems which occured during the development of NASTRAN. We are concerned here only with those aspects of organization and management which had an important effect on the content of the program. The first and most important factor was that the development was done under a cost-type government contract with well-defined budget and delivery schedules. The contract called for delivery of the completed program within 20 months at a cost slightly in excess of one million dollars, not including computer usage which was provided exclusively on government-owned computers. Both targets were overrun by slightly more than a factor of two, in spite of strenuous efforts to control costs and to meet schedules. The overrun was in part due to difficulties beyond the contractor's control, such as the irregular availability of government-owned computers, but was mostly due to simple underestimation of the magnitude of a task with few direct precedents. As has been stated earlier, the force method was deleted in order to conserve cost and schedule, as was structural partitioning. One of the more serious consequences of the effort to control costs was that the dynamics portion of the program, which was finished last, was not completed to the same standards of efficiency, user convenience and validation as the statics portion, a circumstance which, it must be said, is shared by most other general-purpose structures programs. The deficiencies have largely but not completely been overcome by subsequent efforts.

An important feature of the initial NASTRAN development team was the large geographical separation of the contributing organizations. Only Computer Sciences Corporation (CSC) and The MacNeal-Schwendler Corporation (MSC) were located in the same city. This fact was recognized in the division of work, in that MSC and CSC *shared* the development of the displacement method, whereas Martin had total responsibility (engineering specification, coding and validation) for the force method. A further consequence of the division of labor and of the 3000 miles between Baltimore and Los Angeles was that CSC and MSC jointly developed an internal organization structure for the program following concepts that were *not completely shared by Martin.* These differences never came fully to light due to the premature termination of effort on the force method.

Another consequence of the division of labor among independent companies was that the interfaces were treated by formal written documents. For example, the interface between MSC and CSC was a set of documents which described the engineering content of the displacement method in terms that were directly usable by programmers in writing the code. This practice was later adopted as a standard in the post-1970 phase of NASTRAN, even in cases where engineering and programming were performed by the same group. It is recommended to all developers of computer programs.

One of the more unusual features of the initial development team was that the prime contractor's top technical personnel were widely recognized experts in systems programming but had very little experience in structural analysis. This had two important consequences. The first was that an excellent job was done on the internal organization of the program, and especially on the executive system. The second was that the management of the engineering content of the program was actually in the hands of subcontractors, which lead to a situation which Butler [1] has described as "management collapse." Since the program that was eventually completed did in fact meet or surpass the original specifications (except as noted earlier), it is difficult to maintain that the management was ineffectual. It was, however, one of the more frustrating aspects of the NASTRAN experience.

3.2 Organization of Maintenance and Distribution

Distribution of NASTRAN began even before the program was completed as evidenced by the many dliveries documented in Table 2. Final deliveries to NASA centers were completed in November 1969, and the program was offered in December to a limited number of other government agencies and aerospace companies, primarily for the purpose of evaluation. Nevertheless, the original development team, including the NASTRAN project office at Goddard Space Flight Center, was disbanded in February 1970 before any permanent policies had been established regarding distribution, maintenance and continued development. Two of the original contractors (CSC and MSC) were retained temporarily with small independent development contracts.

The crisis which ensued was resolved during the summer of 1970 by the decision to form a permanent office for the management of NASTRAN at Langley Research Center. The site chosen was favorable because Langley Research Center is NASA's primary center for structural research and includes a large community of structural analysts.

One of the first actions of the new NASTRAN System Management Office (NSMO) was to supervise the public release of NASTRAN in November 1970. Announcements were distributed that the program would be available from NASA's official distribution agency, COSMIC, located at the University of Georgia, for a price ranging from $1500 to $2000, depending on options, including source, object and executable tapes and accompanying documentation. A few months later, in June 1971, NSMO selected contractors to carry on the continued development and maintenance of the program, and announced plans for a User's colloquium to be held in September 1971.

The organization for NASTRAN maintenance and distribution which was established in 1970 and which continues to the present (June 1973) is outlined in Figure 3. The only recent addition (Fall 1972) is the NASTRAN Industrial Advisory Board (INAB) composed of representatives from large aerospace firms. The NASTRAN Advisory Group (NAG), composed of representatives from NASA centers, is the direct descendant of the committee responsible for the original NASTRAN specifications in 1965. Both INAB and NAG provide feedback from user groups which is useful in planning improvements to the program. The annual User's colloquium serves a similar purpose. In addition, users are encouraged to report suspected program errors directly to NSMO so that prompt corrective action may be taken.

The role of the maintenance contractor is not only to correct errors but also to handle all matters concerning the internal organization of NASTRAN, including modifications of the executive system, validation and installation of improvements developed by other contractors, and the creation of new standard levels of NASTRAN. The new levels are first created on the resident CDC 6600 computer at Langley Research Center and are then converted into IBM 360/370 and Univac 1108 versions using computers at other NASA centers.

Three standard levels have been released from COSMIC since the formation of NSMO. They are Level 12 (November 1970), Level 15 (August 1972), and Level 15.5 (June 1973). Neither NSMO nor COSMIC provide service or assistance of any kind to users, and since NASTRAN is a large sophisticated system, many users have experienced difficulty in installing and maintaining the program on their own computers. This defect of the distribution system has, in part, been remedied by some of the larger users. For example, the United States Navy has its own NASTRAN management office which provides assistance to user groups within the Navy. Similar services are offered, for a fee, by private companies. Users who do not have their own computers will find that NASTRAN is available at many commercial data centers both in the United States and abroad.

Another sensitive matter is the process by which development tasks are selected. As can be imagined, many more suggestions are made for the improvement of NASTRAN than the budget can support, so that priorities must be assigned carefully. Until recently this matter was largely left to the judgement of the director of NSMO, who considered the advice of the NASTRAN Advisory Group and requests from other user groups. Within the last year direction has come from NASA Headquarters to pay greater attention to the needs of the larger American aircraft manufacturers. With few exceptions these companies prefer their own proprietary programs to NASTRAN, which is a circumstance that NASA would like to change. The Industrial NASTRAN Advisory Board was formed, in the first instance, to provide a forum which would encourage the large aircraft companies to suggest improvements for NASTRAN. Their requirements, as can be inferred from the nature of aircraft structural analysis, include a higher degree of automation (particularly in the area of substructuring) and better integration (by means of improved input and output processors) into the overall aircraft design process. They do not include a strong demand for more sophisticated structural elements, such as those desired by civil and mechanical engineers.

The general question of NASA's responsibilities regarding the distribution of NASTRAN has been discussed frequently. The original specification spoke only of distribution to NASA centers, but the distribution network which was eventually set up included a general public distribution without, however, any provision for service to users. An important segment of current opinion feels that NASA's primary responsibility is to the American aerospace industry and that their needs should be given priority over those of other users, perhaps to the point where each new level of NASTRAN would be released to preferred users well in advance of a general public release.

From the viewpoint of the general community of users, the distribution system would be more effective if the releases were more frequent, if some level of service were provided, and if the needs of non-aerospace users were also considered in selecting improvement tasks. A significant feature of the present distribution system is a growing tendency on the part of prime users to make their own modifications, and also to set up secondary distribution networks with "improved" versions of NASTRAN. Before long, it is likely that the ambition of the original development team to create a universal standard for communication between structural analysts will be nothing more than a vaguely remembered dream.

References

[1] BUTLER, T.G., "Considerations for the Design of a General Purpose Structural Analysis Program," in Synthesis of Vibrating Systems, presented at ASME meeting, Nov. 30, 1971.

[2] MACNEAL, R.H. (ed.), "NASTRAN Theoretical Manual," NASA SP-221(01), April 1972.

[3] MCCORMICK, C.W. (ed.), "NASTRAN User's Manual," NASA SP-222 (01), June 1972.

[4] HENNRICH, C.W. (ed.), "NASTRAN Programmer's Manual," NASA SP-223 (01), Sept. 1972.

[5] Anon. "NASTRAN Demonstration Problem Manual," NASA SP-224 (01), June 1972.

[6] MACNEAL, R.H., and MCCORMICK, C.W., "The NASTRAN Computer Program for Structural Analysis," Computers and Structures, Vol. 1, pp 389-412, 1971.

[7] "NASTRAN: User's Experiences," NASA TMX-2378, September 1971.

[8] "NASTRAN: User's Experiences," NASA TMX-2637, September 1972.

[9]. "Specifications for the NASA General Purpose Digital Program for Structural Analysis," Prime Contract NAS5-9974, Exhibit (A), December 13, 1965.

TABLE 1. NASTRAN FEATURES

A. GENERAL FEATURES	December 1965 (specification)	November 1970 (public release) Level 12	July 1973 (current) Level 15.5	Future (currently under development)
1. Computers	IBM 7094/7040 DCS + "future" computers	IBM 360/370 Univac 1108 CDC 6400/6600	(same)	(same)
2. Program Language	FORTRAN IV (plus assembly language where necessary)	(same)	(same)	(same)
3. Precision Options	$\geq 10^{16}$	all double precision	some single/double precision options	all single/double precision options
4. Problem Size - Static - Dynamic	 2000 dof 1000 dof	 unlimited unlimited	(same)	(same)
5. User Control - Matrix Abstraction - Rigid Formats - Alters to Rigid Formats - Restart Between Modules - Restart Within Modules	 yes yes no yes yes	 yes yes yes yes no	(same)	(same)
6. Approach to Static Analysis - Displacement Method - Force Method	 yes yes	 yes no	(same)	(same)
7. Approach to Dynamic Analysis - Modal - Direct	 yes yes	 yes yes	(same)	(same)
8. Structural Partitioning	yes	no	yes	greatly improved

TABLE 1. NASTRAN FEATURES (Continued)

B. ANALYSIS TYPES	December 1965 (specification)	November 1970 (public release) Level 12	July 1973 (current) Level 15.5	Future (currently under development)
1. Static Structural Analysis			(same)	(same)
- Basic Static Analysis	yes	yes		
- Static Analysis with Inertia Relief	no	yes		
- Static Analysis with Differential Stiffness	no	yes		
- Piecewise Linear Analysis	yes	yes		
2. Elastic Stability Analysis	yes	yes	(same)	(same)
3. Dynamic Structural Analysis			(same)	(same)
- Vibration Modes	yes	yes		
- Complex Eigenvalue Analysis	yes	yes		
- Frequency Response	yes	yes		
- Random Response	yes	yes		
- Transient Response	yes	yes		
4. Fluid-Structure Interaction	no	no	yes	(same)
5. Heat Transfer	no	no	yes	(same)
6. Aeroelastic Analysis	no	no	no	yes

TABLE 1. NASTRAN FEATURES (Continued)

C. STRUCTURAL MODELING	December 1965 (specification)	November 1970 (public release) Level 12	July 1973 (current) Level 15.5	Future (currently under development)
1. One-dimensional Structural Elements	Extension Bending Torsion	ROD BAR	(same)	(same)
2. Two-dimensional Structural Elements	Membrane Plate Bending Plate	Membrane Plate Bending Plate Shear Panel Shell of Revolution	same plus isoparametric quadrilateral membrane	same plus higher order plate and shell elements
3. Three-dimensional Structural Elements	none	Solid of Revolution	same plus constant strain tetrahedra (alone and combined)	same plus isoparametric hexahedra
4. Other Structural Elements	none	Scalar springs, masses and dampers general element nonlinear dynamic elements	same plus improved general element	(same)
5. Mass Properties	"Consistent"	"Consistent" Concentrated	(same)	(same)
6. Rigid Constraints	nonspecific	single-point and multi-point constraints	(same)	same plus rigid elements
7. Static Loads	Concentrated Distributed Thermal Enforced displacement	same plus gravity and centrifugal force	(same)	(same)

TABLE 1. NASTRAN FEATURES (Continued)

D. OTHER FEATURES	December 1965 (specification)	November 1970 (public release) Level 12	July 1973 (current) Level 15.5	Future (currently under development)
1. Matrix Decomposition	"automatic selection of most efficient method"	bandwidth plus active-column method	(same)	active/passive column method
2. Plotting	Perspective Sterographic	Orthographic Perspective Stereographic X-Y Plots	(same)	same plus contour plots
3. Symmetry	---	Reflective	Reflective Cyclic	(same)
4. Real Eigenvalue Methods	"several methods"	Determinant Iter. Givens Inverse Power	(same)	(same)
5. Complex Eigenvalue Methods	nonspecific	Determinant Iter. Inverse Power	same plus Upper Hessenberg	(same)
6. Dynamic Reduction	---	Elastic(Guyan)	(same)	same plus orthogonal iterate method
7. Structure-Control System Interaction	"determine stability"	direct representation of control systems by "extra points"	(same)	(same)
8. Input of Substructure Properties	Static Influence Coefficients, Vibration Modes	General Element, Direct Matrix Input, User-assisted modal synthesis	(same)	(same)

TABLE 2. NASTRAN CHRONOLOGY

A. THE GODDARD EPOCH

1964	NASA Ad Hoc Committee formed to find a structural analysis computer program best suited to NASA's needs. They advise development of a new program.
1965, July	Request for Proposal for new computer program issued from NASA Goddard Space Flight Center (GSFC)
1965, December	Contracts awarded to two industry teams (Team I: Computer Sciences Corporation (CSC), MacNeal-Schwendler Corporation (MSC), and Martin (Baltimore Division); Team II: Douglas, Bell Aerospace, Phioco-Ford and Computer Usage) for preliminary design.
1966, March	Preliminary design documents delivered.
1966, July	Contract for development awarded to Team I.
1967, March	Static analysis by displacement method becomes operational.
1967, May	Disclosure of major slippage in development schedule.
1967, September	The mnemonic NASTRAN adopted.
1968, January	Static analysis by force method becomes operational. Installation of static capability and training course at GSFC.
1968, Spring	Delivery of static analysis capability to NASA centers.
1968, Summer	Decision made to stop development of Force method.
1969, Spring	Delivery of complete NASTRAN capability and training courses at GSFC. Begin installation and training at other NASA centers.
1969, November	Complete conversion to CDC 6600 and install at Langley Research Center (last NASA installation).
1969, December	Release to a limited number of aerospace companies and government agencies.
1970, February	Completion of development contract; GSFC disbands the NASTRAN project office.

TABLE 2. NASTRAN CHRONOLOGY (Continued)

B. THE LANGLEY EPOCH

1970, October	Formation of NASTRAN System Management Office (NSMO) at Langley Research Center (LaRC).
1970, November	First public release (Level 12) from COSMIC.
1971, June	Award of Maintenance Contract to MacNeal-Schwendler (MSC). Award of Element Development Contract to Bell Aerospace.
1971, September	First NASTRAN User's Colloquium at LaRC.
1972, June	Award of contract for Aeroelastic Addition to MSC.
1972, August	Release of Level 15 from COSMIC.
1972, September	Second NASTRAN User's Colloquium at LaRC.
1973, June	Release of Level 15.5 from COSMIC.

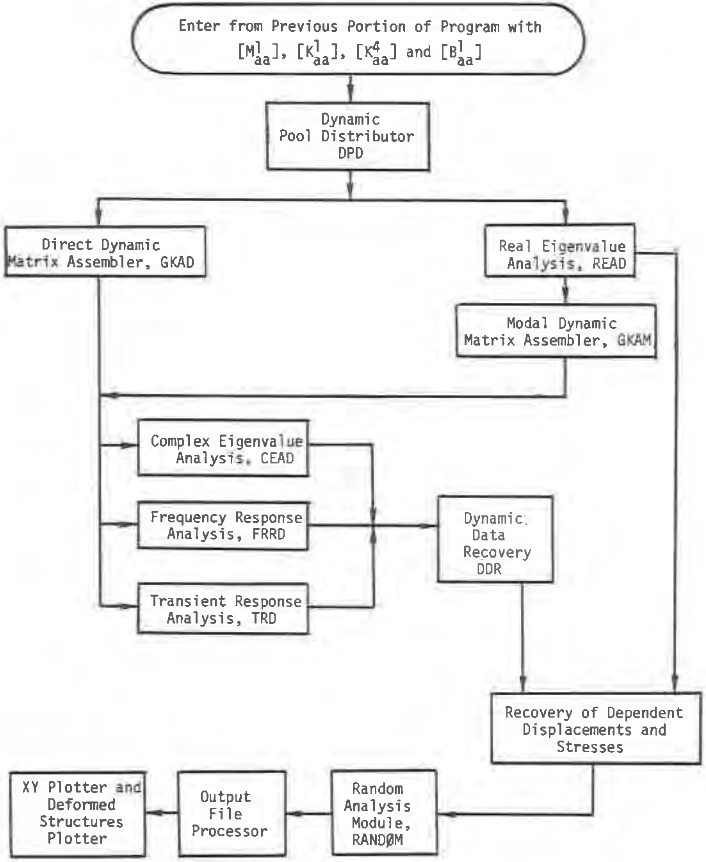

Figure 1. Simplified Flow Diagram for Dynamic Analysis within NASTRAN

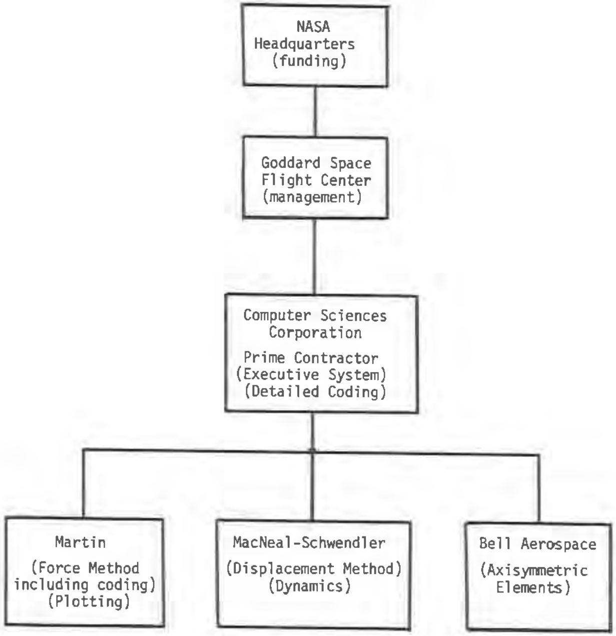

Figure 2. Organization of the Initial Development of NASTRAN

M $1/3^x$

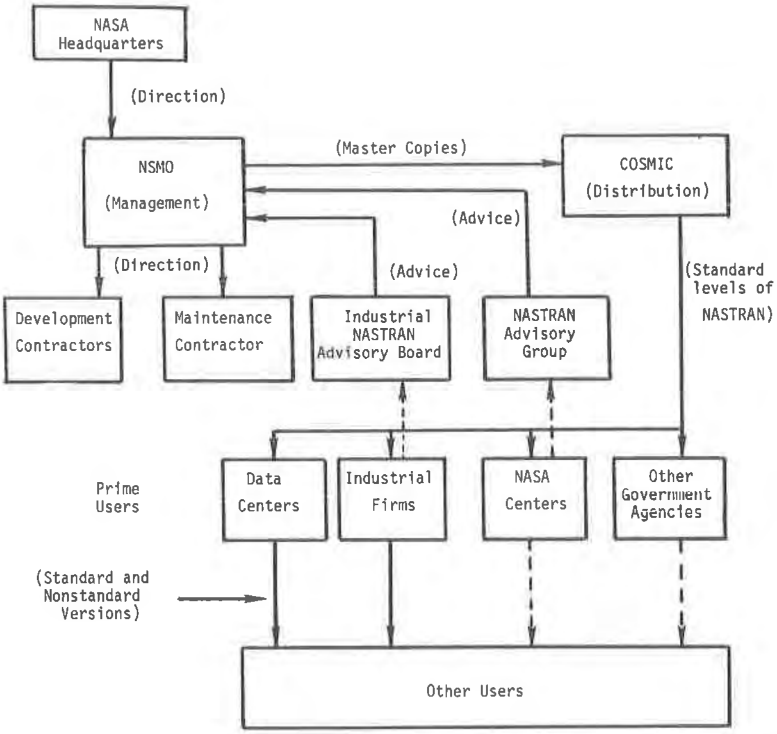

Figure 3. Organization for NASTRAN Maintenance and Distribution