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Symposium on the Use of the Digital Computer in Aircraft Structural Design and Analysis

(Farnborough - 15th April 1966)

Edited by

G. G. Pope

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SYMPOSIUM ON THE USE OF THE DIGITAL COMPUTER IN AIRCRAFT STRUCTURAL DESIGN AND ANALYSIS

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G. G. Pope

SUMMARY

A Symposium on the use of the digital computer in aircraft structural design and analysis was held at Farnborough on 15th April, 1966, and was attended by representatives of the aircraft industry, the computer industry, academic institutions and the Civil Service. This Report reproduces the papers presented at the Symposium, and includes an edited version of the discussions that followed the papers.

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*Replaces R.A.E. Technical Report 66239 - A.R.C. 28703

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CHAIRMAN'S INTRODUCTION

Mr. L.F. Nicholson welcomed the visitors to the Symposium and said that the large high-speed digital computer is changing the whole way of thinking in almost every branch of engineering science, and in many other fields as well. These changes of thinking and the changes of doing which arise from them will all come about inevitably wherever aeronautical research, design and construction take place. It is not a matter of accepting or rejecting the computer in any of these fields; the important thing is the timing and the quality of the thinking on how we use computers. We can only win markets for our aircraft if our reaction to the computer is both quick and well conceived.

The use of the computer in aircraft structural design is increasing rapidly in this country. The purpose of this Symposium is to review the whole field and to set British effort in perspective in the world scene. The papers and discussion should help us to see whether we are lagging seriously or not, and they should also help us to assess more clearly where we are going, where we should be going, and how to get there more quickly and more surely. We should also get a clearer picture of where the main pay-off in the use of the computer may lie. Is it in time saving in structural analysis and in the design development process? Is it in the freedom to analyse a wider range of alternative solutions in more detail? Is it in the saving of weight by more efficient design optimisation, or is it in some other way? Will the use of computers lead to changed priorities in other fields? Will it, for example, lead to demands for more precise definitions of loads and manoeuvres? A major change in one part of the aeronautical field nearly always leads to corresponding changes elsewhere. This Symposium will have been worthwhile if it helps us to answer even a few of these questions.

SOME THOUGHTS ON THE IMPACT OF THE DIGITAL COMPUTER ON THE AIRCRAFT INDUSTRY

by

J.H. Argyris (Technische Hochschule, Stuttgart and
Imperial College, London) and
P.C. Patton (Technische Hochschule, Stuttgart)

SUMMARY

In the past decade there has been a tremendous growth of digital computers and computing methods in the aircraft industry. This has been particularly apparent in the United States where the aircraft and aerospace industry showed a pioneering spirit in applying digital computing machinery and techniques. The latter was all the more remarkable since many of the ideas originated in Europe (which includes Britain!), but were not properly applied due to the lethargy and lack of foresight displayed by many people on the technical and commercial management side. Imagine that we sunk nearly £400 million into the development of the Concorde but did not provide its imaginative designers and stress analysts with the corresponding computing power.

Although the initial custom-built computers were used by universities and by military establishments for logistic studies, the first major commercial machines for scientific computations were introduced by the American aircraft industry. The availability to aircraft engineers of computers of ever increasing power has naturally heightened interest in procedures for using them with greater sophistication. Indeed, in the field of analysis of complex structures it has brought about a complete revolution. Matrix methods which were possibly mainly of academic interest only 10 to 15 years ago, have undergone a stormy development in the last decade and are now widely applied by industrial firms. The complete aeroelastic investigation of flying vehicles is being programmed today, and programmes are being written even for highly complex three-dimensional, nonlinear, elasto-plastic investigations of re-entry configurations under extreme heat gradients.

Most aeronautical engineers would probably agree by now that the digital computer has replaced older graphical, analogue and analytical methods, and is about to replace such stand-bys as lofting, drafting and other engineering design operations. However, at the same time one finds no agreement on the philosophy of approach to the computer. Initially, computers were considered basically to be the same sort of machinery as the desk calculator, merely

larger and faster. Such a philosophy naturally limits the user's mind to the applications and solutions he may obtain on a desk machine but for the fact that he does larger problems in less time. We have found, on the other hand, that the power of computer computations commands a complete reorientation of our mental processes in order to obtain the optimum from the valuable machinery.

We have found, inter alia, that the engineer must use the computer as best suits him, rather than allowing himself to be limited to the present-day high-level programming languages like ALGOL and FORTRAN. These languages are designed to translate algorithms and formulae into machine languages and are neither elegant nor efficient for the formulation of structural analysis involving problems with very large matrices and supermatrices. In this connection we have developed some interpretive matrix codes which allow the user roughly 150 matrix operations at a level of efficiency only slightly lower than that of special purpose hand-coding. We have under development languages of an even more general character for the solution of engineering problems involving branched data structures of any kind; in particular, many-levelled supermatrices. This code, denoted as ARGMAT, is a generalization of ALGOL and allows procedures which output lists formed as matrices, supermatrices, or "trees", as well as the real, integer and Boolean procedures of ALGOL 60. Parallel to this mathematical software, we have initiated powerful structural languages like ASKA (Automatic System for Kinematic Analysis) which allows the engineer a very general yet efficient computer solution for problems to be solved by the matrix displacement method. As a matter of fact, ASKA includes the possibility of describing with relatively few orders highly complex two- and three-dimensional topological assemblies of elements.

It should be our aim that fast, efficient, easy-to-use methods of analysis should be at the centre of automated design systems implemented on a computer. Within the next decade we expect computer-based methods of analysis to be so extensive and efficient that the aircraft designer will be able to ask the computer for an instantaneous stress or dynamical analysis of any structural grouping he can imagine and sketch on a graphical computer input device. At the same time, we shall be using the so-called conversational approach to the computer whereby a dialogue is effectively taking place between the engineer and the computer. The requirements of such advances in technology are tremendous. We must do a lot of work in nonlinear methods. Also a systems approach to synthesis of structures by simulation and analysis will be necessary. Many engineers will have to change their philosophy of computer utilization, and we can also expect to exert some feed-back towards computer developments. For example, efficient solutions to nonlinear problems will require more sophisticated, faster and less costly computers.

Finally, a computer revolution in aircraft design and analysis should have organisational implications within the aircraft firm tending to elevate the importance of the engineer who has tamed the computer. This, however, will require earlier changes in engineering education; such changes are actually taking place already in some universities.

INTRODUCTION

The computer's role in engineering technology has become more apparent during the past few years. The engineers who developed the first computers considered them to be logical engines and often as "ends-in-themselves". We are all happy to leave behind this over-consciousness of the computer as merely a logical machine. The current conservative philosophy of computation might best be summarized as the concept of "the computer as a rapid desk calculator". This latter outlook may not be quite as sterile as over-fascination with the machinery <u>per se</u>, but still dooms its holder to computer solutions no more imaginative than those he could have obtained on a desk calculator, merely produced in less time and on a somewhat larger scale. It is interesting to note that Babbage and his associates, who were so limited by the engineering technology of their day, were perhaps not as limited in imagination as some of the scientists and engineers of our own time[1].

Let us look at some of the more recent attitudes regarding computers. Early results coming from research based on these newer attitudes seem to indicate that they may be far more fruitful than former notions. Firstly, we might consider the computer as an abstract symbol manipulator. This is certainly the philosophy of the systems programmer who develops machine translators and interpreters for the artificial languages in which computer users code their problems. This concept has proved fruitful in the application of the computer to natural languages as well; e.g., translation of natural languages, computer literary studies, authorship tests, character recognition, etc. But, aside from these first fruits from the fields of application, this concept leads to an even more valuable one. The human brain has a tremendous, well-organized data store, the largest, most rapid computer operating today, the UNIVAC Nike-X military computer[2] approaches one per cent of the storage capacity of the human brain but is not nearly so cleverly organized. The human brain, while complex and vast as a data store, is limited to the number of symbols it can consider at any given instant and is even more limited by the speed at which it can relate this small set of "current" symbols. A well-trained mind can handle about 10 to 20 small expressions or related groups of symbols at a time. The computer is relatively less limited in the number of symbols it can consider in an instant and even less limited in its ability to relate these symbols rapidly. Now most thinking, even of the most abstract sort, ultimately amounts to relating or organizing sets of symbols. To the extent that the computer can do such tasks at the behest of a human being or "source" of human intelligence, the computer is an "amplifier of human intelligence". This philosophy of computation is proving very useful in such areas as decision-making, command and control systems, information systems, theorem proving, pattern recognition, etc.

It is a short step from the computer as an amplifier of human intelligence to the notion of artificial intelligence itself. The mere mention of artificial intelligence raises the bugaboo of machine ascendency over humanity, first expressed by Samuel Butler in Erewhon and Erewhon Revisited in 1833. This is not what researchers in artificial intelligence are trying to do; they are merely attempting to push the capability of machines in the direction of man's capabilities[3]. One might say that this theory of computation has divided the computer field into two factions: the conservatives and the progressives; however, engineers have always been willing to accept a philosophy on a pragmatic basis and thus we are interested to know whether this attitude is useful rather than whether it is true or not. A short survey of the field[4,5] is sufficient to convince even the cynic that this approach to the computer is useful. Research already done in this field may be gathered under five headings: Search, Pattern Recognition, Learning, Planning, and Induction. The theme of most efforts is the following: if one does not know how to solve a certain problem, one may write a computer programme to search through some large space of solution possibilities and selectively narrow these down against not necessarily distinct nor predetermined criteria[4]. The thinking of the MIT school of computer philosophers following this approach has had much to do with the development of the man-and-computer technology and, in particular, project MAC. As a result of such new approaches, within 10 years engineers will find themselves dealing with computers more as colleagues or team members than as machines. Computer scientists will be arguing about artificial creativity by that time, for by then artificial intelligence will be taken for granted.

Much of the effort of elevating the behaviour of computers is devoted to teaching them to communicate; and over the past decade or so it has become commonplace to be able to communicate with them more nearly on our level by employing phrase-structured artificial languages rather than the bits, digits and characters of machine languages. In the recent past we have witnessed the transition from machine languages to high-level languages, like FORTRAN, ALGOL, COBOL and their derivatives, to interpretive languages for many special fields of study[6,7] and to the current applications languages for special problems. This progress has definitely been from machine orientation towards human orientation, and in the future it will be even more so. Current research in the field is leading to the development of sophisticated graphical languages for communication with computers; these require new input/output devices, hardware innovations and, in practice, more sophisticated computer organization. Soon, every engineer and designer will be able to communicate with the computer in the language of graphics, just as today the mathematician communicates with it by employing mathematical formulae (FORTRAN) or algorithms (ALGOL); the businessman by a subset of his own natural language (COBOL). There are more than 1700 different programming languages in use today in more than 700 different application areas, but current research is leading towards a unified linguistic framework, which will span differences in these many diverse fields[8].

COMPUTER-AIDED ENGINEERING ANALYSIS

Our own primary interest in computer application is to engineering analysis and thus ultimately to engineering design. The methods of engineering analysis play a central role in research and development, for, at this level, problems could - at least in the past - be slightly isolated from the real world, linearized, compartmentalized, sub-divided, etc. until "the state of the art" applies with reasonable accuracy. If engineering analysis played a somewhat less important role in the later stages of product design and actual production, it is because the problems become too complex for the convenient mathematical assumptions chosen earlier. Since these assumptions and linearizations date from an era in which the tools of analysis were pencil and paper, we should be willing to leave them behind and make less conservative assumptions more suited to our modern tool, the computer.

The fact that good design and efficient production are art rather than science is a curse, not a blessing. We can point with pride to aircraft design and production achievements of the past, but we cannot repeat them upon command, even when the aeroplane is a similar one. Only a year ago the popular press was asking: Why wasn't the TSR-2 as successful as the Spitfire? We couldn't plug new variables into the old design and production formula because nobody could say what the old formula was. One might say that this is an over-simplification, or that it is far beyond today's technology, or, as some rightly call it, "the state of the art", but this is the direction we should be going and it is the direction in which some aircraft firms are already going.

The Boeing Company has developed computer procedures[9] which allow the designer, assisted by a computer mathematician, to express his ideas to a computer. The machine then does in 20 minutes what would take about 80 hours of a high-level draughtsman's time. It allows the designer to refine his design, employing methods of analysis already programmed for the machine. Having developed a tentative design after several "conversations" with the computer, the design/engineering team may request automatic machine tool outputs for the preparation of models at any scale desired or for templates to aid in building a full size wood and plaster mockup. Having finalized the design, the man/computer team may then provide automatic machine tool outputs for the production of prototype vehicles. Does this sound far-fetched? But for the vicissitudes of government contracting, the Boeing DynaSoar re-entry research vehicle would have been the first product 100 per cent designed, analyzed, simulated and produced automatically by computer and computer-driven machines.

The impact of computers in aircraft engineering extends not only towards design and production but also towards the process of creating the new methods of engineering analysis required to allow automated design. The senior author has pointed out this relationship between the computer and the theory at greater length in a previous lecture[10]. A few examples from the matrix analysis of structures should suffice to show the influence of our new tool the computer on the theories we develop to employ on it.

The first problem, a linearly elastic one, is that of a cylindrical arch dam which, for the purpose of comparison with model studies, is considered to be fully built-in at the valley-dam interface. The geometry of the dam and the support idealization is shown in Fig.1, whilst Fig.2 illustrates the idealization of the structure into a series of quadrilateral CUB6 elements, each consisting of six ten-point tetrahedra (TET10)[11,12]. With this assumed idealization the problem reduces to one with 1800 unknowns. The water pressure loading is applied in such a way as to be kinematically consistent with the assumption of a linearly varying stress and strain within the TET10 element. This is illustrated in Fig.3. The next three figures (4, 5, 6) show some of the results we obtained, with Fig.4 illustrating the deflexions and Figs.5 and 6 the tangential and vertical stresses σ_t and σ_z at the vertical plane of symmetry. The next example, Fig.7, that of a plate with a semi-crack in the middle, loaded uniformly at the ends, shows our method as applied to problems of nonlinear elastoplasticity. The approach is that of Ref.13 whereby, in the first elastic analysis, the Prandtl-Reuss equivalent stress just attains at one or more points the yield stress; note that, due to the finite element technique, the strictly infinite stress concentration is reduced to a finite one. However, the finer the net the greater becomes the initial stress concentration. From this point onwards the loading increases incrementally. Within each step the initial load vector J, associated with any region that has gone plastic, is calculated and used in the following step. This is the direct incremental procedure given in Ref.13, which indicates also a more refined method. Some of the results are shown in the following two figures (Figs.8, 9). The first of these indicates the development of the area of plastic deformation with increasing applied load and the second shows the distribution of the (lengthwise) stresses, for three layers adjacent to the crack. With the spread of the plastic zone the influence of a finer net becomes less pronounced. A group under J.B. Spooner was closely associated with the numerical solution of both problems.

It will be obvious that, with increasing demands on accuracy and more complex problems, matrix methods require more refined basic elements. Two such new developments based on a generalization of the TRIM6 (linear stress)-(linear strain) triangular element[14] are TRIM6T[15] and TRIAX6[15,16]. TRIM6T is a TRIM6-type element but which takes into account a linear variation also of the thickness. TRIAX6, a rotatable TRIM6 element, shown in Fig.10, is used for the idealization of an axisymmetric body and loading, to enable the programmer to consider only one longitudinal section, and therefore the whole problem, as though it were two dimensional. This proves enormously helpful in reducing the number of unknowns in this type of three-dimensional analysis as they occur, for example, in certain re-entry body configurations.

The subject of structural optimization or structural synthesis is receiving considerable attention at the present time and will no doubt receive more in the future. One aspect of the problem is that of layout design where a prescribed loading is to be carried across a given space by a structure of minimum weight, its geometry to be obtained. Another is the "dimensioning" aspect where the geometry is given in advance, such as the external shape being fixed by aerodynamic considerations, and the sizing of the covering and internal supporting structure is to be determined.

Our past studies have been directed towards the latter, an example of which is illustrated in Fig.11, showing the structural idealization employed for a hypothetical supersonic transport aircraft[10,11]. Using what we might call an engineer's optimization procedure (Fig.12) whereby, starting with the minimum prescribed sheet thicknesses and boom areas, these are appropriately factored up in the ratio of the largest stresses occurring under a number of loading cases to the allowable stress; several analysis loops are performed until convergence is achieved (Fig.13). This procedure was, in fact, the basis of aircraft structural design when wings and fuselages were slender and only one loop was necessary, but modern configurations tend to be more and more of an integrated, complex form. The result may or may not be the lightest possible structure, for a variety of reasons.

Firstly, where solutions of the simplest statically indeterminate framework exist, they indicate that some bars may not be fully stressed in a loading case. This follows from the kinematic requirement of strain compatibility (which is avoided in Michell structures by the bars always crossing at right angles) and may possibly cause convergence to a configuration which is not the lightest. Furthermore, the convergence is greatly influenced by the number of significant loading cases and the relative magnitude of the minimum allowable sheet thickness. Other traps may lie in the idealization and choice of elements in the calculation. More sophisticated elements like the aforementioned TRIM6T will permit a less restricted approach to optimization.

A more rigorous approach to structural synthesis has been developed by Schmit at Case Institute of Technology[17,18] (Fig.14) but, as yet, its complexity restricts its application to very simple systems. The problem is reduced to one of mathematical programming and the method mainly employed is that of steepest descent. This general method could, of course, optimize for minimum cost or some other criterion instead of minimum weight, depending upon the objective function chosen.

The first method is, on the one hand, nonrigorous but usable and the second, on the other, rigorous but restricted at present by its complexity to simple systems. We are pursuing at present in a group under Nigel Benson the synthesis problem for large complex systems. Clearly, a thorough optimization study is well worth its cost in computer time before embarking upon a major project, such as a supersonic transport aircraft.

Although we have been much too busy developing theories to stand back and formulate a pattern, metatheory or philosophy of our approach to structural problems, perhaps a few guiding principles may be of interest. Firstly, we have given up pencil and paper methods and the continuous analysis born of such primitive tools. The computer is able to consider all the elements of a complex structure simultaneously, and thus we develop theories which allow it to use its capabilities to the utmost; for example, the kinematically consistent mass matrix and its associated nodes-within-element technique for representing displacements is a "micro-Rayleigh-Ritz" idealization which allows for more accurate and uniform prediction of dynamic behaviour than previously possible[11,19]. Our new matrix codes and application languages are able to cope with the data volume and computer time problems which result from so fine a representation of a basically discrete nature because they are self-adaptive; i.e., the software moulds or adapts itself to the theory and the current problem. It can be efficient even on a present-day computer, like the UNIVAC 1107, because it is self-organizing in its use of the 1107's hierarchy of backing stores. In short, we strive to bring the computer to the problem rather than bringing the problem to the computer. We think results, the true test of pragmatic validity, have shown this philosophy to be a very fruitful one.

A grand approach to the applications is not without its labours and headaches, however. We have paid the price in software development and, as you all know, software comes at only one price: extremely dear. Our experience with the use of high-level compiler languages, such as FORTRAN IV and ALGOL 60, both of which exist in very good implementations on the UNIVAC 1107, has not been very rewarding. For large-scale-matrix work, these languages are rather clumsy and not always efficient; however, as a medium for preparing subroutines for various input/output formats, data reduction and smoothing, computing the properties of new structural elements, etc. we find them very valuable. Good as these languages are for the general run of small engineering problems, we feel that interpretative programming languages will be much more used in the next five years than they have in the past.

In the advanced military command and control field, computers currently in design (and at least one in actual use) have up to 25 central processors, 64 banks of high-speed memory, 16 input/output processors, each having 16 I/O channels. A configuration like this leaves concepts like FORTRAN, ALGOL and static translators or compilers behind. The super computers of the next decade will probably follow this pattern in hardware and will thus require similar approaches to software, i.e., interpretative, self-adaptive programming languages which extend the recursion and dynamic storage allocation features of ALGOL in a single core store to be effective over P processors and S storage devices occurring on L levels of a hierarchy of stores.

We have set the task but are not content to wait for manufacturer's systems programming teams to complete it. Our own software developments are primarily orientated towards the matrix interpretative codes needed to implement our theories. Our early experience was with the Pegasus matrix code, very advanced for its time, and later with our own SELMA code[20] for the UNIVAC 1107. SELMA has more than 150 matrix operations and is rather similar to the Pegasus code; however, it takes advantage of the 1107 A-package multiprogramming executive system and thus allows several different programmes to run in parallel with each other and with real-time data collection and media conversion operations. We recently announced BEMAT[21], a new code which has all the features of SELMA but also allows the user to extend the system by coding his own FORTRAN IV subroutines to be called from the interpretative programme string.

Our current project in this area is the new code, ARGMAT[22,23], a language for processing data manifolds or any complex branched data structures that may arise in engineering analysis or, in fact, general analysis on a directed graph. A special case of such a data manifold is a super-matrix; an even more special case is of course an ordinary matrix. The features required for this language are:

(1) that it be able to handle large supermatrices efficiently,

(2) that it have dynamic storage allocation over a hierarchy of stores,

(3) that it be easy to programme and check out a new programme,

(4) that it be not only easy to write but also easy to read, so that an existing programme be intelligible and documented by its own text, and finally,

(5) that it will be implementable in less than one calendar year and about four to five man-year's effort.

Our response to these self-imposed requirements is a high-level language which in form is essentially an extension of the Generalized ALGOL language of Wirth[24]. ARGMAT, viz., Generalized ALGOL, is so generalized that it is translated to an intermediate language which is still more general than FORTRAN, consisting mostly of syllables and numbers in reversed Polish notation with the original block structure. This intermediate language is processed by an interpreter which essentially simulates a self-adaptive computer designed to process data manifolds rather than individual rational numbers. One might characterize this language as an ALGOL which types variables as either global or local (i.e., not real, Boolean, array, integer), and allows procedures to output highly structured lists via their names (in addition to real, integer, Boolean, and complex single variables). We have attempted to follow Iverson's notation[25] as much as possible, in order to allow ease of expression and conceptualization of matrix-like and graph-like data-manifolds.

Good as ARGMAT will be, it still is not the full answer to the engineer or designer's needs, but merely a language in which we can implement our theories and realise them on the computer. The trend in computer applications nowadays is towards so-called applications languages, e.g., APT, LP, STRESS, and the ASKA language developed by Dr. Hussein Kamel and his Applied Programming Group at the Institute in Stuttgart[26]. Applications languages allow virtual automation of production, planning, and analysis procedures but they still require some human effort for modelling, data preparation, linear idealization, coordinate determination, etc. Such application packages will improve in at least two major areas in the next five to ten years. Firstly, they will have to allow communication with the engineer or designer in his own language, the language of graphics. Secondly, this very facility will require that more sophisticated methods of analysis be embodied in the subroutines of the package itself. For example, a designer should be able to have an instantaneous stress or dynamical analysis of any three-dimensional object or grouping of structural elements he can draw on a light pen display console.

COMPUTER-AIDED DESIGN AND ITS SIDE-EFFECTS

The classical design process is too little known to describe in a few words. This, in fact, is its fault. On the other hand, to employ a slightly different sense of the same word, it is also too well known to need further description here. We are much more interested to know what the computer-aided design process of the future will be. The computer will not only be essential to this new technology, it will be central to it. The computer will first be used to define the problem. Computers are being more and more used by marketing and product planning specialists to determine the specifications of the products desired by all types of consumers, both private and industrial. Having helped delineate the problem by specifying a product, the computer will then be employed by the designer in his creative response to the challenge of the problem. After some graphical conversation with the computer, he then needs to analyse his design with respect to many criteria: stress, dynamic response, flutter, production cost, works scheduling, etc. Since the computer does the stress analysis, the stress analyst will now be employed to develop methods which will keep pace with the designers imagination; his theories must handle anything the designer can imagine. Finally, having established a design that meets all the criteria in some optimal way, the computer can be requested to prepare tapes for automatic programmed tools, to lay out and plan assembly lines and then to schedule them, to prepare drawings and documentation, etc.

The design process of the future will go from demand to its hopefully economic satisfaction through a sequence of interrelated processes called problem definition, design response, engineering and economic analysis, and finally, production and transportation. Feedback from one stage to the next is the rule and is probably significant over the entire process. The benefits of future automated design systems will be tremendous but, unfortunately, the requirements will likewise be great. Firstly, we will have to do an enormous amount of research in nonlinear mechanics and corresponding numerical methods of analysis. In the field of dynamics, computer methods already fall far short of achievements in the sister field of stress analysis. These much needed new methods may require computers 1000 times faster than our UNIVAC 1107. Such machines (e.g., the UNIVAC Nike-X) exist today but only for military applications; they are probably very expensive and certainly not commercially available now. Automated design and associated methods of analysis will bring computers even closer to the real problems and, as real problems are very complex, we will need very large, very fast computers at a very low price.

To see what the aircraft industry might expect from computer hardware developments in the next decade, we must go to the computer designer[27]. Integrated circuitry will bring revolutionary changes in size, cost, and reliability of components but circuit speed may not improve so very much, perhaps only 10 times faster than the UNIVAC 1108 or IBM 360/75. Memory technology will provide significant improvements in speed, capacity, cost, reliability and size. We may expect economical high speed 0.5 micro-second memories of a quarter-million words and auxiliary memories of four million words at one microsecond. As backing stores, large drums may increase to 250×10^6 characters at an access time of 80 milli-seconds. For conventional input/output, we may look forward to 400-kcs tapes (character rate), 2000 lpm impact printers, and 5000 lpm non-impact printers. As human orientated input/output devices, we may expect character recognition and printed page readers, voice recognition and voice output (by synthesis, not recorded), nonmechanical keyboards, and graphical input/output devices with colour capability. Such extras as associative memories may be practical by then but the main emphasis will be low cost computing power. One prognosticator predicts that within 10 years we may have the computing capability of an IBM 7094 packaged in a shoe-box at a cost of a few thousand dollars.

But these predictions look more like a factor of 10 improvement than a factor of 1000; and already today there is a tremendous speed difference between electronic and electro-mechanical computer components. The solution to both of these difficulties is indicated by military computer developments; increasing multiplexity and more complex computer organization. Hopefully, this solution will be within reach of civilian as well as military budgets within 10 years.

Computer-aided design will probably bring the engineer associated with production and the engineer working as a designer considerably more importance within their organizations. In fact, the line compartmentalization of companies into marketing/engineering/production, with associated staff groups research/accounting/personnel, may change considerably. The computer has allowed better control and thus more centralization in business applications. Just as companies have become more tightly integrated from a divisional standpoint, they may, due to computers, become more integrated from a departmental-within-divisional standpoint. As the computer becomes the focal point of the company, then the engineer will increase in importance as he is better able to communicate with the computer and to use it more effectively. As the engineer and his technically trained assistants increase in importance to their companies, they will also increase their status in society.

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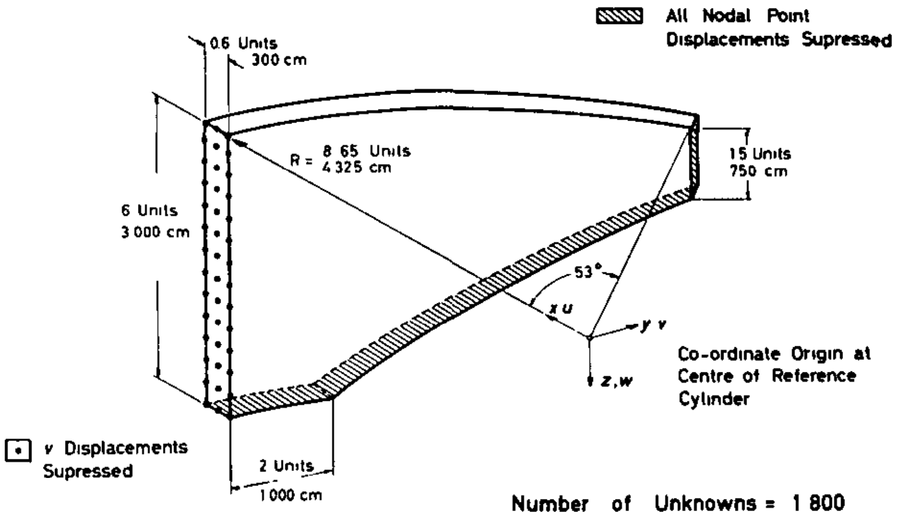
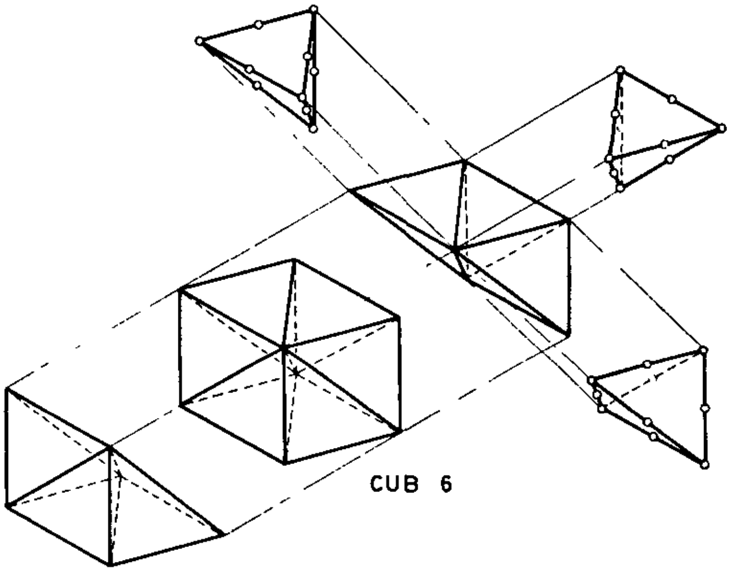


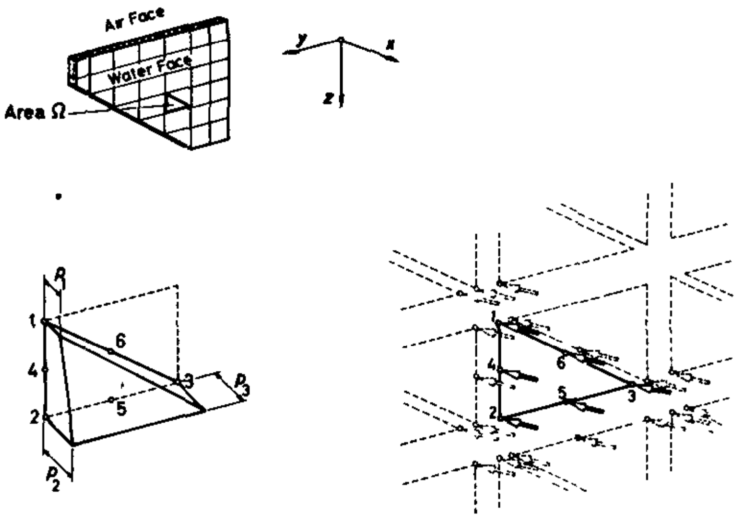
Support Idealisation and Geometry of Dam

Fig.1



Idealisation of Dam into TETRA 10 Elements
Basic Qadrilateral Prism (CUB 6) with Six Constituent Tetrahedra

Fig. 2

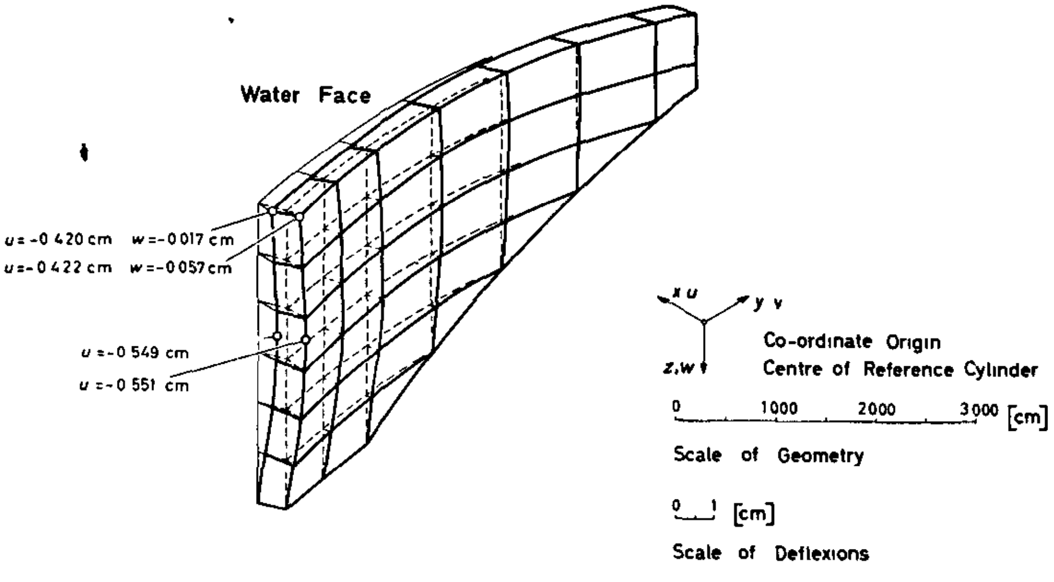


$$\begin{bmatrix} P_1 \\ P_2 \\ P_3 \end{bmatrix} = \frac{\Omega}{60} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}$$

$$\begin{bmatrix} P_4 \\ P_5 \\ P_6 \end{bmatrix} = \frac{4\Omega}{60} \begin{bmatrix} 2 & 2 & 1 \\ 1 & 2 & 2 \\ 2 & 1 & 2 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}$$

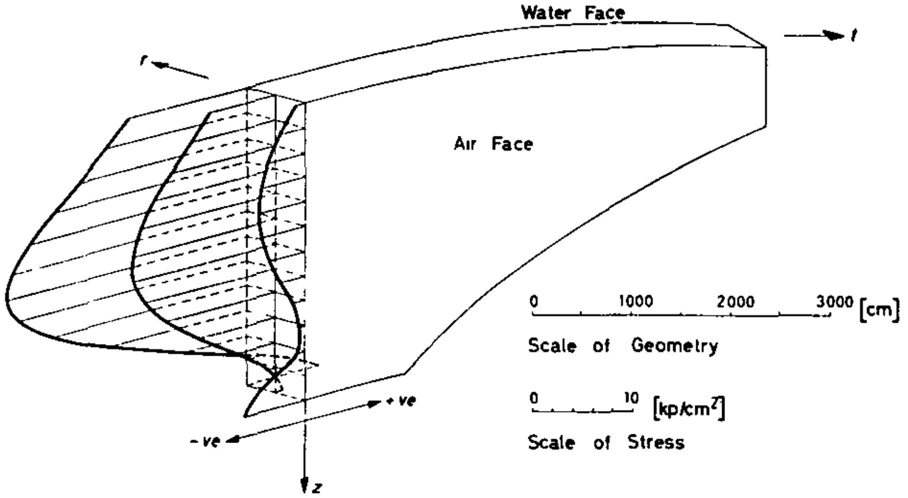
Idealisation of the Water Pressure Loading

Fig. 3



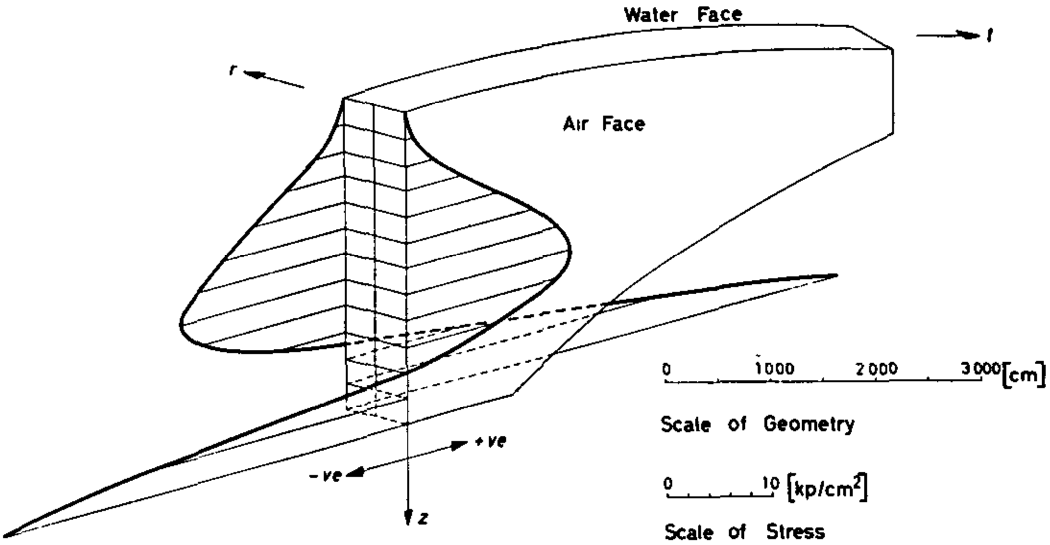
Deflexions of Uniform Arch Dam
under Water Pressure

Fig.4



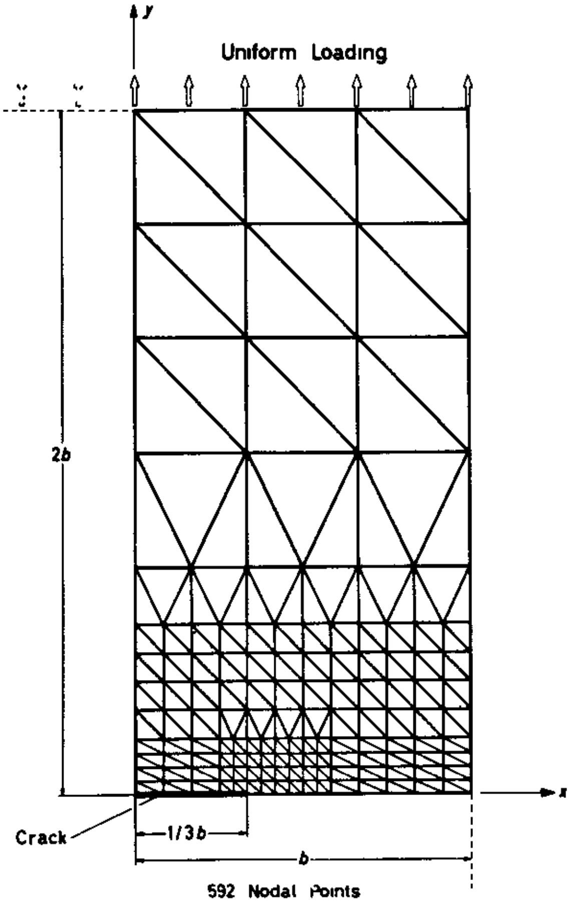
Stresses σ_t in Symmetry Plane

Fig.5



Stresses σ_z in Symmetry Plane

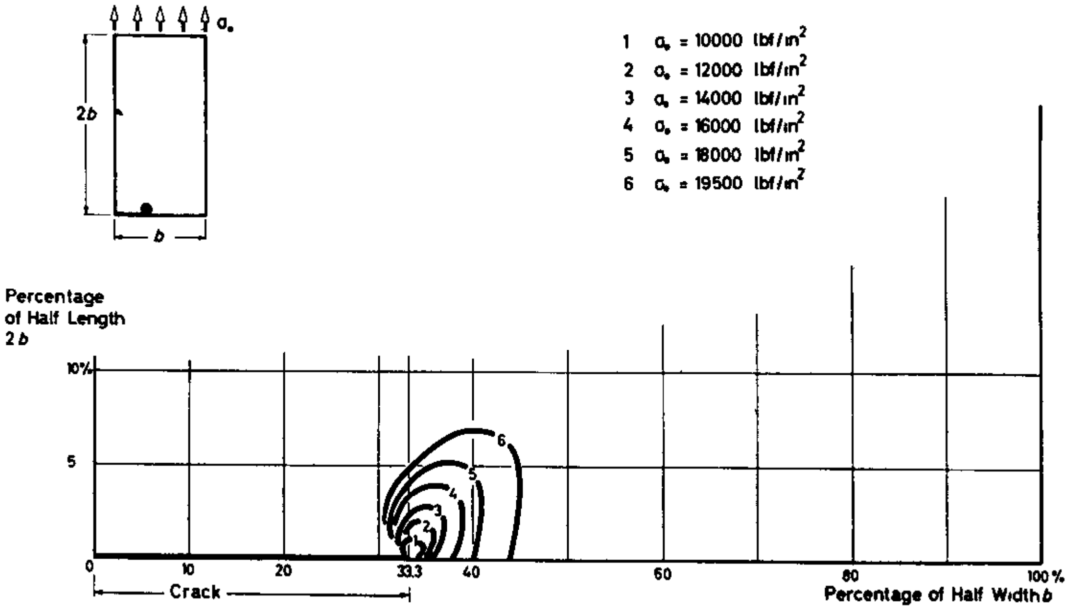
Fig.6



592 Nodal Points
273 TRIM 6 Elements
1134 Unknowns

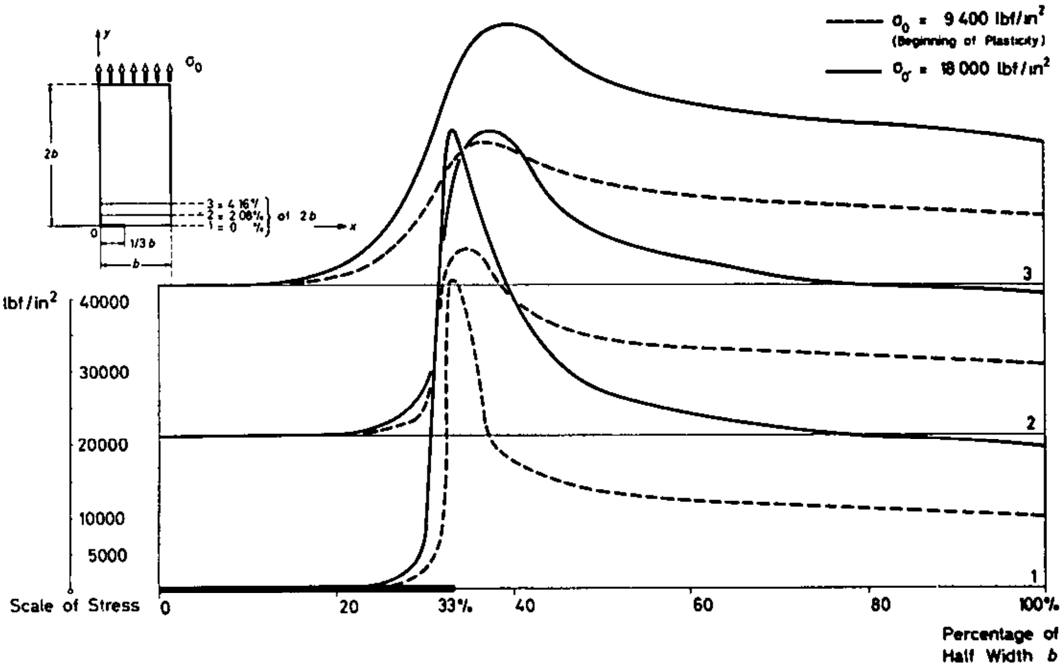
Semi - Crack
(One Quarter of Plate Shown)

Fig.7



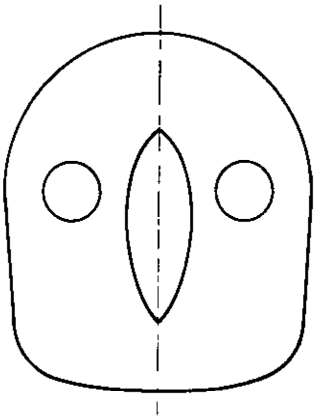
Extent of Plastic Deformation

Fig.8

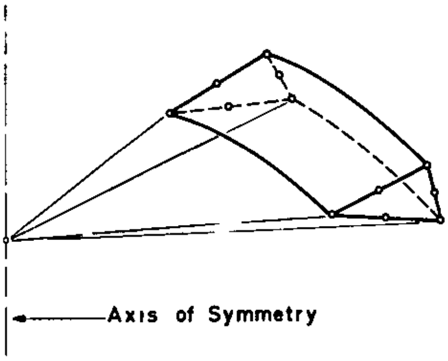


Distribution of σ_y in the Region of Crack

Fig.9

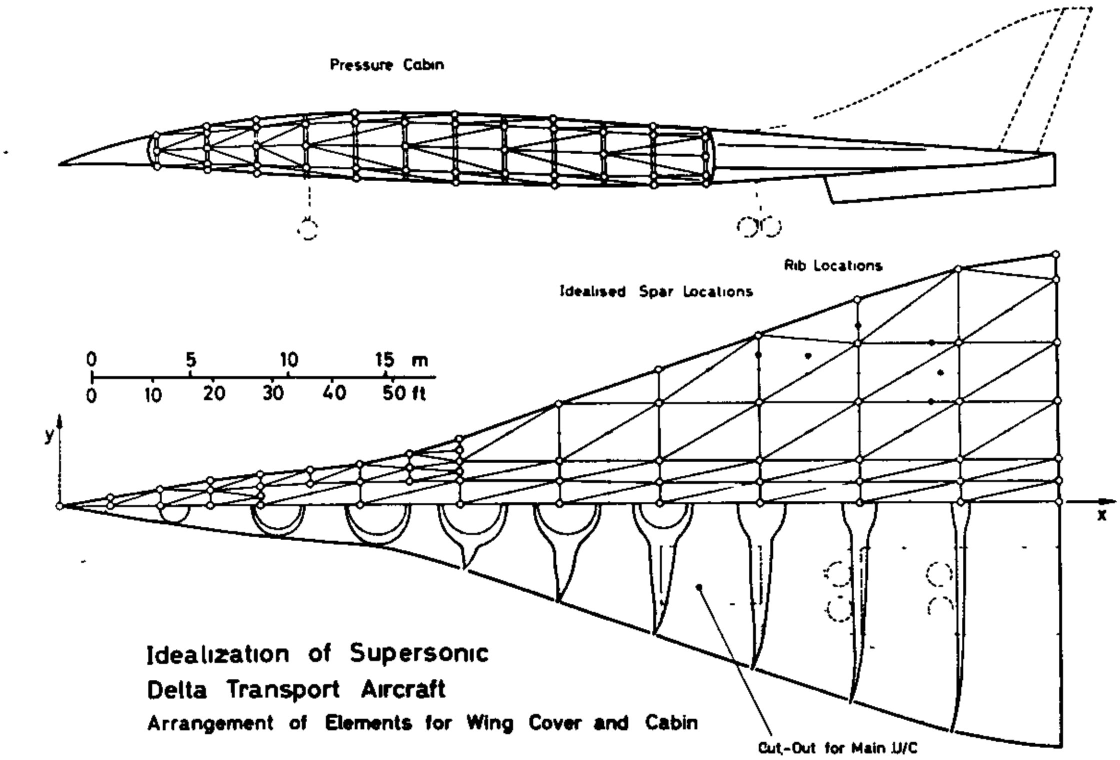


Axisymmetric Body



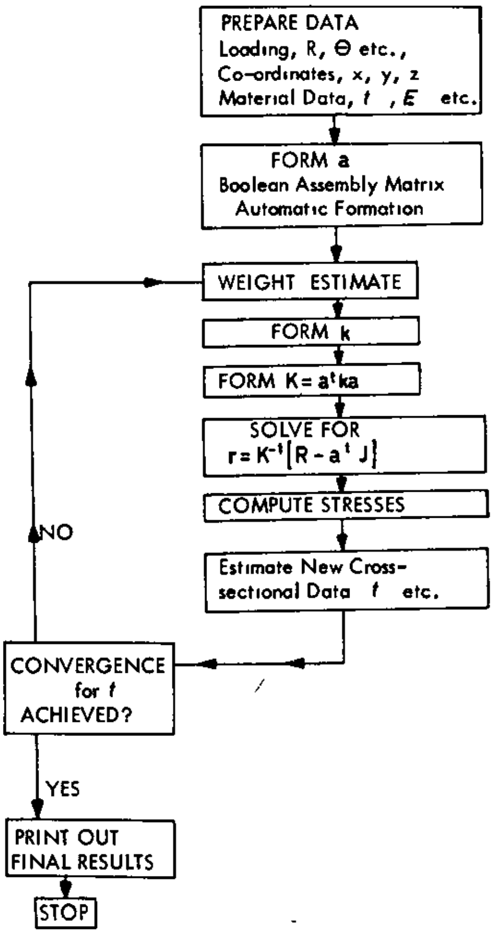
TRIAX 6 Element for Axisymmetric Bodies and Stress Distributions

Fig.10



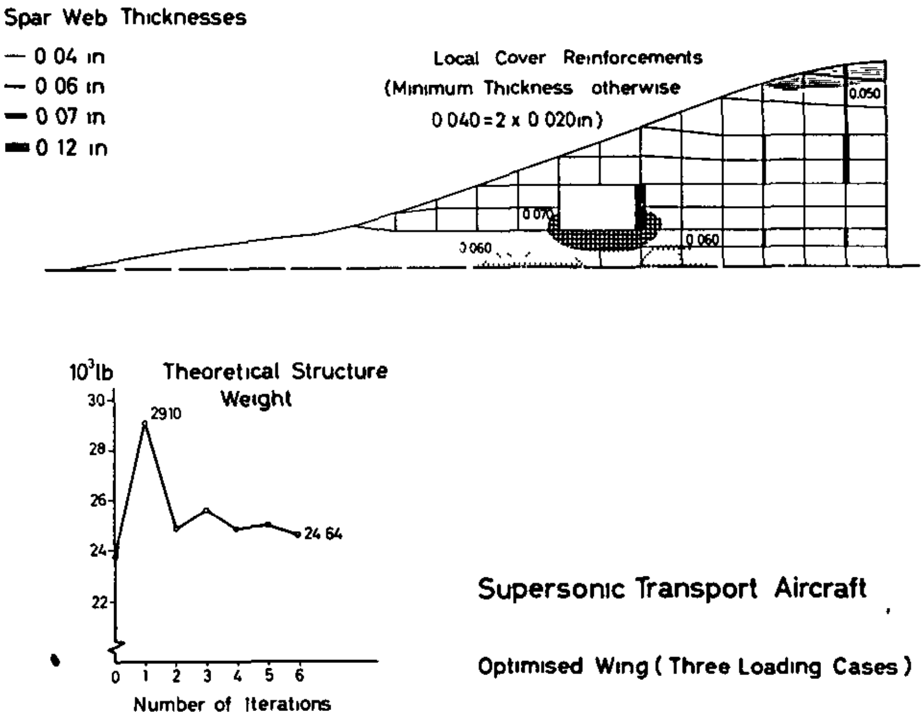
Idealization of Supersonic Delta Transport Aircraft
Arrangement of Elements for Wing Cover and Cabin

Fig.11



FLow Diagram for Engineers' Structural Optimization

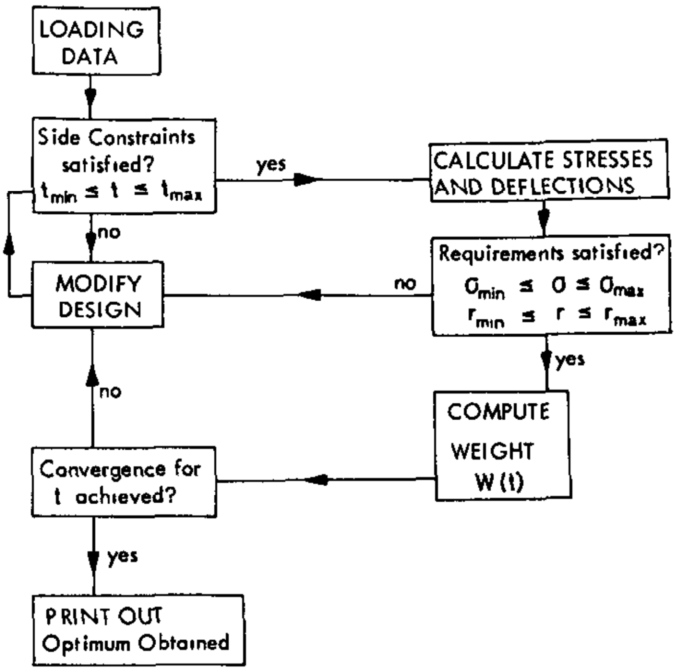
Fig.12



Supersonic Transport Aircraft

Optimised Wing (Three Loading Cases)

Fig.13



Flow Diagram for Structural Synthesis Method of Schmit

Fig.14

PRACTICAL DEVELOPMENTS IN THE STRUCTURAL APPLICATIONS OF COMPUTERS

by

I.C. Taig

(Preston Division, British Aircraft Corporation)

SUMMARY

Current and future developments in the application of medium sized computers to structural design and analysis are discussed. Emphasis is given to developments necessary to improve computer utilisation in all stages of aircraft design. It is shown that the current approach to computer application will fail to make use of potential capacity unless far more attention is given to automatic formulation of problems and computer communication. An integrated structural analysis technique is described which should overcome this problem and provide our industry with a balanced capability for efficient structural design.

INTRODUCTION

During the past 15 years the computer has become established in the aircraft industry as the principal tool for the solution of technical problems and handling routine commercial tasks. At the present moment, most of the aircraft industry establishments in this country are in the process of re-equipping with medium-sized second-generation computers or have recently made such a change. It is inevitable, in this situation, that much of the current effort in computer applications is directed towards the establishment of fundamental computer software to perform familiar functions rather than to development of new techniques. However, it is an ideal time at which to survey the developments which will follow once the basic facilities are in operation.

This paper describes both the immediate and near future developments foreseen within a large design organisation where computer utilisation is pursued solely as an aid to competitive design. The first part, dealing with the present situation, emphasises the broadening scope of computer application in the structural field. The second part is concerned mainly with the development of a higher level of automation and integration of the numerous separate facilities into a comprehensive scheme for structural analysis and efficient design.

1 DEVELOPMENT OF BASIC PROCEDURES FOR STRESS ANALYSIS AND DESIGN

The use of computers in structural analysis is commonly associated with the determination of the response of structures to static and dynamic loadings. This is indeed the most important single application and has received the greatest attention in recent years. Today there are many other ways in which the computer can assist the structural analyst and designer: the object of current developments is to provide a balanced capability for handling most of the repetitive tasks in a modern stress office. These can be grouped under a number of broad headings which are illustrated in Fig.1 in such a way as to indicate their interconnected nature. At present the automation of the activities has not reached a uniformly advanced stage and they tend to be approached piecemeal. Ideas which have existed for many years are gradually being put into practice and each facet of the overall problem requires considerable detail development before integration into a coordinated stress analysis scheme. This section describes some of these current activities taking place within B.A.C.

1.1 Internal stress and deflection analysis

The basic matrix techniques for analysis of structures by the force and displacement methods are now extremely well known. The most forceful demonstrations of the scope and power of these methods, particularly when allied to advanced computing equipment, have undoubtedly been presented by Argyris[1] and his co-workers. It is unnecessary, in this survey, to consider the many theoretical and practical developments in this field which are already widely reported. It will suffice to outline some of the characteristics of matrix analysis facilities at present under development in industry and their relationship to the analysis of actual airframe structures.

The most important feature of present and future matrix analysis procedures is generality. That is to say a fully tried and tested set of programmes must be developed which can, with little or no modification, be used to analyse the full range of structures likely to be encountered. Fig.2 gives some idea of the range of problems associated with a typical aircraft structural component. A single set of programmes is required to handle the whole range of problems from the three dimensional local stress concentration scale to the major internal load and deflection analysis of the complete structure. As is well known, the matrix displacement analysis technique is particularly suitable for providing this flexibility and forms the basis of our current and future analytical facilities. Fig.3 shows some of the key features of a specification prepared two years ago for the current series of B.A.C. programmes. In parallel with the displacement analysis procedures, matrix force methods are also under active development for the analysis of fuselage structures and slender frames. A particular feature of this work has been the development, mainly due to R.I. Kerr, of an automatic general method for the analysis of irregular multicell tubes without recourse to regularisation and cut-out techniques.

The basis of all current and future general purpose analysis facilities is a flexible and sophisticated matrix handling scheme which has just reached the operational stage on B.A.C.'s IBM 7040. This set of programmes makes it possible to specify standard and non-standard matrix operations on matrices of unlimited size and complexity by simply writing down a formalised set of algebraic equations. Single symbols can be used to identify large matrices compounded of numerous sub-matrices in a variety of different forms as illustrated in Fig.4. All questions of storage allocation, sequencing of sub-matrix operations and so on are handled automatically, thus making the organisation of highly complex matrix operations an almost trivial matter. The central parts of the matrix force and displacement analysis methods, once the data are set up in matrix or array form, are very simply written and likewise easily modified to suit any unforseen requirements in a particular analysis.

To complete the facilities for formal matrix analysis, special routines are required to derive stiffness, flexibility loading, constraint and assembly matrices from standard data defining an idealised structure and conversely to determine stresses, strains, flexibilities and boundary loads in the idealised structure. Automatic programmes of this type have been available for many years and their extension to new computers, or to include later developments in structural representation is almost a routine procedure. Further routines, as developed by Argyris[1] and others, can be introduced to perform non-linear analysis, including large deflection effects, and general instability calculations. A still more familiar extension of the basic technique introduces inertia matrices and dynamic loading so that vibration and response calculations may be handled. Surprisingly enough there are not yet many integrated programme facilities available within the aircraft industry capable of carrying out all these related functions without cumbersome data manipulation between stages. Our current plans are to produce a closely coupled set of programmes for linear, non-linear, static and dynamic analysis of idealised structures.

Even with modest computing equipment such as B.A.C.'s IBM 7040 and EELM.KDF 9 these basic programmes should enable most problems currently envisaged to be solved in a matter of hours, provided that they relate to the analysis of fully defined, idealised structures. This brings into sharp focus the next major problem which is receiving urgent attention in our current development phase.

1.2 Structural idealisation and analysis interpretation

To make the analysis of large, complex structures practicable, some degree of idealisation of the real structure is inevitable. The analyst, starting with an external shape and given a free hand, can generate idealised data to represent a reasonable structure and its principal loadings with very great rapidity, and with a little ingenuity can use the computer to assist him. At a later stage, the aircraft stressman is faced with a large number of drawings defining the structural details, a number of components too large to be fully represented, and a complicated mixture of aerodynamic and inertia data to assemble into design loading cases. The analysis of a fully-schemed structure is, in this case, preceded by the time-consuming chores of idealisation[2], and loading case preparation. The results of the computer analysis finally need re-interpretation in terms of the real structure. These procedures require painstaking attention to detail and even with careful checking can become a source of significant errors. There are two basic methods of automating this type of work which are under development at present. A piecemeal approach can be used in which the rules for idealisation of particular types of structure are programmed, and the labour of conducting repeated calculations such as, stringer moments of inertia and centroidal depth corrections, can be transferred to the computer. This approach requires a large amount of input data to be prepared for the computer but simplifies the derivation of the data. A more promising method for the future is suggested in Ref. 3. This requires that the real structure should be described in compact numerical terms by definition of surfaces, sections and intersections, etc., that the structural analysis grid should also be defined in relation to the basic structural surfaces and that the behaviour of the real structure within the regions bounded by the grid lines should be determined by a substructure analysis representing all significant features of the real structure. The method is only practicable when it is incorporated in a sophisticated scheme which integrates geometrical manipulation with structural analysis as described in the second part of this paper. One of the great benefits of this approach is the precision which can be achieved in interpreting the results since it is always possible to obtain, in a fully consistent manner, the local stresses at different parts of the real structure within any idealised element.

1.3 Component strength and stability

The second major task of the practical stress analyst is the determination of the load-carrying capability of structural members of given design. This has for many years been the province of the structures data sheets, of which the best known, and almost certainly the best example is the series published by the Royal Aeronautical Society[4]. In many cases, particularly those of a non-repetitive but standard nature, a good data sheet provides the most rapid method for an experienced engineer to assess component strength. But in the design of many common aircraft structural components such as reinforced skin panels, wing spars and ribs, fuselage frames and longerons and structural joints, the repetitive application of data sheets can involve large amounts of routine ancilliary calculations of section constants, local stiffnesses, structural and loading parameters and so on. Several alternative modes of failure and many loading cases may need investigation. It is generally recognised that this type of work forms the largest part of the load in a present-day stress office. Piecemeal application of computers to these detail stressing tasks has been taking place ever since digital machines first became available but it is only comparatively recently that their automation has been tackled on a large scale.

Within B.A.C. there is considerable current effort being devoted to the determination of strength and stability of reinforced skin panels under combined direct, shear and bending stresses by automatic, general purpose computer programmes. Similar developments are being made with regard to corrugated sheet and sandwich panel structures and rapid extension to many other detail stressing problems is intended. The programmes are being developed to perform optimum design of components of prescribed form in the presence of many types of practical restrictions. Some impressive results have been obtained even with the most elementary programmes and Fig.5 illustrates through an actual example the dramatic effect such programmes can have in the design timescale for typical structures.

At present this type of development is centred around the direct automation of the classical approaches to strength and stability determination as exemplified by the familiar data sheets. As in the case of structural idealisation a longer-term approach using the basic stress analysis procedures looks promising. Overall stability calculations as an extension of matrix analysis are already familiar and there is no fundamental barrier to applying these techniques at local buckling scale. This has already been demonstrated for individual problems, but as a general technique for application throughout a complicated airframe, practical implementation must await the development of the integrated stressing procedures discussed later.

1.4 Structural optimisation

A number of active developments are now taking place in the field of optimum design. These are generally extensions of basic techniques for internal stress analysis and strength and stability calculation. In B.A.C. most effort in this field is being devoted to the extension of the detail design analysis routines to carry out optimum design of practical structures. For example, the procedures for determining the load-carrying capacity of skin-stringer panels are being extended so as to perform the selection of optimum, varying, dimensions of a complete skin sub-assembly subject to a prescribed form of load distribution and to practical restrictions imposed by continuity and ease of manufacture. If the stringers are required to be parallel and the whole structure is restricted in depth, a range of possible stringer pitches can be selected and a programme is written to determine values of the unspecified local section dimensions (within the depth and thickness restrictions) such that strength and stability are just satisfied at all points in the panel and the weight is least. The overall minimum is then determined by search and interpolation amongst the minimum weights for each of the initially selected design parameters. For this simple problem no sophisticated technique is required for searching for the design of least weight. Likewise, if the optimum material distribution problem is treated by iterative re-analysis of the structure (using modified component sizes such that stresses are kept within prescribed limits and weight is reduced to a practical minimum) some very simple iterative techniques can be effective as demonstrated, for example, by Argyris[1]. Both these procedures are illustrated in Fig.6. Far more development is required to deal with the complete problem in which design parameter variation influences both the internal load distribution and the strength and stability of components. Some interesting ideas are emerging, for example from Schmit[5] and his associates but so far the demonstrated techniques of search for the minimum weight design are too demanding in terms of computer time to be economical. It seems very probable that a breakthrough will soon be made in this field, which will open up a vast potential optimum design capability in those organisations equipped with the basic automated analysis facilities. But even without this comprehensive capability the simpler techniques already being introduced will go a long way towards improving structural efficiency and the rapidity of initial design. Furthermore these techniques are known to be well within the capabilities of our current range of computers.

1.5 Geometrical manipulation

A large variety of developments can be grouped under this heading, ranging from simple functions such as the determination of section constants to highly complex problems of layout optimisation. The simple, repetitive problems have been programmed for many years on an individual basis, and the facilities available in any organisation tend to depend on which routine tasks are found to present the largest burden. It is only proposed to discuss here some of the more far-reaching developments at present in hand.

There are already in existence, numerous schemes and programmes for the definition of surface geometry in numerical terms and for performing the standard operations of fairing, interpolating, sectioning, etc. which are traditionally associated with full-scale layout draughting. Within B.A.C. we are currently working to establish such facilities on our present computers and also to investigate extended facilities to give wider assistance to design. The principles have been established for numerically defining the boundary surfaces and sections of the major structural members and most of the geometrically simple items of equipment and systems. One of our first applications will be the automation of structural idealisation as already discussed.

Whilst existing geometrical manipulation schemes can be defined as "numerical lofting", the facilities anticipated by defining solid objects as well as surfaces can be used to create a "numerical mock-up" of the airframe and its installations. The design problems of space utilisation which may nowadays be conveniently solved by use of a physical mock-up could in future be handled by interrogation of the numerical model of the airframe. It is easy to visualise very many direct uses for such a model, for example, the determination of volumes, location and shapes of available spaces within the airframe, determination of volume (and hence weight) of the solid members such as structure, and the assessment of clearances, fouls and effects of tolerances. The next stage in escalation of facilities would involve the investigation of alternative layouts by systematic re-deployment of major items and their interconnecting systems within the available spaces. A vast and complex optimisation process is then set in motion which can culminate in the optimisation of the whole aircraft layout.

It is easy to talk of such possibilities and fundamentally there is no single obstacle to their realisation. But returning to reality it must be recognised that the numerical definition of the contents of a space the size of an airframe down to the detail necessary to be of any use in design is an undertaking of staggering proportions. A radical appraisal of the simplest and most condensed definition of surfaces and solids is required in order that the basic data can be fed to a computer in the first place. The information must also be stored in a highly condensed form and expansion into a detailed local definition of component boundaries may only be possible where it is specifically required. It could well be that advanced facilities of this sort will only be practicable with computers having storage capacities and access times orders of magnitude in advance of current equipment, and with very highly developed peripheral equipment for communicating with the computer.

1.6 Weight and cost estimation

Weight accounting programmes are another familiar facility available in most aircraft design establishments today. In their simplest form they accept detailed weights, moments of inertia and coordinates of individual items and produce updated information on total weight, C.G. position and inertia distribution. An overdue development in computer application in this country will be in the field of weight prediction. Starting with empirical and statistical methods a great deal could be done to improve on current methods, which tend to be very unreliable through practical failure to identify the correct design parameters and their relative significance.

A more satisfactory method of weight prediction will be obtained by an obvious extension of automated design techniques. If basic areas and thicknesses of structural members can be rapidly determined it is a straight-forward matter to calculate basic structure weight. By introducing empirical factors to allow for joints, tolerances, access penalties, etc. practical structure weights can be estimated.

A far more difficult problem, but one which requires serious attention is that of cost estimation in terms of the design parameters. In the increasingly competitive industry today it is as important to optimise designs for cost as it is for weight. At present cost data are not sufficiently detailed to permit any accurate correlation with the familiar design parameters. There are many fundamental difficulties in obtaining adequate cost information chiefly due to pronounced interaction between the effects of different parameters and changes in fabrication or assembly methods which may be introduced through parameter variation. There should be no difficulty in harnessing our computers to assist accurate cost optimisation once the basic engineering problem of cost assessment has been properly rationalised.

2 INTEGRATED STRUCTURAL ANALYSIS TECHNIQUES

The extension of computer applications right across the field of structural analysis and design is now generally accepted as an inevitable, and for the most part, welcome trend. But even with the development of programmes specifically designed to reduce labour, the present system of development of separate routines to tackle different facets of the overall design problem is bound to lead to a blockage in the extent to which current computing facilities can be utilised. This arises from the limited capacity of the designers and engineers to carry out the formulation and interpretation of the separate analyses. With first generation computers it was possible to use partially automated routines and balance formulation time against computing time, albeit with severe limitations on the total level of computer utilisation.

Current computers being introduced in our industry have 50-100 times the potential work capacity of the earlier machines but the level of automation now being programmed is unlikely to do more than treble the capacity for formulation and interpretation with a fixed number of staff. Since we are attempting to cut design timescales by a half with the use of less than half the manpower per aircraft to which we have recently been accustomed we are in danger of being able to make less use of computers than heretofore except for logging up large numbers of computer hours performing, for example, non-linear analyses and partial optimisation analysis cycles whose return in terms of design economics is arguable.

Our real need is to utilise the capacity which will shortly be available to provide all the necessary data on which to base early design decisions and to carry out all stressing calculations, large and small scale to a common standard and with a minimum of "design by eye". To do this we must overcome the computer communication problem by introducing automation at such a level that the design engineer can use the computer as easily and quickly as he can specify, in familiar engineering terms, the details of the problem he wishes to pose. We believe that this ideal can be realised by the development of a fully integrated set of routines for geometrical, structural and optimum design analysis linked by a high level problem language resembling technical English and normal mathematical symbolism. Much of the ground work for the establishment of such a control language and its implementation in FORTRAN IV has been carried out at B.A.C. by W.A. Coles (now of Salford R.C.A.T.) and P.H. Roberts.

Integration of subroutines implies that all procedures for analysis of structural behaviour, strength determination, cost/weight optimisation, etc. can be called upon in any rational sequence, so that an infinitely variable set of problems can be specified merely by writing them down in the formal language. Integration also implies that data are completely compatible in physical content and format for all subroutines, or alternatively can be transformed by additional subroutines without manual intervention. The aim must always be to eliminate all manual operations which are not absolutely necessary to the description of the problem. Furthermore, sufficient data should always be retained on tape so that a previous problem sequence can be restarted in order to continue the design process or introduce modifications.

The introduction of a new system on the scale envisaged presents very serious problems in an aircraft design firm where first priority must always be given to design work on specific projects rather than long-term development. It is not conceivable that the task should be tackled as a single entity: it must develop gradually. We are learning the hard way some of the problems encountered in writing open-ended programming systems - trying to anticipate the requirements of facilities on which development has not begun. We outline below the main steps in our proposed progression towards the ultimate objectives of integrated stress analysis and finally indicate the expected utilisation of the developed system.

2.1 Development of the integrated system

The developments described in Section 1 are already well under way in at least a simple form and it is expected that individual facilities for analysis, partial idealisation, detail design and simple optimisation will be available in B.A.C. within 6 months. When this stage is reached the essential facilities needed for adequate design and approval of our current aircraft will be available and we shall be able to turn our attention to the fully integrated analysis system which is our real objective.

The first step will be the gradual development of an improved facility for matrix stress analysis incorporating, in particular, facilities for data condensation, automatic substructure analysis and interaction, selection of locally detailed solutions and inspection and interpretation of the output. The scheme was described more fully in our recent paper[3] and differs fundamentally from existing schemes in its infinitely recursive nature. That is to say the programming, data formats and internal storage arrangements are designed from the outset to include the "nesting" of substructure within structures down to any level. The control language for detailed specification of problems using this scheme is envisaged as a "sub-set" of the ultimate general structural analysis language. The basic scheme will be expanded to provide facilities for non-linear analysis, simple optimisation by cycles of modification and re-analysis, general instability investigation and natural vibration and response determination all under the control of the common problem-specification language.

The next stage of development will involve linking in a set of programmes for surface and simple solid geometry manipulation as described in Section 1.6. These will be used primarily for idealisation and for interpretation of solutions at this stage. It is visualised that the significant features of the real structure will constitute the structural input data rather than a formalised definition of an idealised structure. As soon as it is possible to describe the real structure for matrix analysis purposes it is also possible to carry out strength and stability analyses using exactly the same definition. If, idealisation by substructure analysis is employed, then stability analysis can be carried out in the same way, assuming that the problems of general instability of interconnected substructures (where local and overall modes may interact) can be satisfactorily solved. In this case the only extension of basic facilities required is the provision of a link which uses the internal loading distributions determined by matrix analysis as the basis for determining instability load factors. It is worth observing that whilst full-scale numerical geometry facilities as described in Section 1.5 may be beyond the capacity of current computers, the limited facilities required for description of basic structure are within this capacity. All the analytical steps mentioned above have already been demonstrated so the integrated idealisation - analysis - stability assessment procedure can be stated categorically to be feasible and achievable within a quite modest timescale.

To incorporate design modification and optimisation into the system on a comprehensive scale it is necessary to develop the strength and stability analysis facilities to the point at which a complete functional relationship is established between component load capacity (and stiffness including non-linearities), and the variable design parameters (component sizes, material properties, etc.). It is also necessary to incorporate into the system automated procedures for assessment of structural merit (i.e. weight, cost or balanced weight:cost effectiveness) as mentioned in Section 1.6. Once again the procedures must be fully compatible both in data format and in control by extension of the basic problem language.

At this stage a full optimisation of structural design is possible by manual intervention in the redesign cycle. This need not be very time consuming provided that convergence to an efficient design is rapid. The incorporation of a simple "design modifier" procedure will be straightforward provided that a simple criterion of efficiency (e.g. the so-called uniformly stressed structure) is used. The economics of developing more sophisticated automated optimisation must, however, be questioned with the present computing equipment. There is a need for a great deal more research into the general problem of search for the optimum design when the number of design variables may be numbered in thousands and the constraints varied and interrelated as they are in the case of complex structures. Until a method is developed which can ensure rapid convergence to the optimum and a reduction to the absolute minimum of the cyclic reanalysis of the structure, there is little point in adding this type of facility to the integrated scheme.

The ultimate goal in integrated structural design will be to incorporate the optimisation of airframe layout as mentioned in Section 1.6 into the overall scheme so that structures can be optimised as part of a complete airframe. This is not considered feasible on a practical scale with current computers, and work in this field could only be considered as pilot development for an eventual higher standard of equipment.

2.2 Some forecast capabilities of the integrated system

The structural applications of a present day medium sized computer will be discussed in relation to an arbitrary 3-year aircraft design period which we shall divide into three 12 month stages as follows:-

Design study
Initial design
Design confirmation.

The automated facilities which we have been describing could be used in all three stages - the practical extent of this utilisation being outlined in these concluding paragraphs.

2.2.1 Design study phase

Comparative studies can be made of various structural layouts to determine the influence of major design variations upon the static stress distribution, **aeroelastic** and resulting structure weight. It is considered that up to 6 complete aircraft structures could be investigated at about the level of detail indicated in Fig.7. Many more local investigations could be made to study the effects of relatively minor changes such as numbers and type of major attachments, rib and spar layout, etc. In particular, the rapidity of assessment of a complete design down to determining weight and stiffness will enable a proper evaluation of the design implications of aeroelasticity on loading and integrity to be incorporated at this stage.

At the detail design level it will be possible to make extensive and detailed weight comparisons between different materials and construction methods, and also cost comparisons when techniques are sufficiently advanced. This sort of activity is not likely to be limited by time and manpower so much as by availability of detail design routines.

2.2.2 Initial design phase

At this stage of design the integrated facilities will be used to provide the internal load distribution analysis, perform the bulk of routine detail design specification and produce regularly updated weight data. The analyses will be continually modified as design progresses and the detail design stages will include several cycles of re-analysis to achieve a high level of structural efficiency. It should be feasible to conduct two major analysis formulations for each main structure component (i.e. with different basic structural idealisation if necessary) and within each of these, many cycles of analysis and static structural design should be possible.

By use of substructure methods, or by separate formulation, static analysis and dynamic, non-linear analysis could be conducted at different scales, the latter with roughly the same degrees of refinement as the project phase analysis, the former at a scale sufficiently small to represent primary stress distributions with good accuracy and including all principal structural members in their correct position. It is not considered practical, with our current equipment, to perform the vast number of analysis cycles required for dynamic response, creep and overall automatic optimisation at this detail scale.

At the detail design level it should be possible to select skin and stiffener dimensions, spar, rib, frame and longeron sizes and to choose between several alternative forms of construction. All major continuous joints could be sized and local skin reinforcements defined for standard forms of joint and cut-out. Pressure bulkhead, floors, doors and hatches can be analysed and designed comparing various structural layouts.

Weight, and later, cost estimates will be continually revised, being based at first on the results of optimum design analysis. As design of details progresses the actual component weight estimates will be used to replace the values obtained by factoring from basic dimensions.

Aeroelastic data could be derived at various stages of the design and analysis: probably two main derivations will suffice one early on and a second as the design becomes finalised. These would be used to modify design loads and investigate aeroelastic stability at each stage.

2.2.3 Design confirmation phase

The programmes envisaged will provide a capability to replace practically all of the conventional check-stress by computer analysis carried through to systematic type record preparation.

The complete airframe structure could be defined by the numerical geometry facilities and the major airframe components, together with all the control surfaces, doors, hatches, etc. could be conveniently defined as interacting substructures. Structural idealisation to a chosen grid and component strength/stability determination would be carried out by automatic subdivision and local matrix analysis, taking full advantage of repeated structural patterns. Loading, including local inertias and aeroelastics based on the data from the final stage of design, could also be applied at substructure scale. Panel load capacities would first be determined at "grid scale" and compared with calculated loadings. Further investigation down to substructure level would be carried out in regions where strength margins were lowest, and critical reserve factors would be quoted in relation to actual structural members.

Test data could be introduced to amplify or replace calculated strengths as soon as they became available.

3 CONCLUSIONS

The facilities at present under development for utilising the medium-sized computers in the British aircraft industry are not expected to produce any radical advance in structural design applications compared with the best facilities which have been available on first generation equipment. Their use will be severely restricted by the amount of manual effort required for problem formulation and interpretation.

The next stage of development will involve a significant increase in the degree of automation through the use of an integrated stress analysis scheme incorporating geometric, structural analysis, design and optimisation facilities. It is predicted that this type of scheme will provide a very satisfactory capability for the analysis and design of modern aircraft structures from initial study through to check stressing.

REFERENCES

No.	Author	Title, etc.
1	J.H. Argyris	Continua and discontinua. Paper presented at the Conference on Matrix Methods in Structural Mechanics, Wright-Patterson A.F.B. October 26-28th 1965 (to be published) and previous papers cited therein
2	I.C. Taig R.I. Kerr	Some problems in the discrete element representation of aircraft structures. AGARDograph 72, pp.267-315 Pergamon Press, 1964
3	I.C. Taig	Automated stress analysis using substructures. Paper presented at the conference cited in Ref.1
4	Royal Aeronautical Society	Structures data sheets.
5	L.A. Schmit R.L. Fox	An integrated approach to structural synthesis and analysis. AIAA Journal, <u>3</u>, 1104-1112, 1965

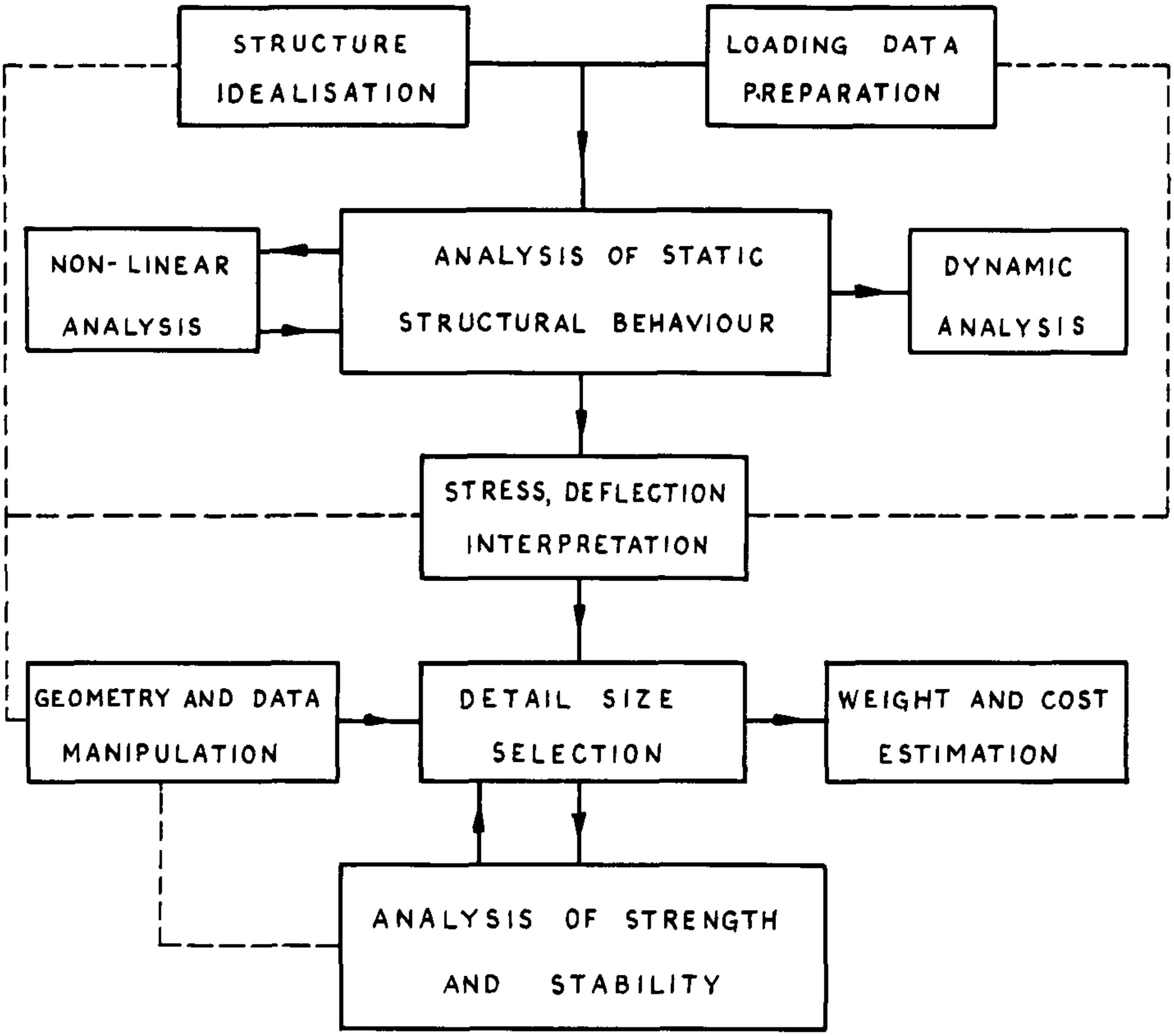


FIG.1 REPETITIVE TASKS IN AIRFRAME STRESS ANALYSIS AND DESIGN

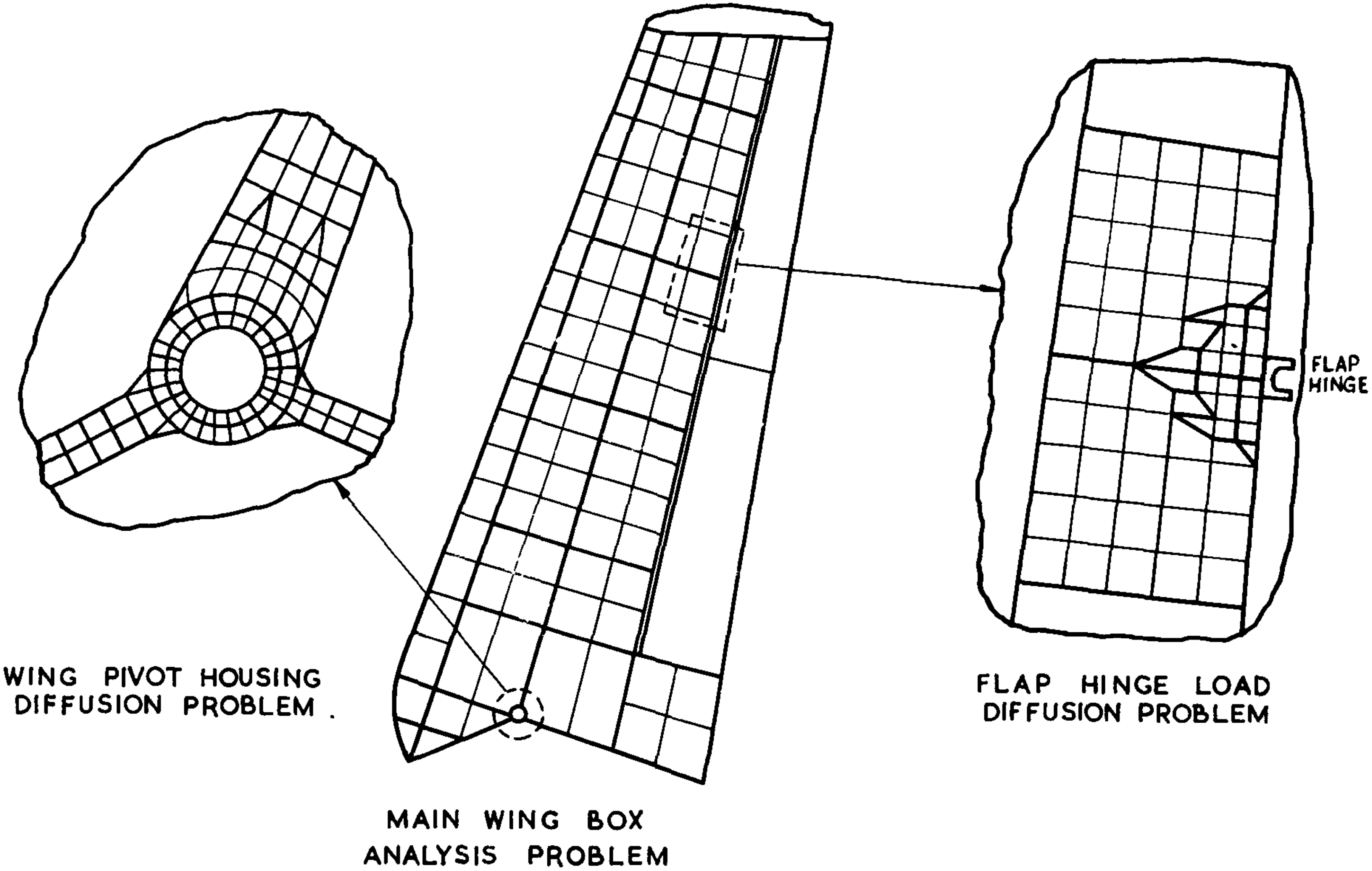
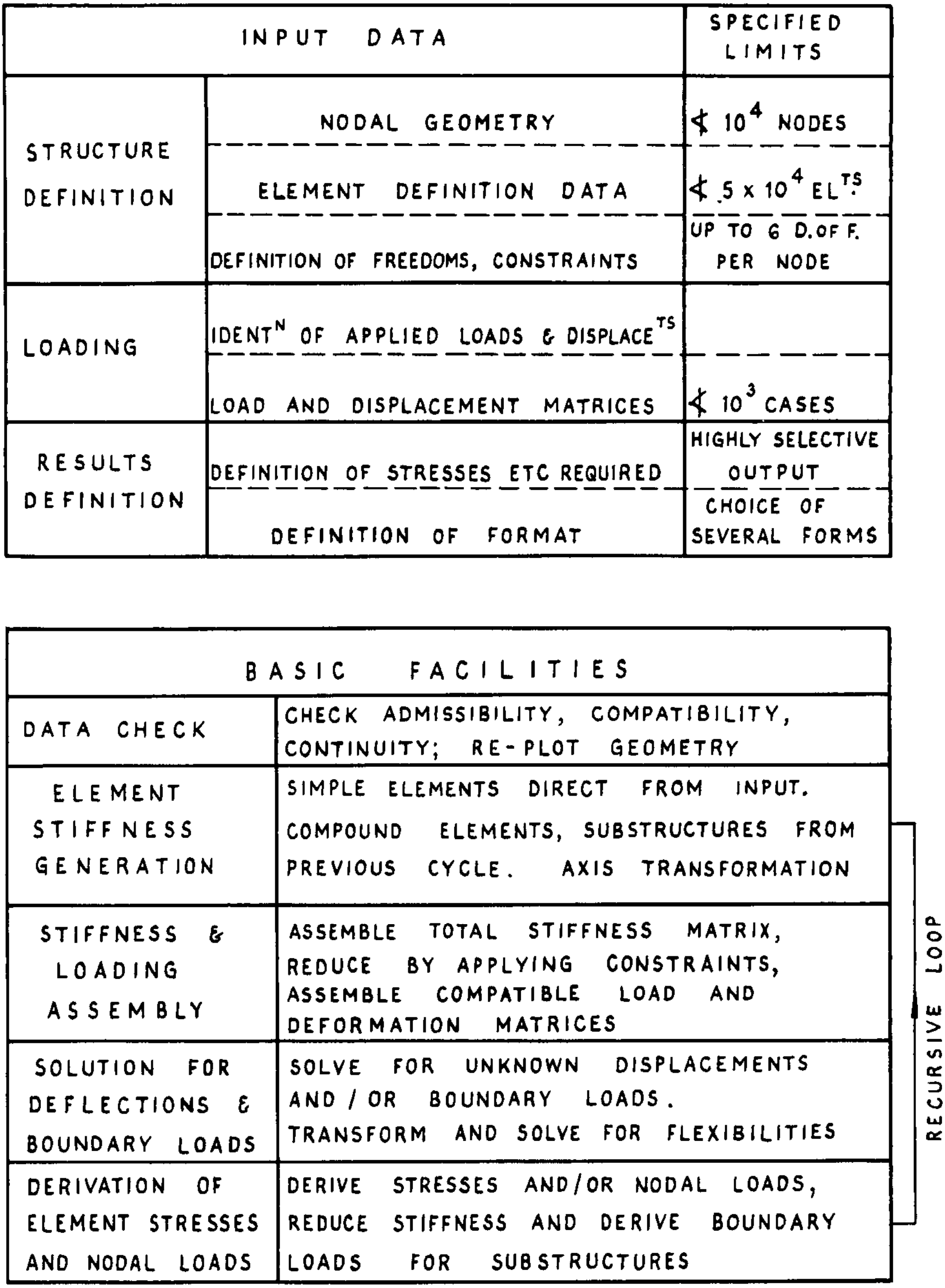


FIG. 2 WING ANALYSIS PROBLEMS AT DIFFERENT SCALES



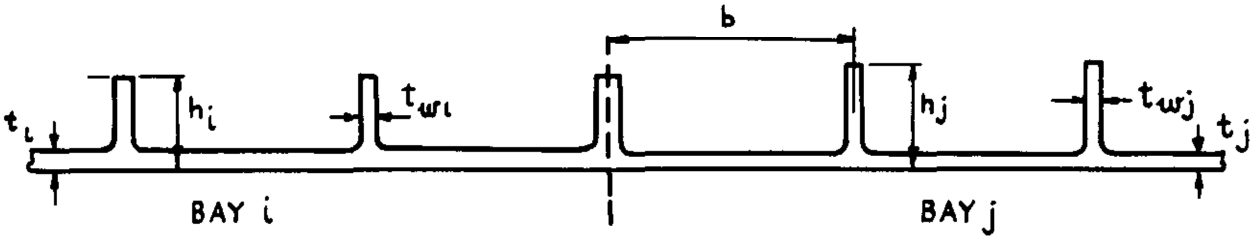
INPUT DATA		SPECIFIED LIMITS
STRUCTURE DEFINITION	NODAL GEOMETRY	$\nless 10^4$ NODES
	ELEMENT DEFINITION DATA	$\nless 5 \times 10^4$ EL^{TS}.
	DEFINITION OF FREEDOMS, CONSTRAINTS	UP TO 6 D. OF F. PER NODE
LOADING	IDENT^N OF APPLIED LOADS & DISPLACE^{TS}	
	LOAD AND DISPLACEMENT MATRICES	$\nless 10^3$ CASES
RESULTS DEFINITION	DEFINITION OF STRESSES ETC REQUIRED	HIGHLY SELECTIVE OUTPUT
	DEFINITION OF FORMAT	CHOICE OF SEVERAL FORMS

BASIC FACILITIES		
DATA CHECK	CHECK ADMISSIBILITY, COMPATIBILITY, CONTINUITY; RE-PLOT GEOMETRY	
ELEMENT STIFFNESS GENERATION	SIMPLE ELEMENTS DIRECT FROM INPUT. COMPOUND ELEMENTS, SUBSTRUCTURES FROM PREVIOUS CYCLE. AXIS TRANSFORMATION	RECURSIVE LOOP
STIFFNESS & LOADING ASSEMBLY	ASSEMBLE TOTAL STIFFNESS MATRIX, REDUCE BY APPLYING CONSTRAINTS, ASSEMBLE COMPATIBLE LOAD AND DEFORMATION MATRICES	
SOLUTION FOR DEFLECTIONS & BOUNDARY LOADS	SOLVE FOR UNKNOWN DISPLACEMENTS AND / OR BOUNDARY LOADS. TRANSFORM AND SOLVE FOR FLEXIBILITIES	
DERIVATION OF ELEMENT STRESSES AND NODAL LOADS	DERIVE STRESSES AND/OR NODAL LOADS, REDUCE STIFFNESS AND DERIVE BOUNDARY LOADS FOR SUBSTRUCTURES	

FIG. 3 MATRIX DISPLACEMENT ANALYSIS SPECIFICATION

SCHEME OBJECTIVE	PROGRAMMING OF MATRIX OPERATIONS WITHOUT REFERENCE TO SIZE, COMPLEXITY OR FORM OF MATRICES	
LANGUAGE	FORTRAN IV WITH SPECIFIC ADDITIONS	
MATRIX FORMS (CAN BE EXTENDED INDEFINITELY)	SUPERMATRIX	PARTITIONED, WITH ANY PATTERN OF NULL AND NON-NULL SUBMATRICES
	ARRAY	CONVENTIONAL FORM
	COMPACT	MAGNITUDE AND LOCATION OF NON-ZERO ELEMENTS
	"BOOLEAN"	MATRIX OF UNITS AND ZEROS
	DIAGONAL	
	DOUBLE LENGTH	ARRAY
	COMPLEX	ARRAY
	SPECIAL FORMS	FOR IDENTIFICATION ETC.
STANDARD OPERATIONS	CONVENTIONAL MATRIX ARITHMETIC :- ADD, SUBTRACT, TRANSPOSE, SCALAR MULTIPLY, MULTIPLY, INVERT, SOLVE EQUATIONS, EIGENVALUES	
	TERM-BY-TERM OPERATIONS :- MULTIPLY, DIVIDE, SPECIFIED FUNCTIONS, EXTRACT OR INSERT ELEMENTS, SPECIAL OPERATIONS FOR CONTROL, REFERENCING ETC EXTEND AS REQUIRED	

FIG.4 FEATURES OF MATRIX HANDLING SCHEME



PART SECTION OF SKIN PLANK

No OF BAYS	56
CONSTRAINTS ON DIMENSIONS	CONSTANT PITCH b Max HEIGHT h FIXED Min THICKNESS t FIXED
No OF LOADING CASES	2
TYPE OF LOADING	BIAXIAL DIRECT STRESS + SHEAR + NORMAL PRESSURE
No OF TRIAL PITCHES 'b'	3
FORMULATION TIME	8 MAN hrs
COMPUTER TIME	KDF 9 (α CODE) 25 min IBM 7040 (FORTRAN) < 5 min

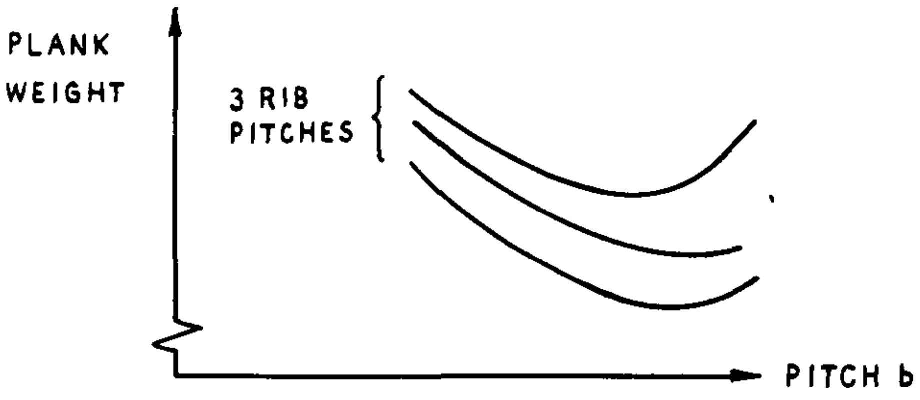


FIG. 5 OPTIMUM DESIGN OF WING SKIN-STRINGER PLANK

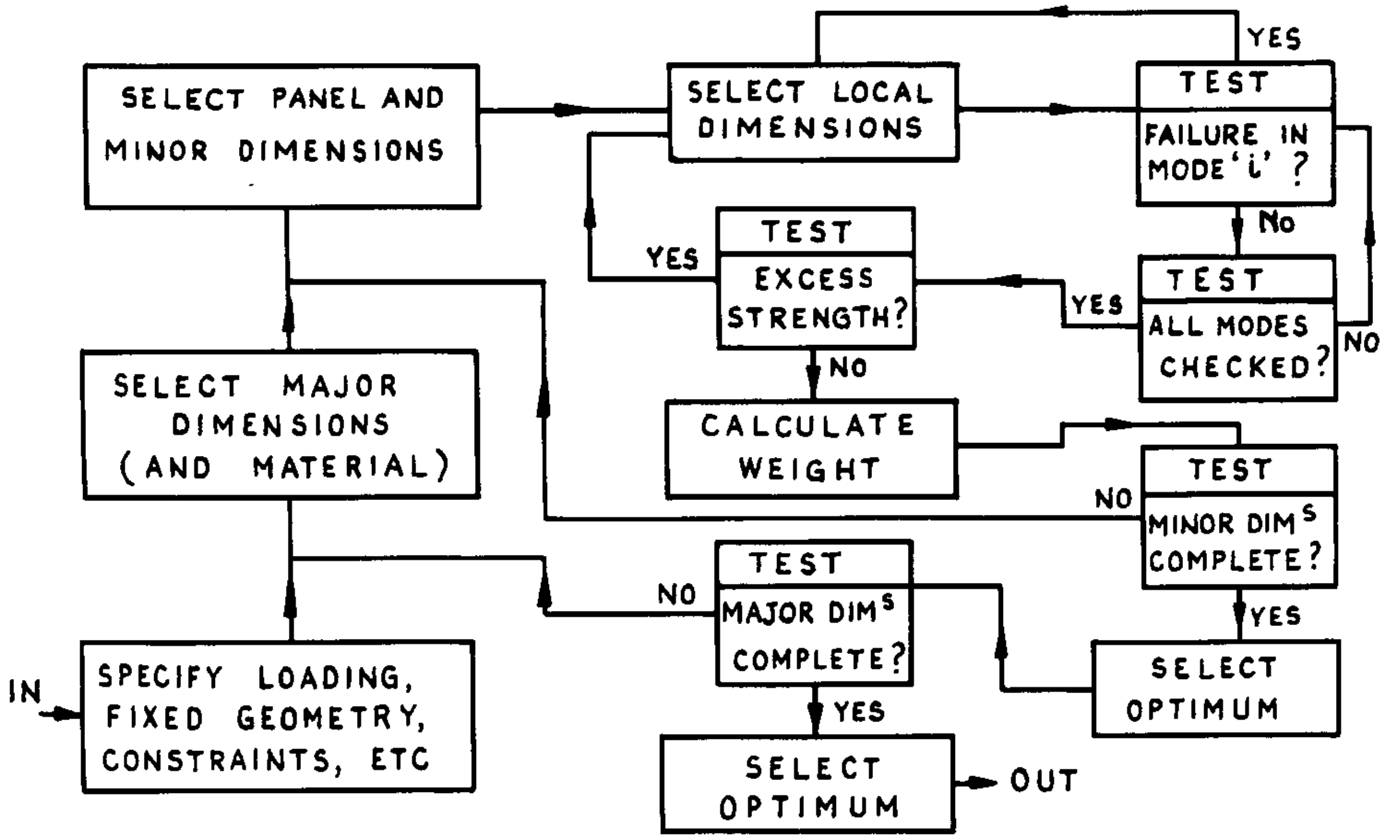


FIG. 6 (a) LOCAL DESIGN FOR LEAST WEIGHT

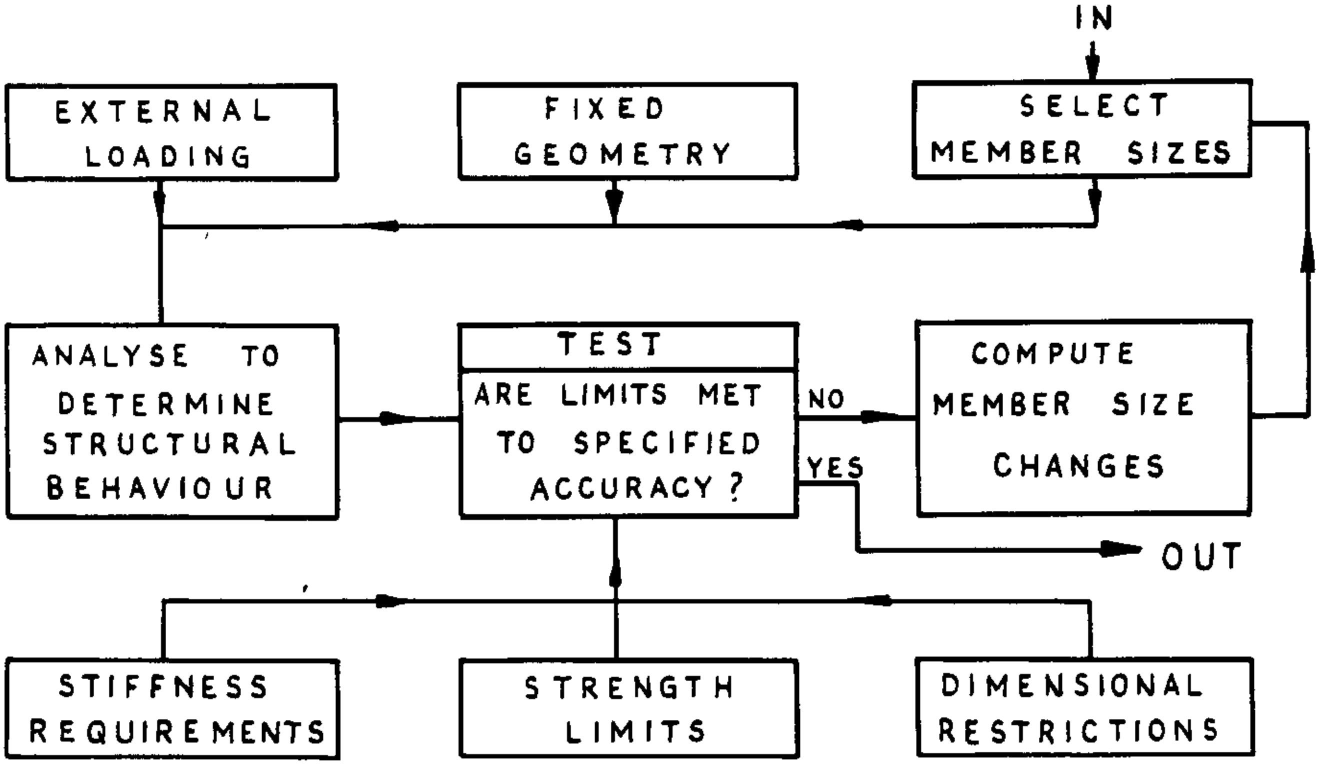
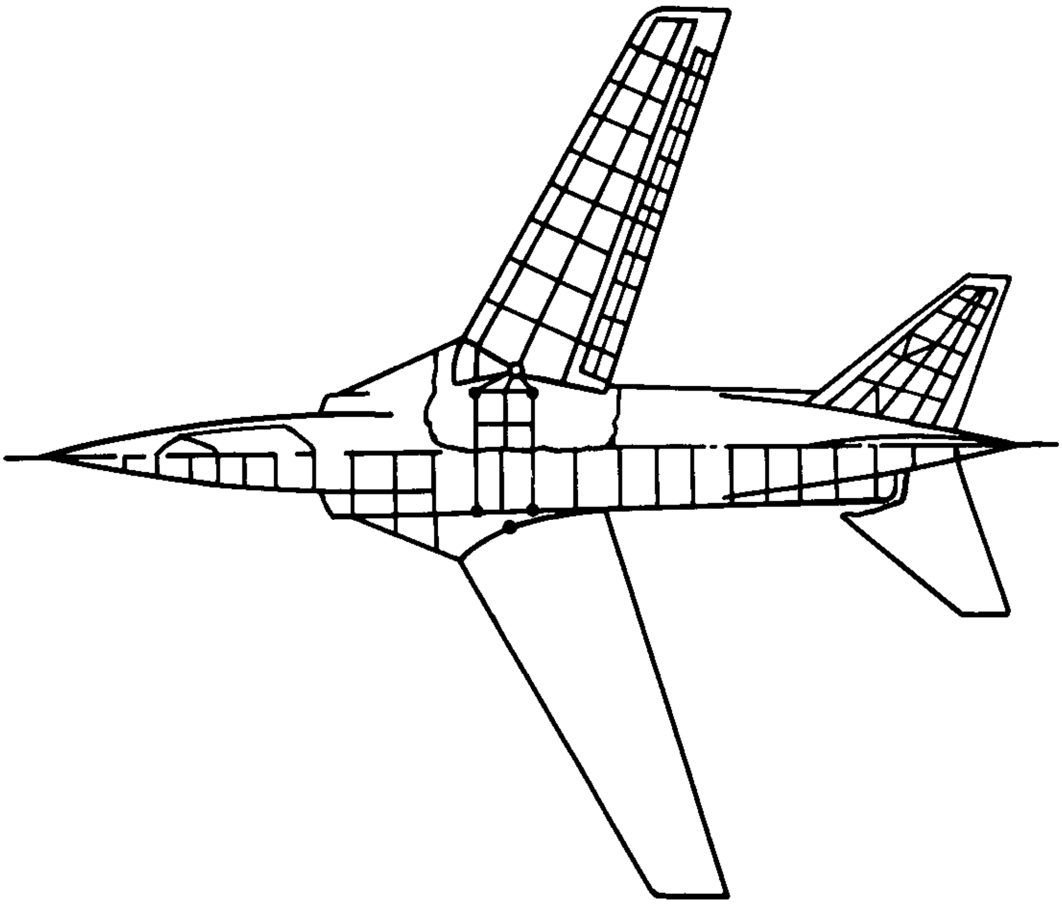
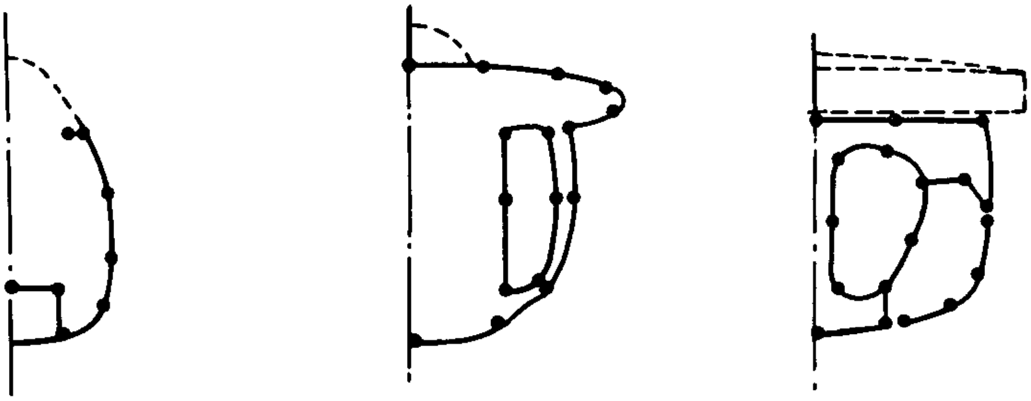


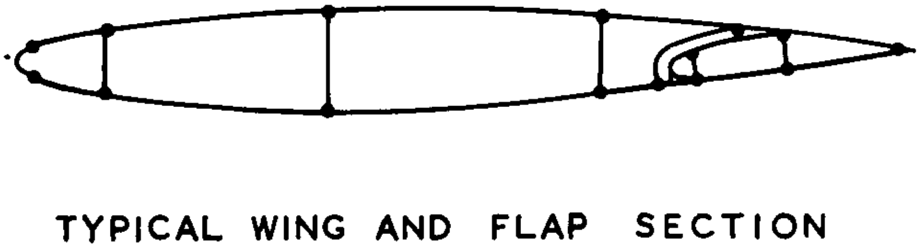
FIG. 6 (b) ITERATION TOWARDS "UNIFORMLY STRESSED STRUCTURE"

FIG. 6 SIMPLIFIED METHODS OF OPTIMISATION





TYPICAL FUSELAGE SECTIONS



TYPICAL WING AND FLAP SECTION

FIG.7 AIRFRAME IDEALISATION FOR PROJECT STUDIES

DISCUSSION

Dr. H. Kamel (Technische Hochschule, Stuttgart) commented that Mr. Taig's paper presented an excellent survey of the problems and possibilities that the aircraft engineer encounters to-day. He then pointed out that a great deal of energy is wasted in relating publications on matrix methods of structural analysis from different institutions which use conflicting systems of notation. Whereas this situation is unfortunate in the basic structural theory, a similar situation in the corresponding high level software would be catastrophic. Many separate groups have been developing their own software packages and, no doubt, they have each had particular success in some aspect of the problem. It would be greatly to the advantage of all concerned if exchanges of information could be arranged between these different groups, and the ultimate user, the engineer, would be forever thankful. Interest in such co-operation is already apparent in the U.S.A. Could Mr. Taig tell us to what extent he thinks an exchange of experience could take place between groups in different parts of the world who have the same aims?

Mr. Taig's paper indicates that the heart of an integrated system must be a language designed to help the engineer describe his problem for computer solution. Dr. Kamel's Group in Professor Argyris' Institute at Stuttgart is developing a language of this kind known as ASKA, and the first programmer's manual was issued last October. This language is also based on the division of a complex structure into a number of substructures. It differs, however, in two important respects from the system advocated by Mr. Taig. Firstly, Mr. Taig's system connects substructures at different levels, whereas ASKA divides the structure into an arbitrary number of substructures, all at the same level, which are then connected through simple instructions. The second difference is that the subdivision employed by Mr. Taig seems to dictate a separate computation of each substructure, and a subsequent assembly computation using one of the standard techniques of the matrix theory. In ASKA, the purpose of the subdivision is merely to simplify the description of the structure and the input of data. While Dr. Kamel was very pleased with ASKA as a descriptive language, he was well aware of the amount of development that must still take place before a really integrated system evolves which also incorporates facilities for the aerodynamicist, aeroelastician, draughtsman and production engineer.

Dr. Kamel emphasized that the ASKA system is not merely a collection of subroutines; it has an interpreter which accepts statements written in a new artificial language easily understandable by an engineer with a logical mind. Structural engineers with very little knowledge of computers have been trained without difficulty to solve practical problems on the computer using this system. He illustrated the descriptive power of the ASKA language with a number of examples. Fig.1 shows a typical aircraft structure divided into several components, each having its own topological pattern. Statements which can describe, with a minimum of information, patterns such as are shown in Fig.2 are a basic feature of the language, and irregular patterns can be described with an appropriate increase in the number of statements. The basic descriptive statements of the language are illustrated in Fig.3, where one, two and three-dimensional element arrangements are described topologically. A specific example describing a three-dimensional pattern of flanges within an imaginary space frame is shown in Fig.4. Examples of standard elements included in the ASKA structural system library are represented in Fig.5 by two triangles, a parallelogram plate in bending and a refined tetrahedron element for three-dimensional analysis. All the standard elements included in the library, and the basic structural theory, derive exclusively from publications of Professor Argyris, but the system is so general that any other element stiffness could easily be included.

Fig.6 shows typical functions of the ASKA repertoire. ASKA has a large library in which the usual computing procedures encountered in the linear and non-linear analysis of structures are included. As examples, all the standard expressions are shown for the computation of element stiffnesses, the formation of the assembled stiffness matrix of the complete structure from those of the individual elements, and the inversion subroutine for this assembled stiffness or, more useful from the practical point of view, the direct solution of the set of equations to obtain the displacements. A number of features currently being introduced include facilities for dynamical analysis such as, for example, the kinematically consistent lumped mass matrix. All the matrices are handled as supermatrices; only non-zero submatrices are stored or enter into the computations. Economic computation times are obtained by using a system of this kind and by making use of special properties such as the symmetry of the assembled stiffness matrix.

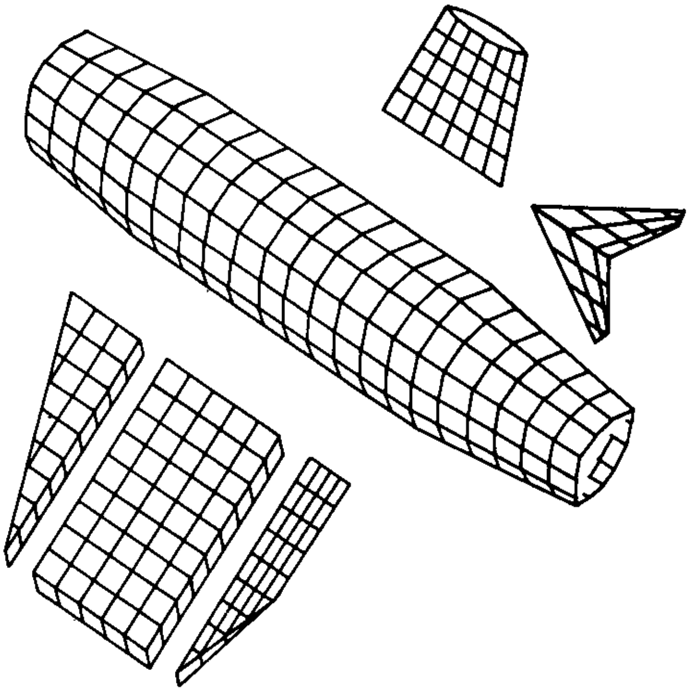
A typical structural problem of very simple topological nature is the diffusion of load into a rectangular panel reinforced by two flanges, as shown in Fig.7. This figure also includes the programme necessary to describe the structure. A slightly more sophisticated problem, shown in Fig.8, is that of a rectangular plate with a hole in the middle. Using this particular arrangement of elements, the pattern is really split into two regions. There is no advantage to be gained, however, from introducing substructures in this example. Fig.9 shows a problem fairly representative of what can be achieved to-day with little difficulty. In order to analyse such a double-cell fuselage with many cut-outs, bulkheads, and double rings, the structure is divided into a number of substructures (Fig.10), the first of which is the outer cover with the attached ring elements. The second substructure is the floor, including the floor beams. For each of the four bulkheads we define a new substructure. The concise programme necessary to describe this complex problem is shown in Fig.11. Some typical computational times involved in examples characteristic of those encountered in aircraft structures might be of interest. Fig.12 shows the time necessary to generate all the control lists required for the problems as a function of the number of unknowns. This subroutine is still called the 'a' subroutine (from the kinematic Boolean matrix a), although it has departed considerably from being a subroutine for computing this matrix alone to becoming the most important supervisory subroutine of the system. Fig.13 shows typical times for assembling the stiffness matrices of complete structures, and Fig.14 gives typical solution times for the calculation of nodal deflections for one loading case.

Finally, Dr. Kamel mentioned the impact of basic software, such as matrix schemes, on specialized applications such as ASKA. There is no doubt that the internal form of applications software will be greatly simplified through the introduction of more sophisticated compilers and interpreters. Mr. Taig mentioned an advanced matrix scheme for the IBM 7040. A similar scheme, which is being developed at the Stuttgart Institute for the UNIVAC 1107 will have a great impact on the ASKA system; this scheme is already partly in operation.

Mr. Taig replied that he was convinced that the time was ripe for more co-operation between the various organisations working on the development of structural analysis techniques and related problems. His own experience had demonstrated to him, however, that co-operation is difficult in this field if there is no controlling authority to direct the work. In this kind of work one is dealing with highly intelligent people with a great deal of pride in their ideas, and it is often very difficult to agree on a common way to proceed towards a common goal. Moreover it is often difficult to find a common goal even within one organisation. For example, one division of B.A.C. may concentrate at a given time on civil aircraft and operating economics, another on aeroelastic problems, and a third on supersonic aircraft problems such as thermal stressing; the short term priorities are thus different in each division.

Another problem is that a good automation system has a tremendous long term commercial potential. Consequently we suspect that the information we obtain from America is of the order of five years out of date; anything that is of real value this year they are probably hanging on to like grim death. They do not make available the FORTRAN IV programmes which can be used to design a DC.9, say, automatically, because they may have spent several million dollars on the development of the programmes and they want a still larger commercial return from them. Similarly when we put effort into our own developments we cannot lightly make them available to our competitors unless there is joint financing and joint marketing. We are, perhaps, getting to the stage now in the British industry where we could work to a National plan on a National scale, but questions of commercial protection are still likely to introduce difficulties. Programme language standardisation is probably one of the easier areas in which to make progress.

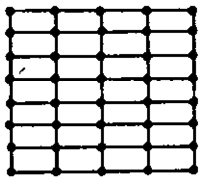
Mr. Nicholson said that everyone would appreciate Mr. Taig's comments on software, deficiencies in which are holding up progress in this country. This is big business rather than pure science, but it is worth remembering that aeronautics has developed at the speed that it has because people have been prepared not to press too hard the commercial value of keeping things to themselves. Aeronautics has been almost unique in the extent to which commercially valuable information has been released quickly.



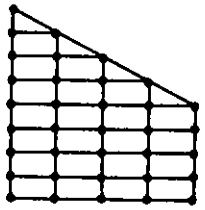
Example of breaking up an idealized model into a number of nets.

Fig.1

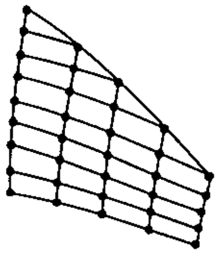
One-dimensional open net



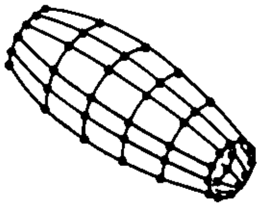
Two-dimensional topologically rectangular net



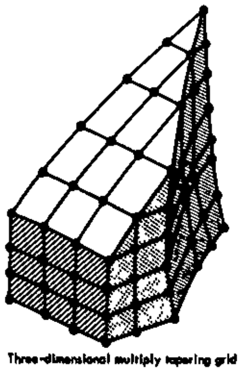
Two-dimensional tapering net



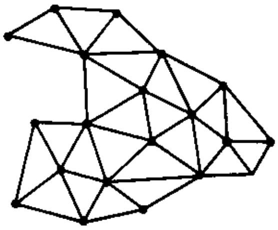
Two-dimensional tapering net



Two-dimensional closed or cylindrical net



Three-dimensional multiply tapering grid



Arbitrary net

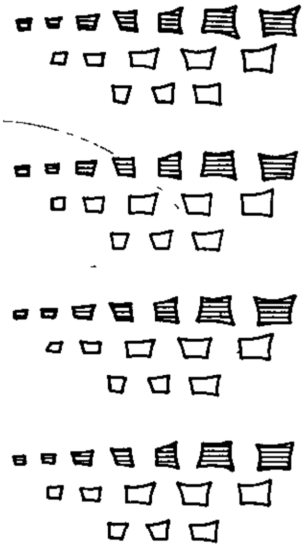
Fig. 2.

TYPE (MAT)(K0)(P1)(P2) . . (Pn)

One-dimensional element pattern and associated programme

TYPE (MAT)(K0)(P1)(P2) . (Pn)
Rn (K1)(K0 △ 1)(P1 △ 1). (Pn △ 1)

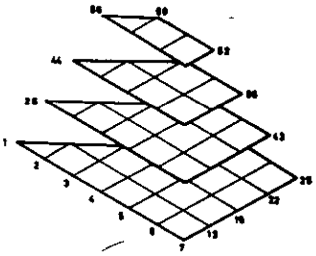
Two-dimensional element pattern and associated programme



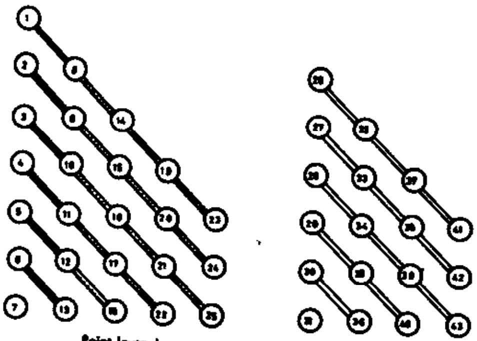
TYPE (MAT)(K0)(P1)(P2) . (Pn)
Rn (K1)(K0 △ 1)(P1 △ 1) (Pn △ 1)
RRn (K2)(K0 △ 2)(K1 △ 2)(P1△ 2)(P1 △ 1△ 2)
(Pn △ 2)(Pn △ 1 △ 2)

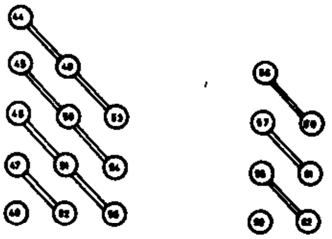
Three-dimensional element pattern and associated programme

Fig.3



Three-dimensional tapering nodal point grid
Three-dimensional view



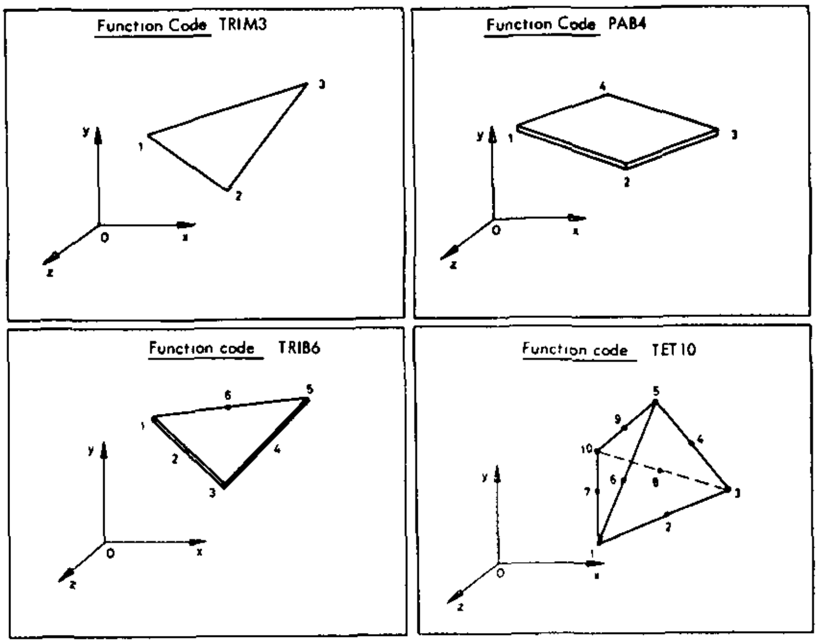


Three-dimensional tapering nodal point grid
Point numbering and flange arrangement

Instructions describing the arrangements

LABEL	FUNCTION	SUB FIELDS
	FLA2	(MAT)(6)(1, 1, 0)(8, 1, 0) :
	R2	(4)(-1)(7, -1)(6, -1) :
	RR2	(4)(-1)(-1)(25, -7, 1)(-1)(24, -7, 1)(-1) :

Fig.4



Typical standard elements in ASKA library

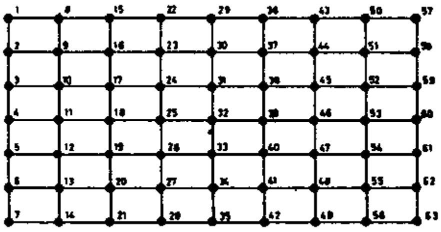
Fig.5

Function Code	Library Name	Description
SA	BASKA	forms a
SK		forms k
BK		forms $K = a^t k a$
BF		forms $F = K^{-1}$
SR		forms $r = K^{-1}R$
STRESS		forms σ
INDA		inputs point co-ordinates and geometrical data
INBR	INPBR	inputs R
INTL	INPTL	inputs θ
PSA	OUTSA	prints a
PSK	OUTSK	prints k
PBK	OUTBK	prints K
PBF	OUTBF	prints F
PBR	OUTBR	prints R
PSR	OUTSR	prints r
PST	OUTST	prints σ
PGD	OUTGD	prints geometrical data
CLBR	NONLIN	Clear R, R_{Δ}
CLTL		Clear θ θ_{Δ}
CLSR		Clear r
CLST		Clear σ
INCBR		Input R_{Δ}
INCTL		Input θ_{Δ}
INCSR		Input r_{Δ}
SUMBR		Add $R + R_{\Delta}$
SUMSR		Add $r + r_{\Delta}$
SUMST		Add σ non-linear

Function Code	Library Name	Description
INT	SUBRIO	Save on tape - interrupt programme
CONT		Restore from tape - continue the programme
SAVE		Save on tape - count
RESUME		Resume programme at specified SAVE
CLTP		Write control lists on tape
SATP		Write a on tape
SKTP		Write k on tape
BKTP		Write K on tape
BRTP		Write R on tape
SRTP		Write r on tape
STTP		Write σ on tape
TPCL		Restore control lists from tape
TPSA		Restore a from tape
TPSK		Restore k from tape
TPBK		Restore K from tape
TPBR		Restore R from tape
TPSR		Restore r from tape
TPST		Restore σ from tape
INFUNK	UNKINF	Information about the unknowns
INFEL	ELINF	Information about the elements
INFBK	BKINF	Information about the K
CHESOL	SOLCHE	Residuals $R_{res.} = a^t(k a R + J) - R$
PEEP	LEEP	Small dump - matrix instruction
SPEEP		Small dump - Sleuth instruction

List of Available ASKA Facilities

Fig.6



Nodal point arrangement

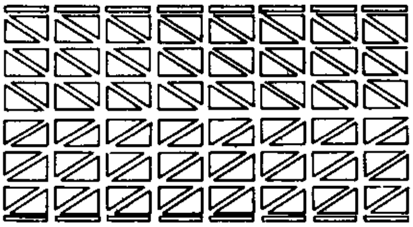
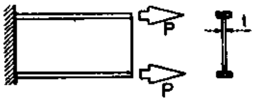
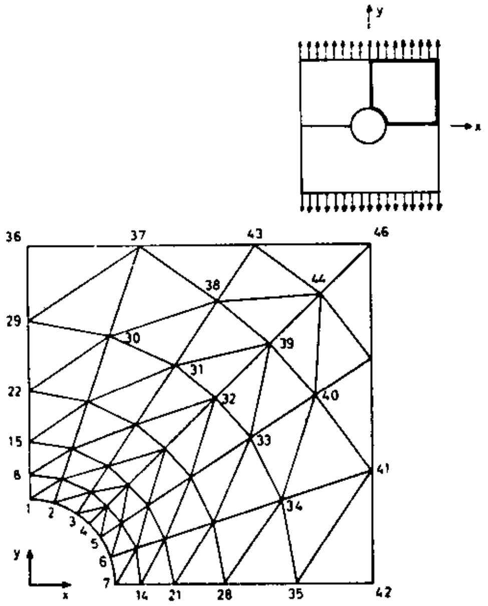


Plate symmetrical element arrangement using FLA2 and TRIM3



LABEL	FUNCTION	SUB FIELDS
ALUM	WF	1,7
	WF	0 3
	NAME	(Difussion Problem)
	NET	(1)
	NOP	(63)
	GRPS	(9),(1,7,0)(7,7,0)
	FLA2	(ALUM)(2)(1,6,0)(8,6,0)
	R2	(8)(0)(7,0)(7,0)
	TRIM3	(ALUM)(3)(1,1,0)(2,1,0)(9,1,0)
	R3	(8)(0)(7,0)(7,0)(7,0)
	TRIM3	(ALUM)(3)(,-1,0)(7,-1,0)(13,-1,0)
	R3	(8)(0)(7,0)(7,0)(7,0)
	TRIM3	(ALUM)(3)(1,1,0)(9,1,0)(8,1,0)
	R3	(8)(0)(7,0)(7,0)(7,0)
	TRIM3	ALUM)(3)(7,-1,0)(14,-1,0)(13,-1,0)
	R3	(8)(0)(7,0)(7,0)(7,0)
	SUPPTS	(7)(1,1,0)
	ENDSTR	

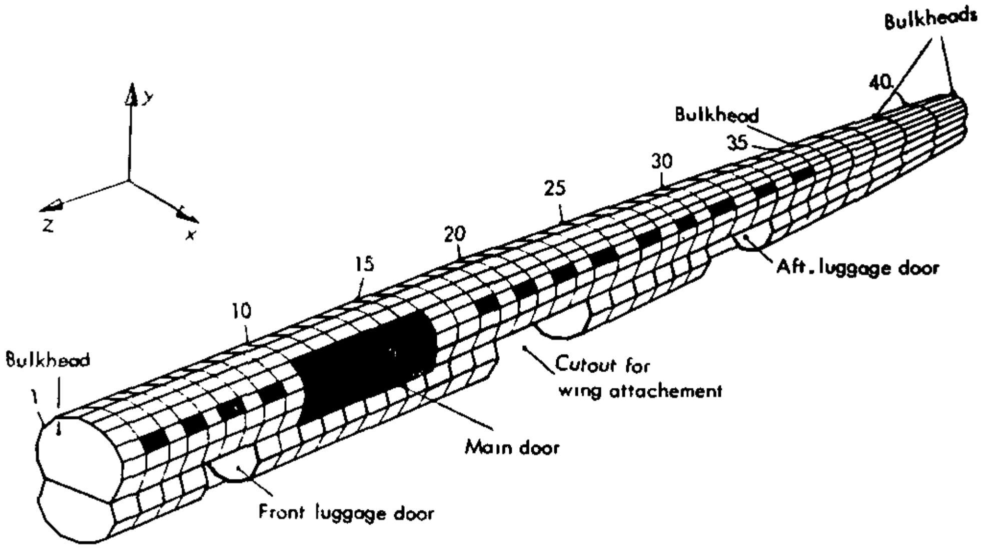
Fig.7



Analysis of a square plate

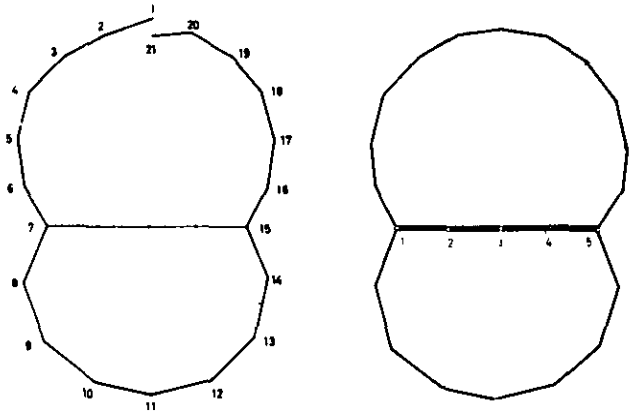
LABEL	FUNCTION	SUB FIELDS
R	W	1
RUBBER	WF	10 0
	WF	0 45
	NAME	(Plate with Hole)
	NET	(1)
	NOP	(46)
	GRPS	(6)(1,7,0)(7,7,0)
	GRPS	(1)(43,0,0)(46,0,0)
	TRIM3	(RUBBER)(3)(1,1,0)(2,1,0)(9,1,0)
	R3	(5)(0)(7,0)(7,0)(7,0)
	TRIM3	(RUBBER)(3)(6,-1,0)(7,-1,0)(13,-1,0)
	R3	(5)(0)(7,0)(7,0)(7,0)
	TRIM3	(RUBBER)(3)(1,1,0)(9,1,0)(8,1,0)
	R3	(5)(0)(7,0)(7,0)(7,0)
	TRIM3	(RUBBER)(3)(7,-1,0)(14,-1,0)(13,-1,0)
	R3	(5)(0)(7,0)(7,0)(7,0)
	TRIM3	(RUBBER)(2)(37,1,0)(38,1,0)(43,1,0)
	R3	(2)(-1)(6,0)(6,0)(3,0)
	TRIM3	(RUBBER)(2)(39,1,0)(40,1,0)(44,1,0)
	R3	(2)(-1)(5,0)(5,0)(2,0)
	TRIM3	(RUBBER)(2)(38,2,0)(44,1,0)(43,1,0)
	SUPW	(46)(1,1,0)
	SUPU	(6)(1,7,0)
	SUPV	(6)(7,7,0)
	ENDSTR	

Fig.8

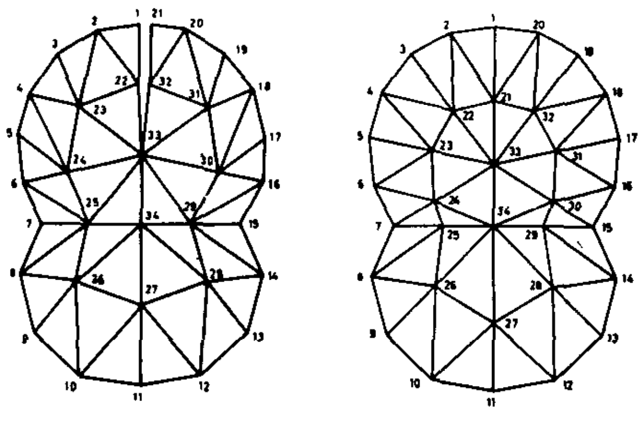


Idealized fuselage structure

Fig.9



Numbering of the nodal points in the first cross-section



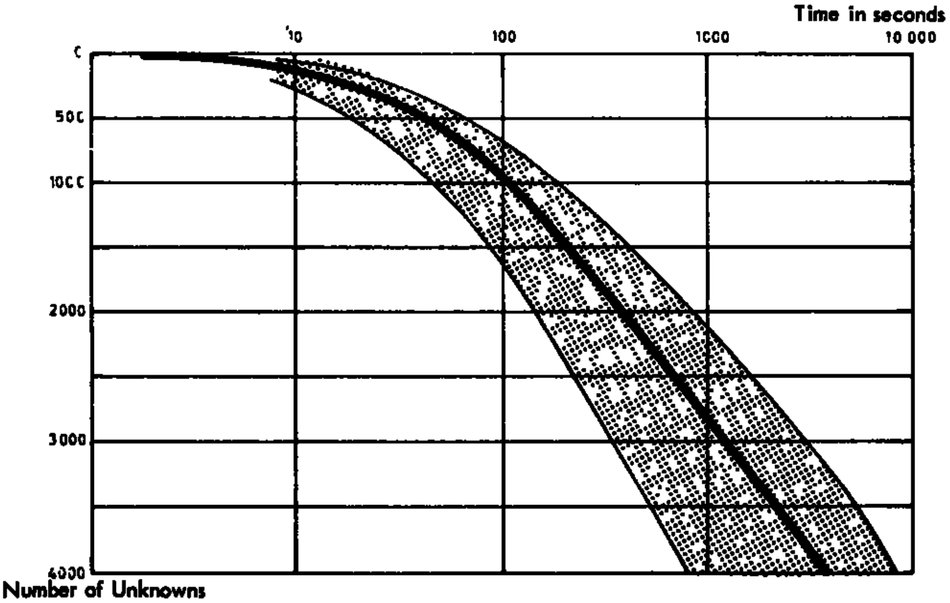
Open bulkhead net

Closed bulkhead net

Fig.10

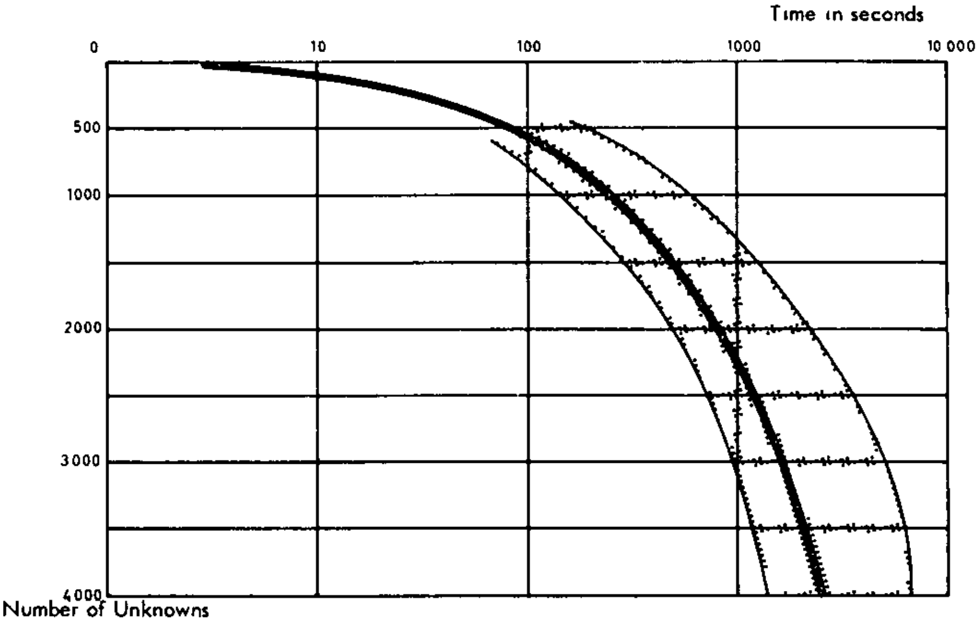
LABEL	FUNCTION	SUB FIELDS
R	W	5 °
ALUM	WF	1,7
	WF	0,32
	NAME	(Envelope with Cut-Outs)
	NET	(1)
	NOP	(861)
	GRPS	(41)(1,21,0)(21,21,0)
	FOTM	(ALUM)(20)(1,1,0)(2,1,0)(22,1,0)(23,1,0)
	R4	(40)(4)(21,0)(21,0)(21,0)(21,0)
	BAKY2	(ALUM)(20)(1,1,0)(2,1,0)
	R2	(41)(8)(21,0)(21,0)
	FLA2	(ALUM)(20)(1,1,0)(22,1,0)
	R2	(40)(8)(21 0)(21 0)
	CUT	(1)(4)(91,10)
	R1	(3)(0)(20,0)
	CUT	(1)(4)(195,1,0)
	R1	(3)(0)(20,0)
	CUT	(1)(8)(37,1,0)
	R1	(3)(0)(20,0)
	CUT	(1)(4)(391,1,0)
	R1	(3)(0)(20,0)
	CUT	(1)(2)(24,13,0)
	R1	(4)(0)(40,0)
	CUT	(1)(2)(347,13,0)
	R1	(9)(0)(40,0)
	CUT	(2)(4)(111,1,0)
	R1	(2)(0)(20,0)
	CUT	(2)(4)(215,1,0)
	R1	(5)(0)(20,0)
	CUT	(2)(8)(387,1,0)
	R1	(4)(0)(20,0)
	CUT	(2)(4)(311,1,0)
	R1	(2)(8)(20,0)
	CUT	(3)(3)(92,1,0)
	R1	(3)(8)(20,0)
	CUT	(3)(3)(196,1,0)
	R1	(6)(0)(20,0)
	CUT	(3)(3)(392 1,0)
	R1	(3)(0)(20,0)
	SUPPTS	(2)(385,0,0)
	R1	(2)(8)(105,0)
	NET	(2)
	NOP	(305)
	GRPS	(41)(1,5,0)(6,5,0)
	FOTM	(ALUM)(4)(1,1,0)(2,1,0)(6,1,0)(7,1 0)
	R4	(40)(0)(5,0)(5,0)(5,0)(5,0)
	BAKY2	(ALUM)(4)(1,1,0)(2,1,0)
	R2	(41)(0)(5,0)(5,0)
	FLA2	(ALUM)(3)(7,1,0)(7,1,0)
	R2	(40)(0)(5,0)(5,0)
	NET	(3)
	NOP	(34)
	GRPS	(1)(1 0,0)(34,0,0)
	TRIB3	(ALUM)(10)(1,2,0)(2,2,0)(22,1,0)
	R3	(2)(0)(1,0)(1,0)(1,0)
	TRIB3	(ALUM)(10)(22,1,0)(2 2,0)(23,1,0)
	TRIB3	(ALUM)(3)(22,1,0)(23,1,0)(33,0,0)
	R3	(2)(0)(7,0)(7,0)(0,0)
	TRIB3	(ALUM)(2)(25,9,0)(34,-5,0)(33,0,0)
	TRIB3	(ALUM)(4)(25,1,0)(26,1,0)(34,0,0)
	NET	(4)
	NOP	(34)
	GRPS	(1)(1,0,0)(34,0,0)
	TRIB3	(ALUM)(10)(1,2,0)(2,2,0)(22,1,0)
	R3	(2)(0)(1 0)(1,0)(1,0)
	TRIB3	(ALUM)(10)(22,1,0)(2,2,0)(23,1,0)
	TRIB3	(ALUM)(3)(22,1,0)(23,1,0)(33,0,0)
	R3	(2)(0)(7,0)(7,0)(0,0)
	TRIB3	(ALUM)(2)(25,9,0)(34,-5,0)(33,0,0)
	TRIB3	(ALUM)(4)(25,1,0)(26,1,0)(34,0,0)
	NET	(5)
	NOP	(34)
	GRPS	(1)(1,0,0)(34 0,0)
	TRIB3	(ALUM)(10)(1,2,0)(2,2,0)(22,1,0)
	R3	(2)(0)(1,0)(1,0)(1,0)
	TRIB3	(ALUM)(10)(22,1,0)(2,2,0)(23,1,0)
	TRIB3	(ALUM)(3)(22,1,0)(23,1,0)(33,0,0)
	R3	(2)(0)(7,0)(7,0)(0,0)
	TRIB3	(ALUM)(2)(25,9,0)(34,-5,0)(33,0,0)
	TRIB3	(ALUM)(4)(25,1,0)(26,1,0)(34,0,0)
	NET	(6)
	NOP	(34)
	GRPS	(1)(1,0,0)(34,0,0)
	TRIB3	(ALUM)(10)(1,2,0)(2,2,0)(22,1,0)
	R3	(2)(0)(1,0)(1,0)(1,0)
	TRIB3	(ALUM)(10)(22,1,0)(2,2,0)(23,1,0)
	TRIB3	(ALUM)(3)(22,1,0)(23,1,0)(33,0,0)
	R3	(2)(0)(7,0)(7,0)(7,0)
	TRIB3	(ALUM)(2)(25,9,0)(34,-5,0)(33,0,0)
	TRIB3	(ALUM)(4)(25,1,0)(26,1,0)(34,0,0)
	JOINPT	(41)(1)(21,21,0)(1)(1,21,0)
	JOINPT	(41)(2)(1,5,0)(1)(7,21,0)
	R2	(2)(0)(4,0)(8,0)
	JOINPT	(2)(3)(21,21,0)(3)(1,11,0)
	JOINPT	(2)(4)(21,21,0)(4)(1,11,0)
	JOINPT	(2)(5)(21,21,0)(5)(1,11,0)
	JOINPT	(2)(6)(21,21,0)(6)(1,11,0)
	JOINPT	(20)(3)(1,1,0)(1)(1 1,0)
	JOINPT	(20)(4)(1,1,0)(1)(70,1,0)
	JOINPT	(20)(5)(1,1,0)(1)(76,1,0)
	JOINPT	(20)(6)(1,1,0)(1)(80,1,0)
	JOINPT	(3)(3)(25,9,-14)(2)(2,1,0)
	JOINPT	(3)(4)(25,9,-14)(2)(176,1,0)
	JOINPT	(3)(5)(25,9,-14)(2)(191,1,0)
	JOINPT	(3)(6)(25,0,-14)(2)(201,1,0)
	ENDSTR	

Fig.11



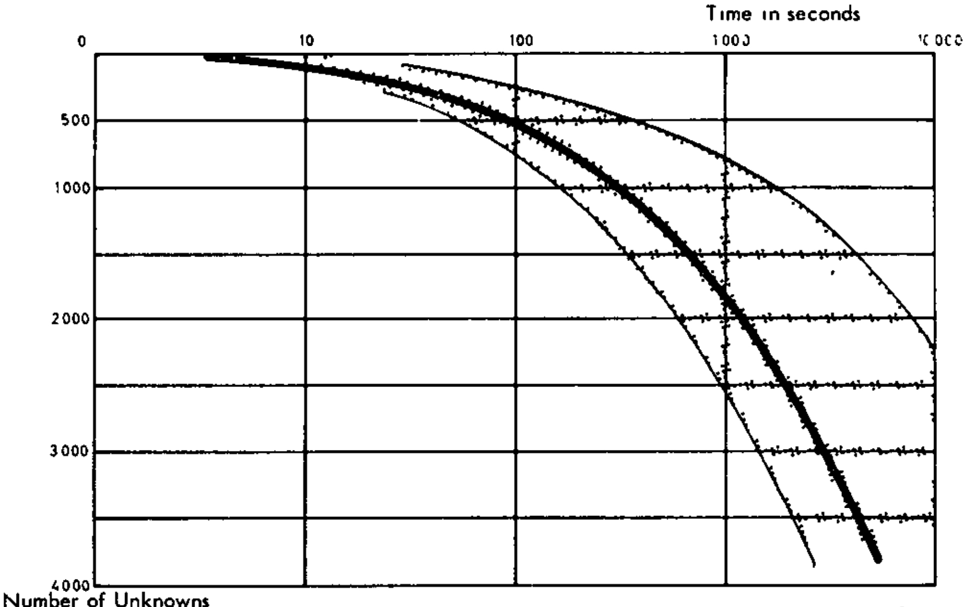
Measured and expected computation times for the Q matrix for a two-dimensional system

Fig.12



Measured and expected computation times for the $\mathbf{K}$ matrix for a two-dimensional system

Fig.13



Measured and estimated time for the solution of a system of equations $\mathbf{r} = \mathbf{K}^{-1}\mathbf{R}$ for one loading case in a two-dimensional system

Fig.14

THE DIGITAL COMPUTER IN THE DRAWING OFFICE AND PRODUCTION ENGINEERING

by

G.E.G. Bishop
(Hawker Siddeley Aviation, Hatfield)

INTRODUCTION

The object of this paper is to provoke discussion on the use of computers for handling geometric work in aircraft design and manufacture. The geometry is the "real" aircraft geometry and not some idealised mathematical model of it (as used for instance in structural analysis work).

What geometric work is done now?
Can the methods improve?
How can computers help more?

The two fields of application which will be briefly discussed are:-

(a) Geometry as it arises in planning the numerical control of machine tools,

(b) Geometry in detail design work.

NUMERICAL CONTROL OF MACHINE TOOLS

The technique of controlling machine tools by numerical information on magnetic tape is now well established, and its use is rapidly increasing. Future expansion will be limited only by

(1) The abilities of the machine tool and its control system,

(2) The abilities of the descriptive languages, used by the production/planning engineer to describe his workpiece.

These are of equal importance.

The "parts programmer" languages in use in the aircraft industry at present are:-

Profiledata	Developed by Ferranti Ltd. It allows 3 dimensional workshapes, with some restrictions, but these are not severe limitations on most current shapes. It is a language used throughout the British engineering industry.

Cocomat	Developed by Rolls Royce Ltd., incorporates features most useful to the shapes and patterns which occur in engine design.
APT	Developed in the United States, has features which enable any 3-dimensional shape to be described. It is now available for use in this country on some large American and British computers.
CLAM	Developed at Hawker Siddeley Aviation, Hatfield.

There were four main reasons why we decided in early 1964 to develop another language as an alternative to Ferranti Standard Planning (the forerunner of Profiledata):-

(1) We were getting a powerful computer (KDF9) which could be organised to make fewer demands on the planning engineer, and integrate some of the D.O./production engineering work.

(2) We could foresee the growth of numerical control work such that a self-contained system would be necessary and economic at Hatfield to produce the control magnetic tape.

(3) The majority of components being machined at that time were "simple" i.e. 2 or $2\frac{1}{2}$ dimensional.

(4) We wanted the ability to handle aerodynamic shapes (i.e. general curves) easily and consistently.

Fig.1 shows the alternative paths by which numerical control work can now be handled. The initial idea of developing a self-contained system by having a curve generator attached to KDF9, has not yet materialised. One of the current outputs from KDF9 is, therefore, a paper tape in FED1 code, which is sent to Edinburgh for conversion to magnetic tape. This magnetic tape is returned to Hatfield to control the machine tool.

FEATURES OF CLAM

CLAM - Computer Language for Machining is now used on KDF9 as a language which

(i) at present is restricted to $2\frac{1}{2}$ dimensional geometry and machining i.e. the tool can move in a horizontal plane, or in a vertical direction, separately,

(ii) can define work shapes which are any mixture of straight lines, circles and general curves.

A CLAM programme is a series of statements of two types:-

(1)	Definitions	these do not cause any tool movement, but merely define geometric references. Figs.2, 3 and 4 show examples.
(2)	Profiling Statements	these either cause tool movement or control the tool operation. Figs.5, 6, 7 and 8 show typical statements for moving along lines, circles or general curves.

The concept of <u>direction</u> is basic to the language, so that reference is made to

R and L - right and left of lines and curves
1st and 2nd - first and second intersections
CL and AN - clockwise and anti-clockwise round circles.

To help the non-computer expert in getting his programmes correct, very comprehensive error diagnostics are provided and all logical errors are found on the first computer run. Output options are provided for printing the tool edge path, and centre path, and listing all the defined points, lines, circles and curves. FED1 tape corresponding to tool centre path will always be output unless it is suppressed by programme. Fig.9 shows the current list of available codeswords and the context within which they are used. For the "expert" there are alternative abbreviations. Fig.10 shows a small but complete CLAM programme and Fig.11 shows the line printer output of the corresponding tool edge path. To develop CLAM to its present state has involved 2 man-years of programming effort, about one third of which has gone into providing the FED1 tape. This tape contains the same information as the "normal" Profiledata method would give, but automatic allowance has been made for feedrate changes (slow down points) and spacing of points along general curves.

HOW WILL NUMERICAL CONTROL LANGUAGES DEVELOP?

There will be a continuing requirement for both $2\frac{1}{2}$D and 3D languages. If a full 3D language is required, standardisation on one only must be encouraged because of the large investment implied in creating such a scheme. For this reason APT, or a subset of APT is likely to be adopted. On a lower level, a choice of one language only, is not essential. Profiledata, because of its current widespread use is top of the list, but another language is being specified at the National Engineering Laboratory and must be considered. There will always be local reasons why private schemes developed with particular refinements (such as CLAM) will continue to be used. Five years hence, when the first fruits of the current computer-aided-design ideas will be maturing, there may be a completely new approach to design and manufacture. The only certainty is that, if it can be shown that a cheaper and better product can be created using new methods we have all to be prepared and ready to change.

GEOMETRY IN DETAIL DESIGN WORK

The use of computers by Drawing Offices in general, has lagged behind the developments which have occurred in aerodynamics and structural applications.

The main reasons for this are:-

(1) Computer assistance has not been an absolute essential for D.O. work - it is possible to do most of the geometric work manually.

(2) The problem of communication between specialists - appreciating the other man's problem or what he can offer.

(3) Doubts on the reliability of representing general shapes mathematically.

(4) D.O. always require a graphical presentation and until recently automatic plotters of the required size and accuracy were not available. Thus any computed work always had to be drawn manually.

Currently, however, the potential of the computer is being explored and an increasing use is assured.

WORK TO DATE

The work to date has been largely concerned with wing shape design and subsequently getting any cross-sectional slice.

The total process is:-

(a) Given a few master cross section shapes, a series of programmes create straight line generators between these sections.

(b) This envelope of lines then defines the outer wing shape completely and can be sliced by any plane to give the appropriate cross-sectional view.

(c) Extra generators can be added which represent internal slot shapes, flap shapes, positions of spars, cables, pipes etc. and this immediately enables internal items to be located relative to any cross-section.

Cross-sections can be output (as X, Y, Z co-ordinates)relative to any specified axes.

CLAM is now being used by the D.O. as a useful geometric language, e.g. obtaining internal skin profiles etc., given the outer skin profile from the generator cross-section process.

FUTURE DEVELOPMENTS

There is no doubt at all that the recent striking advances in computer design, offering direct access from multiple consoles which consist of typewriters or graphical displays, will have a big impact on design thinking and progress eventually. Whilst keeping an open mind on the feasibility of an early introduction of these techniques, I feel, that on a practical scale, we shall in the next five years be steadily developing our present methods to produce an integrated system for handling total aircraft geometry. Direct access will certainly be used to enable the correction of errors in programmes or data quickly, and the easier and quicker handing over of information from one series of programmes to another. It will be at least five years however, and probably nearer ten before an effective design system utilising graphical display techniques is working. A lot of realistic thinking must be done to decide how best to re-organise and re-educate present departments to make the most effective use of the new total computer-based opportunities.

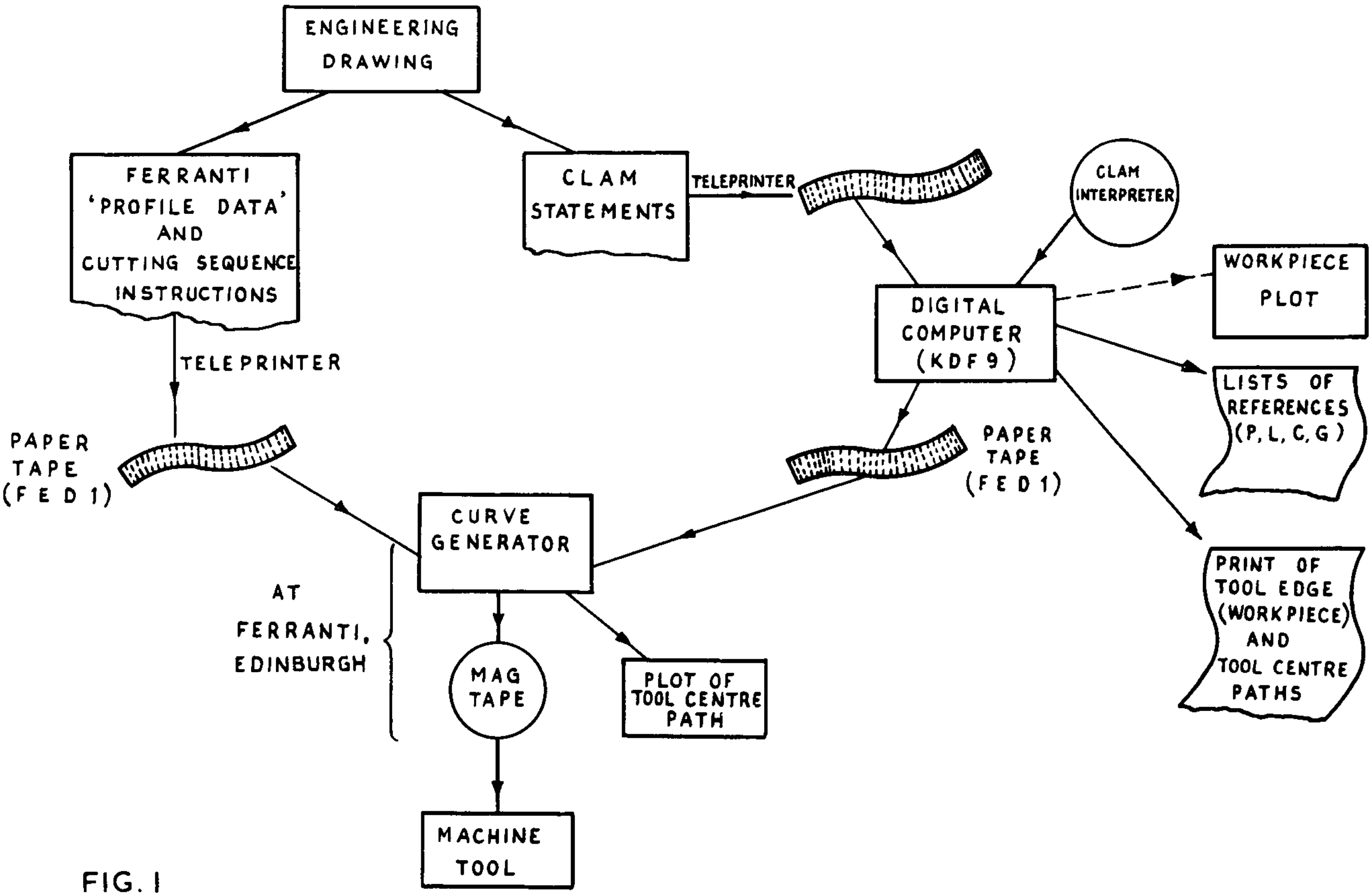
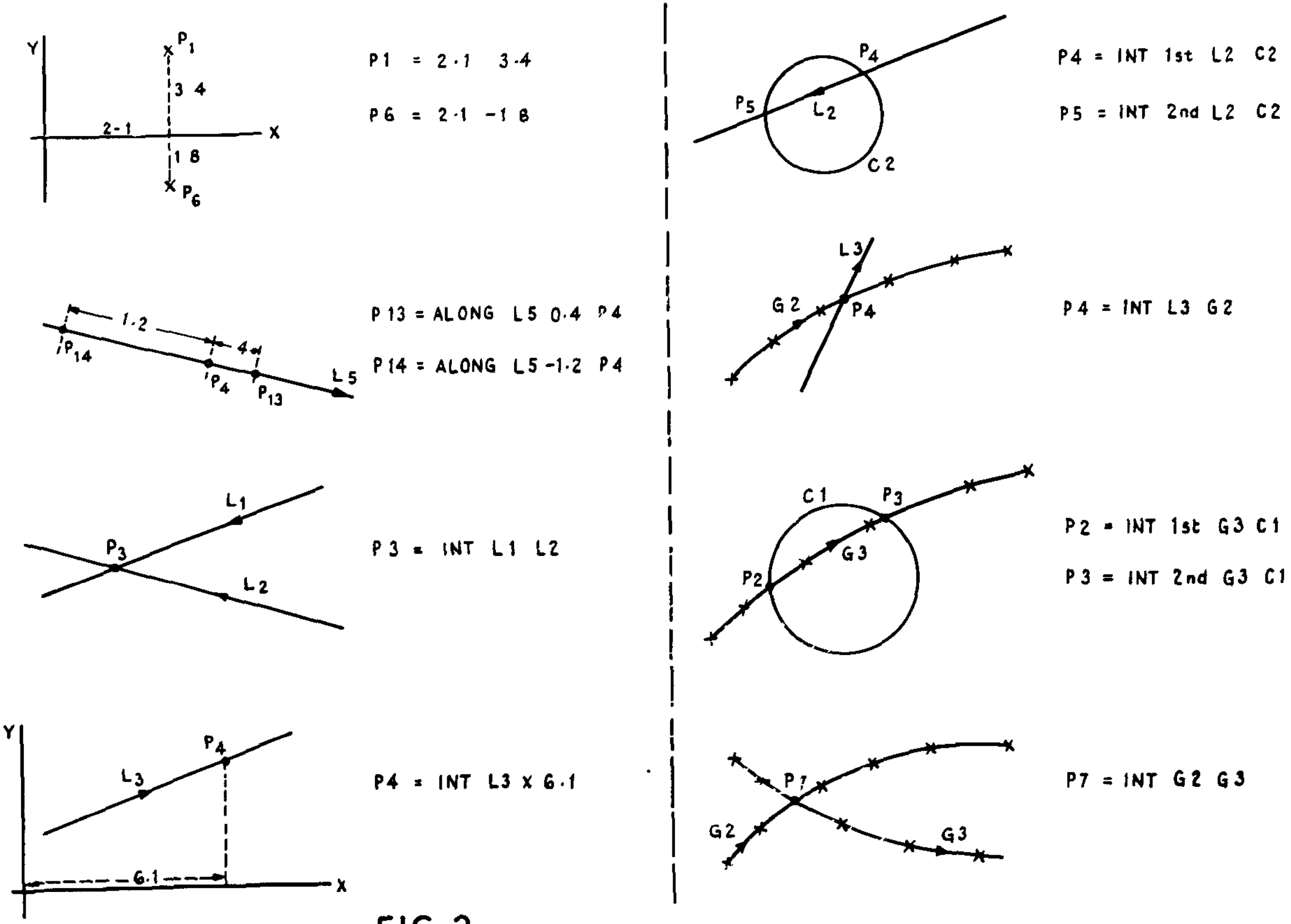

ENGINEERING DRAWING
FERRANTI 'PROFILE DATA' AND CUTTING SEQUENCE INSTRUCTIONS
CLAM STATEMENTS
TELEPRINTER
CLAM INTERPRETER
WORKPIECE PLOT
DIGITAL COMPUTER (KDF 9)
LISTS OF REFERENCES (P, L, C, G)
TELEPRINTER
PAPER TAPE (F E D 1)
PAPER TAPE (F E D 1)
CURVE GENERATOR
AT FERRANTI, EDINBURGH
MAG TAPE
PLOT OF TOOL CENTRE PATH
PRINT OF TOOL EDGE (WORKPIECE) AND TOOL CENTRE PATHS
MACHINE TOOL

FIG. 1

POINT DEFINITIONS



P1 = 2·1 3·4

P6 = 2·1 −1 8

P13 = ALONG L5 0·4 P4

P14 = ALONG L5 −1·2 P4

P3 = INT L1 L2

P4 = INT L3 X 6·1

P4 = INT 1st L2 C2

P5 = INT 2nd L2 C2

P4 = INT L3 G2

P2 = INT 1st G3 C1

P3 = INT 2nd G3 C1

P7 = INT G2 G3

FIG. 2

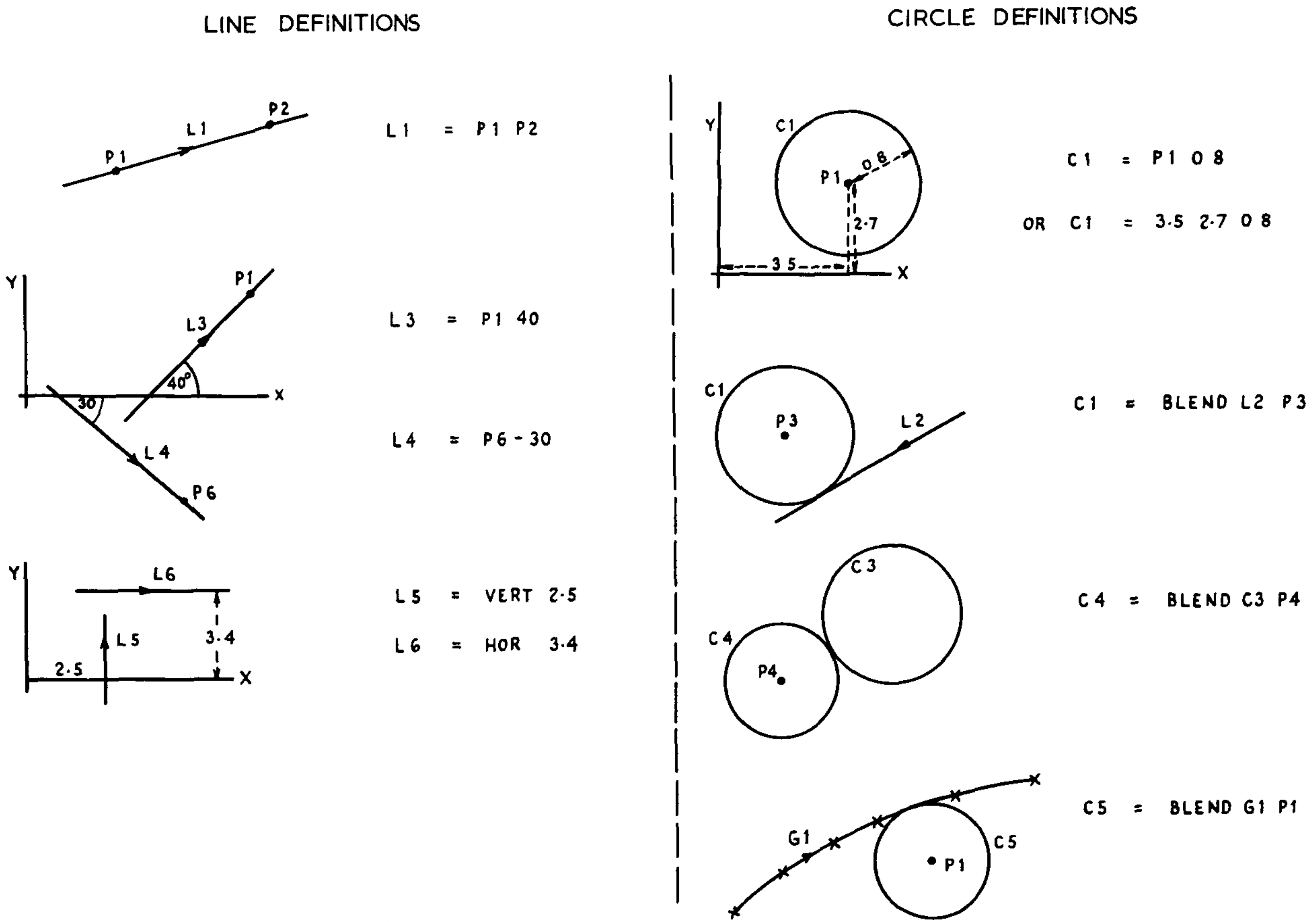
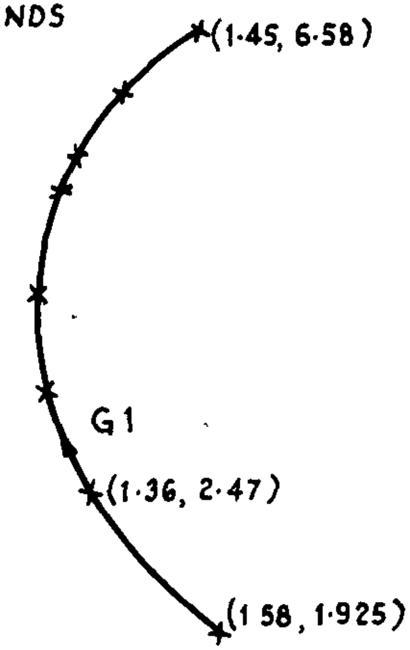

LINE DEFINITIONS
P1
L1
P2
L1 = P1 P2
Y
P1
L3
40°
30
X
L4
P6
L3 = P1 40
L4 = P6 - 30
Y
L6
L5
3.4
2.5
X
L5 = VERT 2.5
L6 = HOR 3.4
CIRCLE DEFINITIONS
Y
C1
P1
0.8
2.7
3.5
X
C1 = P1 0 8
OR C1 = 3.5 2.7 0 8
C1
P3
L2
C1 = BLEND L2 P3
C3
C4
P4
C4 = BLEND C3 P4
G1
P1
C5
C5 = BLEND G1 P1

FIG.3

'FREE' ENDS



G1 = 8 (NUMBER OF POINTS)

1·58 1·925 (X, Y COORDS OF 1st POINT)

1·36 2·47 (2nd POINT)

1·45 6·58 (8th POINT)

CURVE DEFINED AND USED ONLY BETWEEN ITS END POINTS

SHAPE AS BEST SPLINE FIT

END SLOPES FIXED

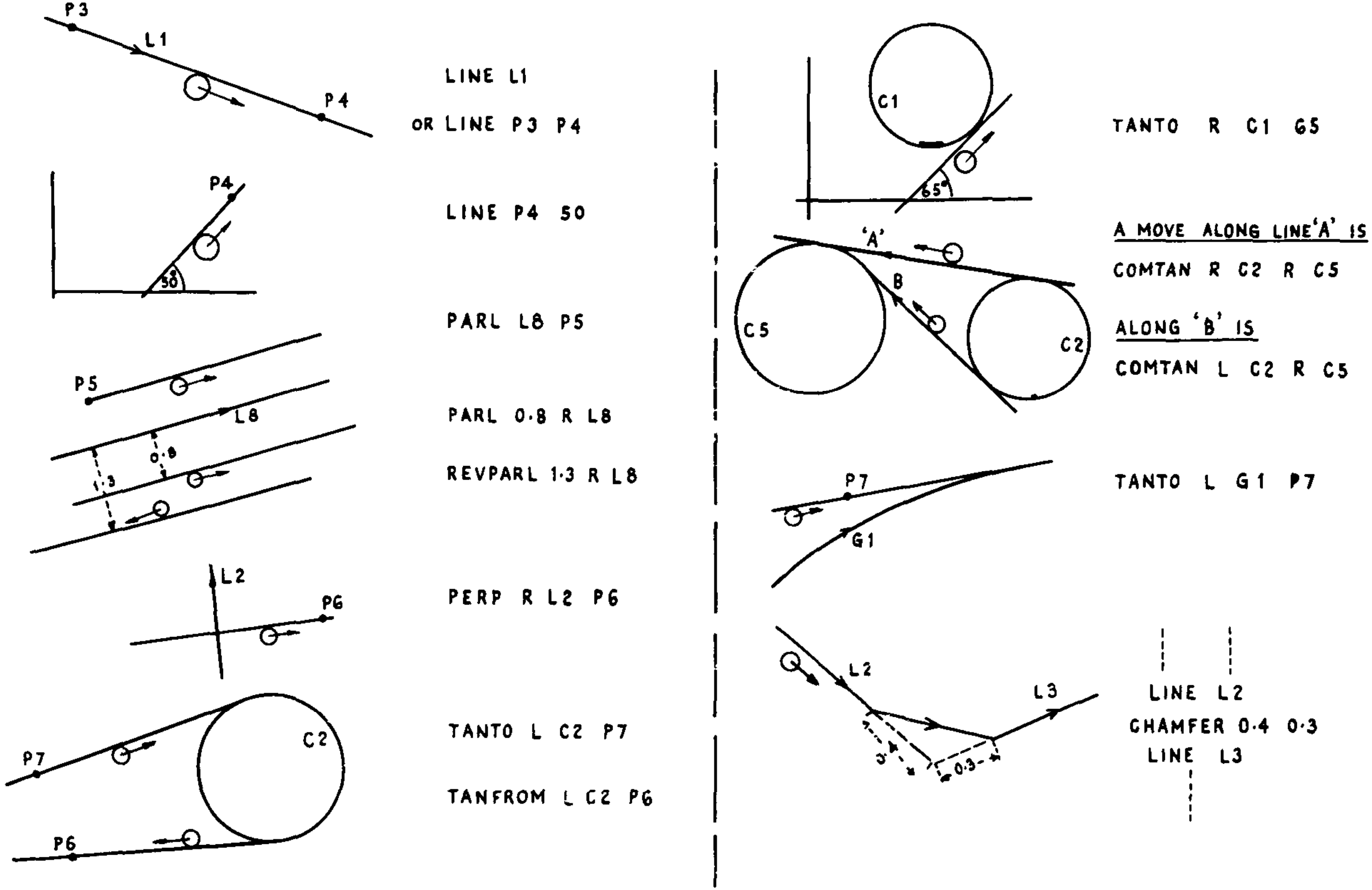
SIMILAR TO ABOVE: G2 = 5

X_1 Y_1 M_1
X_2 Y_2
X_3 Y_3
X_4 Y_4
X_5 Y_5 M_5

DEFINES CURVE AS SPLINE FIT PASSING THROUGH (X_1, Y_1) (X_5 Y_5) WITH SLOPE M1 AT 1st POINT AND SLOPE M5 AT LAST POINT

IF M1 OR M5 IS OMITTED, END IS TREATED AS "FREE"

FIG. 4 GENERAL CURVE DEFINITIONS



```
LINE L1
OR LINE P3 P4

LINE P4 50

PARL L8 P5

PARL 0·8 R L8
REVPARL 1·3 R L8

PERP R L2 P6

TANTO L C2 P7

TANFROM L C2 P6
```

```
TANTO R C1 G5
```

A MOVE ALONG LINE 'A' IS

```
COMTAN R C2 R C5
```

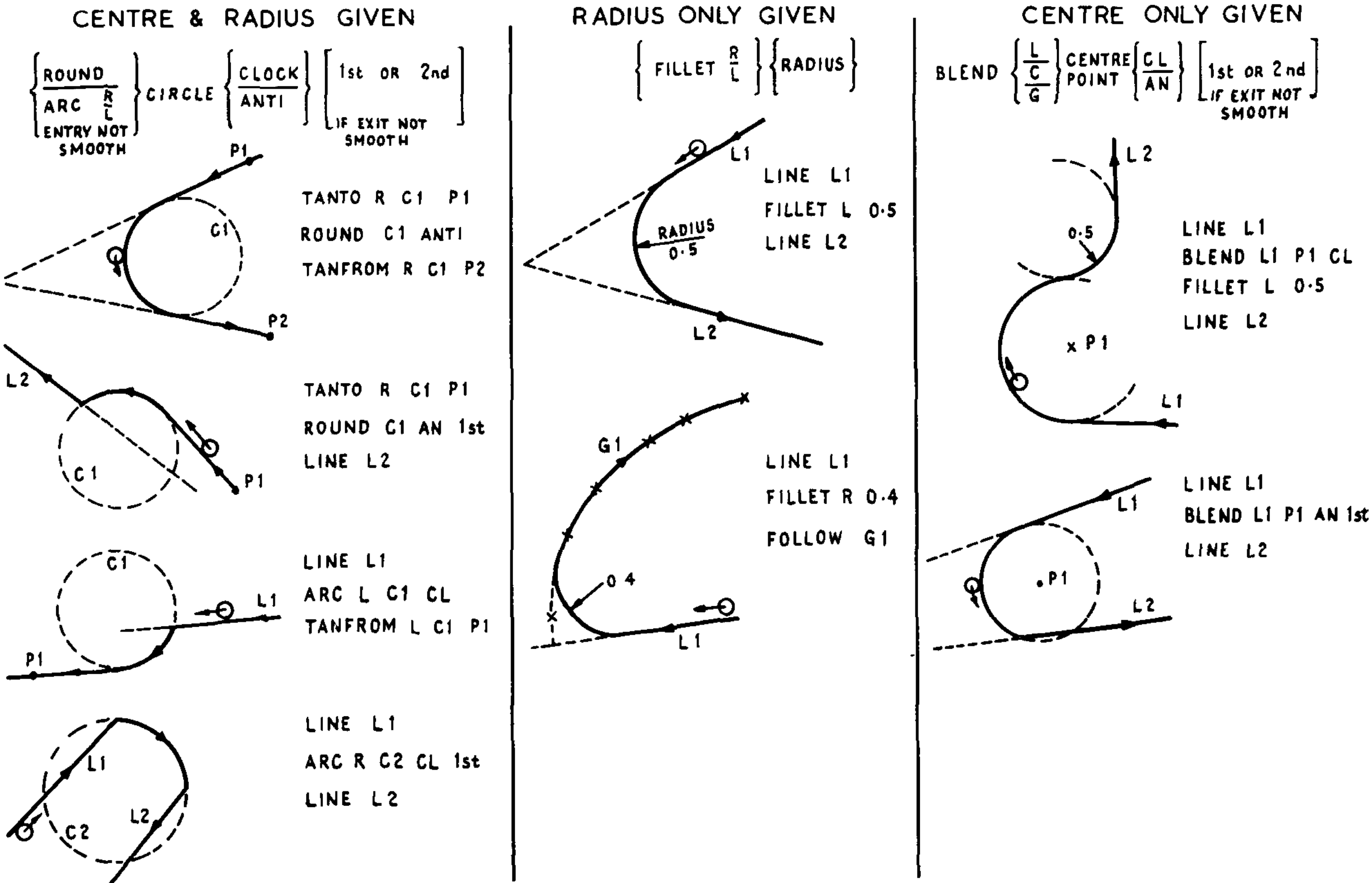
ALONG 'B' IS

```
COMTAN L C2 R C5
```

```
TANTO L G1 P7
```

```
LINE L2
CHAMFER 0·4 0·3
LINE L3
```

FIG.5 STRAIGHT LINE MOVEMENTS
(TOOL ASSUMED ON RIGHT)



```
TANTO R C1 P1
ROUND C1 ANTI
TANFROM R C1 P2
```

```
TANTO R C1 P1
ROUND C1 AN 1st
LINE L2
```

```
LINE L1
ARC L C1 CL
TANFROM L C1 P1
```

```
LINE L1
ARC R C2 CL 1st
LINE L2
```

```
LINE L1
FILLET L 0·5
LINE L2
```

```
LINE L1
FILLET R 0·4
FOLLOW G1
```

```
LINE L1
BLEND L1 P1 CL
FILLET L 0·5
LINE L2
```

```
LINE L1
BLEND L1 P1 AN 1st
LINE L2
```

FIG.6 CIRCULAR MOVEMENTS

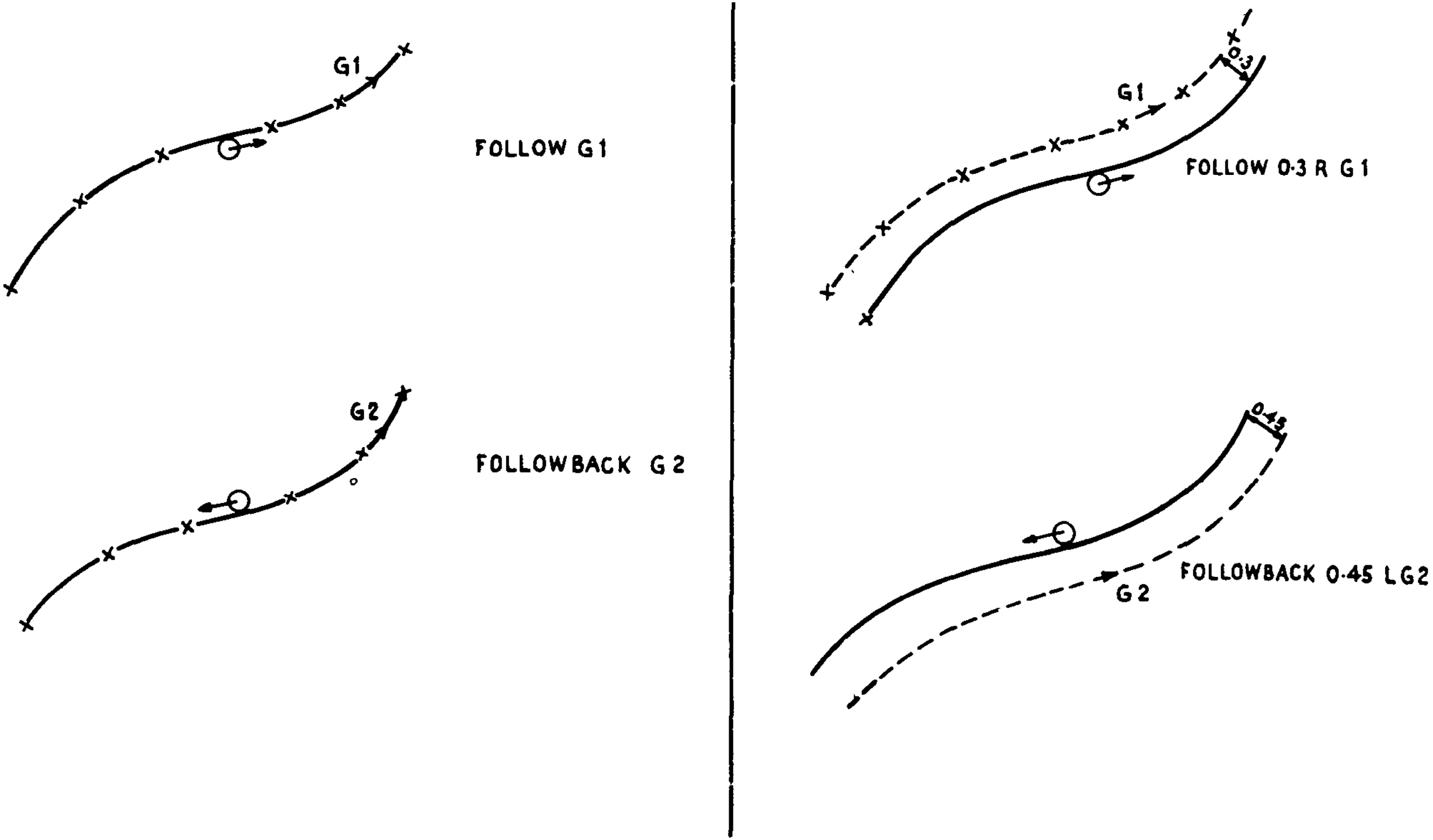


FIG.7 MOVEMENTS ALONG A GENERAL CURVE

VERTICAL MOVEMENTS

DOWN TO	0·7	MOVES TOOL TO AN ABSOLUTE HEIGHT
UP TO	− 1·35	
LOWER	0·125	MOVES TOOL AN INCREMENT RELATIVE TO LAST HEIGHT
RAISE	0·2	

MISCELLANEOUS

INDEX	222114	CAUSES THE SIX DIGIT INTEGER TO BE COPIED ON TO FED 1 TAPE, WHERE IT IS ESSENTIAL FOR THE FERRANTI PROCESSING THUS ON THE TAPE WOULD BE 7 222114 STA –

MODE OF OPERATION OF TOOL

DATUM	−2·0 +1·5 −1·0	DEFINES POSITION OF MACHINE SETTING POINT RELATIVE TO DRAWING DATUM
TOOLDIAM	0·375	COMPUTER CALCULATES THE CUTTER CENTRE PATH ASSUMING A 3/8" DIAMETER CUTTER.
FEEDRATE	10	A FEEDRATE OF 10 INCHES/min WILL BE USED UNTIL A NEW RATE IS SPECIFIED
TOOL	R	TOOL COMPENSATION ON THE RIGHT OF THE WORK WILL BE ALLOWED FOR, UNTIL A NEW COMPENSATION IS SPECIFIED (ALSO TOOL L – TOOL ON LEFT TOOL C – TOOL CENTRAL)
STOP		CAUSES A TAPE STOP WHEN THE TOOL IS AT SETTING POINT P0
STOP	P1	DITTO AT P1
OFFSET	P2	CAN BE USED ON OUTSIDE CORNERS TO LEAVE THE WORK AND STOP AT A SPECIFIED POINT (P2) e g TO CHANGE CUTTERS

FIG. 8

		CONTEXT OF USE OF CODEWORDS					
CODE WORD	ABBREVIATION	POINTS	LINES	CIRCLES	GENERAL CURVES	M/c TOOL SETTING	COMPUTER OUTPUT
ALONG		✓	✓				
ARC				✓			
BLEND			✓	✓	✓		
CHAMFER	CH		✓				
COMTAN	CT		✓	✓			
DATUM						✓	
DOWNTO		✓					
END						✓	
FEEDRATE	FR OR RATE					✓	
FILLET	FT		✓	✓	✓		
FOLLOW					✓		
FOLLOWBACK					✓		
HOR			✓				
INDEX						✓	
INT		✓	✓	✓	✓		
LINE	LN		✓				
LIST							✓
LOWER	DN	✓					
OFFSET						✓	
PARL	PL	✓					
PERP	PP	✓					
PRINT							✓
RAISE	UP	✓					
REVLINE	RL		✓				
REVPARL	RP		✓				
REVSEQ		✓	✓				
ROUND	RD			✓			
SEQ		✓	✓				
STOP						✓	
TANFROM	TF		✓	✓	✓		
TANTO	TT		✓	✓	✓		
TOOL						✓	
TOOLDIAM	TD OR DIA					✓	
VERT			✓				

FIG. 9

```
DATUM  + 4  -3  -3
TOOLDIAM  0·4
TOOL  R

G1  =  4
+ 4 · 274   - 2·045
+ 1   372   - 1 ·716
- 1 · 131   -1·460
- 3 · 100   -1·271

G 2 = 5
- 2  000    -0 576  INF
- 1 ·636    +1·008
-0 ·670     +2·306
+ 1 ·046    +3 515
+ 3 ·200    +4 437

P 1 =  + 1 7   - 1 2
P 2 =  + 1·0   - 2 3
P 3 =  + 0·0   - 0 5
L1  =  + 1 8347     + 3 2141   + 2 993   - 1·1483
L2  =  -1·0         - 1 0      - 2 0     + 1·0

PRINT  E
INDEX 222114

FEEDRATE    2
LINE      P0  P1
LOWER      1 95
LINE      P1  P2
FOLLOW     G 1
FILLET     R 0 5
LINE      L 2
FILLET     R 0 5
FOLLOW     0·334  R  G2
FILLET     R 0·27
LINE      L1
FILLET     R 0·27
FOLLOW    G1
LINE      P 2  P3
RAISE      1·95
LINE      P 3  P0
STOP
END
```

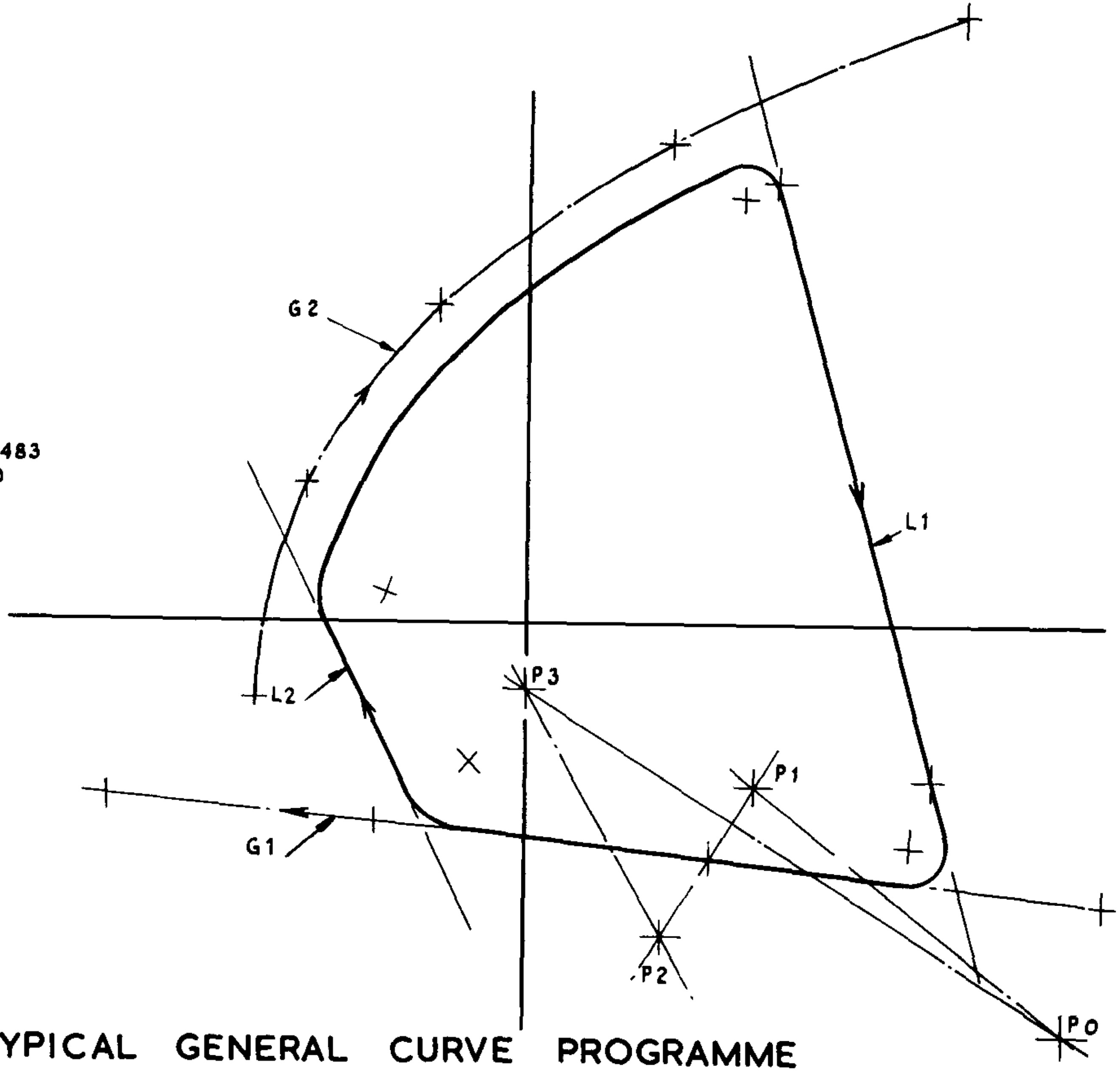


FIG. 10 TYPICAL GENERAL CURVE PROGRAMME

TOOL EDGE

```
WITH CUTTER RADIUS + 0·200
WITH FEEDRATE + 2 000
WITH TOOL COMPENSATION RIGHT
TURN ON TO LINE AT + 4·000 -3·000 AT ANGLE + 141·953
RAISE VERTICALLY - 1 950
TURN ON TO LINE AT + 1·700 - 1·200 AT ANGLE + 237·529
TURN ON TO CURVE AT + 1·372 - 1·716 WITH DISPLACEMENT + 0·000 TRUEDIR
BLEND ON TO CIRCLE AT-0·477 - 1·525 CENTRE & RADIUS - 0·427 -1·027 + 0·500 CLOCK
BLEND ON TO LINE AT - 0·875 - 1·251 AT ANGLE + 116 ·565
BLEND ON TO CIRCLE AT - 1·495 - 0·010 CENTRE & RADIUS - 1·048 +0·214 + 0·500 CLOCK
BLEND ON TO CURVE AT -1 527 + 0·356 WITH DISPLACEMENT - 0·334 TRUEDIR
BLEND ON TO CIRCLE AT + 1·467 + 3·351 CENTRE & RADIUS + 1·584 + 3·107 +0·270 CLOCK
BLEND ON TO LINE AT + 1·845 + 3·177 AT ANGLE + 284· 870
BLEND ON TO CIRCLE AT + 3·096 -1·536 CENTRE & RADIUS + 2·835 - 1·606 + 0·270 CLOCK
BLEND ON TO CURVE AT + 2·805 -1·874 WITH DISPLACEMENT + 0·000 TRUEDIR
TURN ON TO LINE AT + 0·632 -1·638 AT ANGLE + 119·055
RAISE VERTICALLY + 1·950
TURN ON TO LINE AT -0·000 - 0·500 AT ANGLE + 327·995
WITH TOOL COMPENSATION CENTRE
STOP AT + 4·000 - 3·000
```

FIG. 11

DISCUSSION

Mr. Hall (British Aircraft Corporation, Weybridge) said he would like to take Mr. Bishop up, in particular, on the last point he made - the question of money. Engineers have made a poor job over the past few years of selling the use of automation and computers to the financiers, both in the Government and in industry, who provide the money for the aircraft industry. The true cost-effectiveness approach has been neglected and many engineers have merely satisfied themselves that the depth of analysis and the sophistication put into the task are increased by using these facilities. For example he had not yet seen a really good cost-effectiveness case put forward in his own company for the use of tape-controlled machines. Commercial people in industry are not interested in sophistication for its own sake; they want to produce cheap saleable products which may be aircraft or any other engineering item.

Mr. Hall also commented that too much emphasis was being placed on the numerical control of metal-cutting machines. A great deal of the work of the aircraft industry is metal bending, metal forming and light assembly work. Tape control could certainly be applied to these operations but few cost-effectiveness studies have been made of this kind of application. It has also been proved that long production runs are not always a necessary pre-requisite for the effective application of tape control.

Mr. Hall pointed out that the real initial impact of automation in the aircraft industry would be in the field of technical data-processing. Recent studies of the total cost of the design and development of large aircraft such as the V.C.10 show that the most expensive job is not creative design; it is the organisation of data into an integrated whole, and the transmission of this information to the people that cut, bend and form metal. It must be demonstrated to the financiers that although a great deal of money will be needed to develop the software necessary to utilise the computer efficiently in such applications, the return for this investment in terms of time and money saved can be very large indeed.

Mr. Potter (Royal Aircraft Establishment) said he was all for pioneering a research and development field when it was necessary. He wondered, however, whether there was any point in carrying on with the development of CLAM now that Ferranti have evolved COPATH which gives the production engineer, in effect, magnetic tape processing in his own orbit. It is well known that pioneers are often overtaken and this seems to be a case in point. He did not know whether CLAM had a greater use in design rather than in machine tool control, but it seemed to him that Profiledata, along with COPATH, covered the requisite need in the machine tool field.

Mr. Bishop replied that they started work on CLAM in 1964 before the current scheme provided by Ferranti was available; they had involved themselves in two man-years effort so far. The future of this language would, he thought, be mainly on the design side, where it could be used in the integration of geometrical schemes. It saves a lot of effort, moreover, in the retrieval of data such as aerodynamic shapes, outer contours and inner contours which are required by the planning engineer. He thought that an integrated scheme of this kind was necessary. Whether they should put Profiledata on KDF9 was an open question.

In reply to Mr. Hall, Mr. Bishop said that his firm had done a brief cost-effectiveness study on the use of the digital computer in technical data-processing. It was found that ten people, who could more profitably be employed on other work, were spending all their time transferring modifications from one drawing to another in the electrical drawing office. This is a simple job for a computer with a reasonably fast core store, magnetic tape and a line printer, and routing chart, radio cable and wiring diagram modifications are now processed on KDF9. Current modifications are incorporated each week in a single session, and lists are printed containing the relevant information for the man on the shop floor.

Mr. Bishop commented that his firm too only had automatic control on metal cutting devices. He thought that an effort must be made to convince the financiers that a wider range of numerically-controlled machine tools were needed.

Mr. Leslie (National Engineering Laboratory) said that the N.E.L. was attempting to provide some standardisation of computer programmes for the planning engineer using numerically-controlled machine tools. The aircraft industry illustrated this need since there were three other programmes in addition to that described by Mr. Bishop. These all used different languages to describe the required machine tool action. This made it difficult for men to move round the industry, or for work to be sub-contracted where numerical control was involved. Different programmes were provided by different control system manufacturers and this resulted in the user restricting his choice to encompass only one type of control system, or finding it necessary to re-programme if he wished to transfer repeats of a job from one type of controlled machine to another.

N.E.L. were financing the development of yet another computer programme whose planning, or part-programming, language was a subset of a U.S. numerical-control programme known as APT. As Mr. Bishop had indicated, APT is useful when complicated shapes have to be machined on machine tools with 4 or 5 machining axes. A simple subset from APT is used to describe the type of machining widely done in the U.K. on $2\frac{1}{2}$-axis machines, and it is hoped that early in 1967 a compiler will be freely available on current British computers. The compiler will be based on FORTRAN so that it should be easily implemented on any computer having an ASA FORTRAN IV compiler and at least 12K of accessible core store. This numerical-control compiler will be maintained by N.E.L. and lead in due course to some degree of standardisation of part-programming language. It should provide training for both the design office and the workshop planning office, who will later go on to more complicated work requiring APT.

Mr. Leslie also commented that, as an outside observer, he had the impression that the aircraft industry in this country was more concerned about current cost-effectiveness than in the necessity to obtain a proficiency in new techniques so that they would be cost effective tomorrow. This resulted in the application of new techniques, such as numerical control, being delayed until competitors in the U.S. had demonstrated its commercial value. Unfortunately, by the time this value was obvious, a newcomer had a difficult job in learning quickly enough how to use the new technique. It appeared in the U.S. that there was more willingness to back a go-ahead man and let him try a new idea. The commercial safeguard was obtained on the basis that with success the man went up and with failure he went out - a sufficient deterrent to make sure that only potentially viable ideas are put up, and that they are worked on with enthusiasm.

Mr. Macnaghten (Short Brothers and Harland, Belfast) commented that the numerical control language developed at Short Brothers, 'Short Cut', has a final programme output on paper tape which can be plotted directly with a Benson-Lehner plotter; this plotter has been adapted to read the same code as the E.M.I. numerically-controlled milling machine. Graphical output of this kind is much easier to check than the digital output illustrated by Mr. Bishop.

ON THE CLOSER INTEGRATION OF THE DIGITAL COMPUTER WITH DESIGN PROCEDURES

by

G.G. Pope
(Royal Aircraft Establishment)

SUMMARY

This paper reviews computer techniques for the optimum design of stressed-skin structures and discusses the efficient utilisation of digital computers in the design office.

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1 INTRODUCTION

The digital computer is used extensively in the aircraft design office in the solution of complicated analytical problems, and a great deal of effort has gone into the development of efficient techniques for use in such applications. The main emphasis has, however, been on the analysis of the properties of a given design, and comparatively little attention has been given to the wider problem of deciding how the potentialities of the digital computer can be utilised best in the design process as a whole. This paper reviews computer techniques for the design of stressed-skin structures with optimum properties, and discusses a number of ways in which the digital computer might be employed to improve the efficiency of design procedures in general. Attention is concentrated on applications in design and analysis rather than in the organisation of the design office, so critical-path programming is not discussed.

2 STRUCTURAL OPTIMISATION

All engineering design is an optimisation process in the sense that the designer is inevitably trying to satisfy a set of specified requirements as efficiently as possible. It is, however, seldom possible to measure the merit of anything as complicated as an aircraft structure in terms of a single parameter, and many design requirements such as, for example, reliability and ease of maintenance are difficult or, more often, impossible to express mathematically in terms of the design parameters. A design is usually chosen in practice from a number of acceptable alternatives by a qualitative assessment, on the basis of past experience, of the relative importance of a number of merit functions.

Weight is, of course, a merit function of particular importance in aircraft design, and it would be very useful if the digital computer could generate in an efficient manner a minimum weight design for, say, a wing or fuselage of specified external shape, with just sufficient restrictions imposed on the geometry of the internal structural members to leave appropriate space for crew, fuel tanks, payload, etc. It would also be useful if the computer could indicate the range of admissible structures with weights that do not exceed the minimum value by more than a specified percentage, so that the corresponding variation of the other merit functions could also be investigated. Optimisation techniques of this generality will not, however, be available in the forseeable future, and it is more profitable to discuss the capabilities of optimisation procedures that are already either in use or under development.

Systematic optimisation of complete stressed-skin structures has been attempted so far only when the geometry of the basic configuration is fixed, when the material to be employed has been chosen, and when the only variables are the thickness of the skin elements and the cross-sectional area of the reinforcing members. It is then usually possible to generate a design iteratively in which all members are either fully-stressed in at least one load condition, or have a minimum specified size. In general "fully-stressed" designs obtained in this way are not unique. For example, when minimum sizes are not specified and members can vanish altogether, there must be at least as many different "fully-stressed" designs as there are statically determinate combinations of members within the structure which can equilibrate the applied loading. These "fully-stressed" designs usually differ in weight, so the iterative process does not necessarily generate an optimum design. Nevertheless "fully-stressed" designs which have been obtained by a single application of this process often appear to be efficient in practice, and they have been employed by aircraft firms on both sides of the Atlantic. Caution must, however, be exercised in complication problems, such as the design of wing-fuselage intersections, where it may be difficult to see whether or not a given "fully-stressed" design is efficient. The relationship between "fully-stressed" designs in general and optimum designs is discussed in a recent paper by Razani[1].

A general method for optimising structures when the basic configuration is either fixed or is governed by only a few design parameters has been developed recently at the Case Institute, Cleveland by Schmit and his colleagues[2,3]; any merit function may be used, and problems can be handled where more than one load condition must be considered, and where buckling effects are important; side constraints like minimum gauge thicknesses can also be included. The computational process, which is based on a non-linear programming technique, starts from an arbitrary design and finds a local optimum such that a small change in any variable causes an increase in the value of the merit function. This process should strictly be repeated from a number of different starting points if an absolute minimum is to be obtained with reasonable certainty. The computations are seldom repeated in this way, however, and the results of a single minimisation sequence are often accepted if they appear reasonable, without any further confirmatory checks being made. This optimisation procedure makes heavy demands on computational facilities, and consequently only relatively simple examples have been computed so far. Computer programmes are, however, being developed currently at the Bell Aerosystems Company[4] to apply this kind of procedure to complicated structures in general, and to stressed-skin structures in particular. A "fully-stressed" design is obtained first in these programmes by the usual iterative process, and a minimum weight design is then sought by a numerical procedure which is very simple compared to those that have been employed in minimisation problems in other fields. This relatively simple technique has been effective in the examples computed so far, but it may converge less well in more complicated problems where stiffness requirements influence the design to a significant extent, and where the sizes of the various members are established by dissimilar load conditions. In such problems it will, moreover, be essential to repeat the minimisation sequence from different starting points before it can reasonably be assumed that the computed minimum weight design is the true minimum weight design.

It is not yet clear how much use can profitably be made of optimisation techniques of this kind in the design of aircraft structures. The enormous computational effort which would be involved in the overall design of a complete stressed-skin structure using such techniques, would only be justified if it could be shown that appreciably better designs could be obtained in this way than can be evolved in a reasonable time by modifying a trial design progressively on the basis of past experience; no such evidence is yet available. These techniques can, however, be used effectively in the optimisation of local regions of the structure where there are relatively few design parameters, but where failure can occur in a number of different ways. A typical problem of this type is the design of reinforced surfaces which are loaded in compression or shear, and a simple application to the design of integrally-stiffened waffle-like plates is described by Schmit and his colleagues[3]. There is, of course, already a great deal of published information on such problems based on studies where only one load condition is considered, where the number of failure modes is the same as the number of design parameters, and where the design parameters are free to take any value irrespective of the physical implications. Such restrictions are, however, unnecessary with this general optimisation method.

3 DESIGN OF THE BASIC CONFIGURATION OF AIRCRAFT STRUCTURES

The configuration of the internal structure of major aircraft components such as wings and fuselages is normally chosen by assessing a series of tentative design studies based on alternative configurations which have been selected on the basis of published data and previous experience. In relatively simple problems such as the design of regular portions of high aspect ratio wings these studies can be performed adequately on the basis of elementary beam and tube theories, with the assistance of standard information on the strength and the weight of the available forms of construction. When, however, a structure with more complicated deformational properties is being designed, such as, for example, a low aspect ratio wing, there are far more possible configurations and, furthermore, the amount of computation in each study is larger since it is necessary to develop designs based on each configuration, using finite element methods of analysis.

The efficiency of this kind of design process depends not only on the experience and the ability of the designer, but also on the number of structural configurations that he can assess in a reasonable time. A system of computer routines designed to minimise delays in this kind of work would therefore be a very valuable design office facility. Such routines should be written in a consistent form so that they can be combined quickly into an efficient programme for use in a particular application.

Suppose, for example, that the basic structural configuration is to be chosen for a low aspect ratio wing of specified external shape, and that an initial study is to be based on an idealised structure consisting of a stressed skin and a system of ribs and spars normal to a datum plane. If suitable standard routines were available a computer programme could be assembled to generate "fully-stressed" designs for any configuration of this class and to estimate the corresponding structural weight, as illustrated in Fig.1. The designer would specify as data the planform of the proposed structural configuration and the positions of any major cut-outs; minor cut-outs such as lightening holes would, of course, be treated empirically at this stage. The first routine in this programme would calculate the geometry of the idealisation from the structural planform and from the external geometry of the wing, which would be specified in digital form. A standard structural analysis routine would be employed to generate a "fully-stressed" design starting from an arbitrary design which might, for example, be based on the minimum permissible gauge thicknesses of the sheet members. The weight of each tentative design would be analysed with a routine which makes use of statistical information on the weight of connections in the proposed form of construction, and an output routine would be employed which presents the results in a convenient form for rapid assessment. For example, an output tape might be produced which would give the necessary instructions for a draughting machine to make a drawing showing the relative sizes of all the members. The designer would use his experience to decide whether the "fully-stressed" design obtained by the computer utilises the configuration efficiently. If necessary he might use the same computer routines again to investigate the configuration further by modifying the member sizes progressively on the basis of his past experience, or by repeating the iterative design process from a different initial design to see if he can obtain a more efficient "fully-stressed" design. The output of the structural design programme might also be employed as data for simple aeroelastic investigations based on a similar set of routines. Such investigations might lead to modifications in the design which would lead to further applications of structural analysis and weight estimation routines.

The speed and frequency with which the designer can get results back from the computer determines the effectiveness of this procedure, so the relevant programmes should be run if possible as soon as they are received by the computer operator; such priority treatment should be possible with modern computers that have time-sharing facilities, provided that the individual routines are written in a form which is both compact and rapid in execution. Unnecessary elaboration should therefore be avoided in the analytical routines. For example, sophisticated structural analysis programmes, which have been prepared for the detailed analysis of aircraft structures, are likely to be too cumbersome to be used as routines in this context, where the accuracy of the available information on structural weight only normally justifies a relatively crude idealisation.

Each application of this design procedure would normally require a different programme built around the basic routines. Moreover, the requirements of the designer would often change as the design study progressed, so these programmes would frequently require modification. It is therefore desirable that the designer should be able to write and revise these programmes himself. A simple computer language is therefore needed which would enable him to communicate his requirements directly to the computer in the same kind of terminology that he might employ to brief a programmer.

No aircraft design team yet possesses a system of this generality for the design of efficient structural configurations. Several American aircraft manufacturers have, however, developed special programmes for use in specific problems at this stage in the design process. For example, R.E. Miller[5] describes a programme which was prepared at the Boeing Company to assist in the design of low aspect ratio wings and, in particular, the wings of the proposed variable-geometry supersonic transport aircraft. This programme analyses a representative range of structural designs when the load distribution is influenced by elastic distortion of the wing. Structural analysis, weight analysis and the calculation of aerodynamic lift are thus integrated in a single programme. The computations are simplified considerably by employing a common grid pattern for both aerodynamic and structural analyses.

4 FACILITIES FOR THE CLOSER INTEGRATION OF THE DIGITAL COMPUTER WITH DESIGN PROCEDURES

If the full potentialities of the digital computer in the aircraft design office are to be realised, a range of languages must be developed which enables each member of the design staff to communicate directly with the computer in the terminology of his or her particular specialisation. Such languages should be sufficiently versatile for users to be able to assemble efficient programmes for any problem that is likely to arise in the relevant field. These languages should, moreover, be written in an open-ended form so that additional facilities can be added whenever the need arises. Flexibility in the input and output routines is also important, and it should be possible to present data to the computer in a form which requires no preliminary computation on a desk machine; the output should be in a convenient form for rapid interpretation and, when appropriate, for use as data in a subsequent programme.

Most aircraft firms now have standard programmes for use in large scale structural analyses, and experience gained in writing these programmes should be valuable in the development of standard computer languages for the specification of structural analysis problems of any size or complexity in the simplest possible form. Compilers for these languages should incorporate a compact interpretive routine which calls up from an auxiliary tape or disk store only those analytical routines that are required in the current application, so that the computer can be utilised efficiently in both large and small problems.

Two special computer languages have been evolved so far for the analysis of elastic structures. A language known as STRESS[6] (Structural Engineering System Solver), which analyses pin-jointed and stiff-jointed frameworks, is one of a series of problem-orientated languages developed at the Massachusetts Institute of Technology for use in civil engineering problems. A more general structural analysis language known as ASKA[7] (Automatic System of Kinematic Analysis) has been developed recently by a team working under Argyris at Stuttgart. This language enables the user to formulate in the simplest terms the analysis of a finite element idealisation of virtually any kind of structure or solid body.

The development of problem-orientated languages such as STRESS is part of a research programme at M.I.T.[6] which is concerned with the general problem of making communication easier between the computer and the user. An experimental computer facility has been developed there[8] in which a number of users each have a console with virtually immediate access to a central computer on a time-sharing basis. Multiple access devices of this kind are expensive, but they might one day become a useful facility in the design office both for obtaining quickly the results of relatively small computations and for extracting design information from data stored on magnetic tape or disk. However, design procedures which depend on immediate access to a digital computer are only practicable when the necessary facilities are duplicated, so that the design office is not brought to a standstill in the event of a computer breakdown.

A device known as Sketchpad[9,10], which is also being developed at M.I.T., enables the user to communicate geometrical information directly to a computer by sketching on the screen of a cathode ray tube with a light pen. The combination of the path traced by the light pen and instructions communicated with appropriate push-button controls specifies figures on the screen consisting of straight lines and circles. Sketchpad has been demonstrated in a number of fields including the analysis of plane pin-jointed trusses. The user sketches a truss of this kind on the screen and specifies the loading; the stresses and the deflections are then displayed on the screen by the computer. Facilities are available to investigate immediately the effect of varying either the geometry of the truss or the loading. The effect of removing a member can be demonstrated, for example, by pressing an appropriate button on the console and pointing the light pen at the member in the sketch of the truss. The Lockheed Aircraft Company in conjunction with IBM are also experimenting with techniques of this kind. One particular programme they have developed, for example, calculates the properties of a beam cross-section which is sketched on the screen; the profile permitted consists of straight lines and circular arcs and consequently radiused corners on extruded sections can be included. General Motors[11] are experimenting with similar cathode ray tube and light pen devices for two-way graphical communication with computers in the design of car bodies. Their applications are concerned with curves of general profile, however, and the sketching facility characteristic of Sketchpad is not included in their system.

None of the present applications of Sketchpad and similar facilities are likely to be sufficiently useful in the aircraft design office to merit the investment of capital in the equipment. Simpler draughting and display devices which present computer output in graphical form could, however, be used profitably to accelerate the interpretation of a wide range of analytical results. Both the Douglas and Boeing companies employ draughting machines to plot geometrical information such as rib profiles and fuselage cross-sections onto Melinex sheets for use in the drawing office; programmes have, moreover, been developed by these companies for draughting perspective views of three-dimensional bodies. Such programmes are of potential value in the rapid interpretation of many kinds of analytical results.

5 CONCLUSION

The initial cost of developing a versatile set of standard computer routines for use in the design office is necessarily high. Time and money will be saved in the long term, however, if the amount of special programming for individual design projects is kept to a minimum by the intelligent use of such routines. Appropriate problem-orientated languages could be very useful both in speeding up design investigations and in relieving pressure on programming staff at times when there is a heavy demand for their services. Suitable languages of this kind could also increase the range of relatively simple computational and data-processing applications in which the computer can be used economically, and they could thus enable the design staff to concentrate more on the creative aspects of their work.

The rate of development of computer applications in design must, of course, be governed by long term cost-effectiveness considerations. It has already been demonstrated, however, that current computer techniques can be used effectively in accelerating design procedures at a competitive cost, and there is every likelihood that more sophisticated developments in this field will also prove to be commercially advantageous when experience has been gained in their application.

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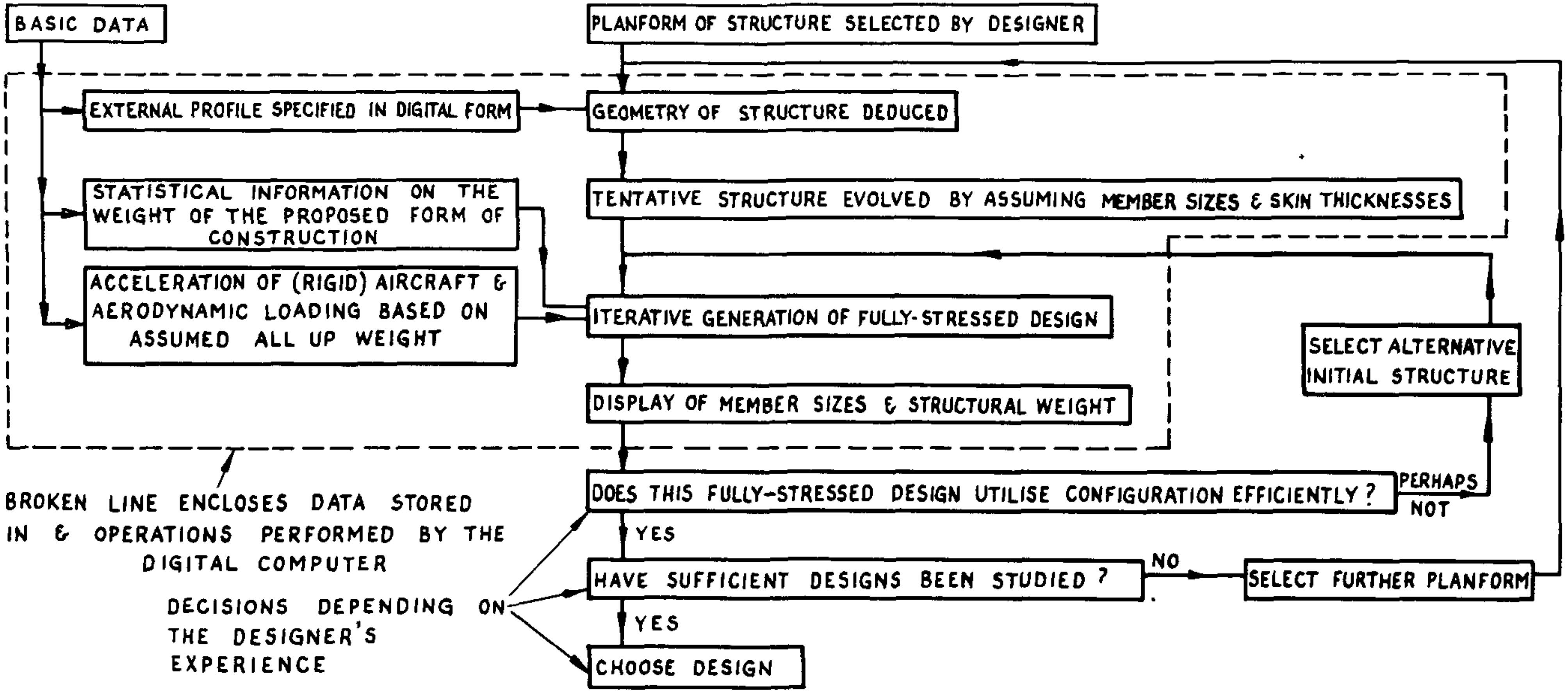

FIG.1 AUTOMATED DESIGN CYCLE FOR THE BASIC STRUCTURE OF A WING - AEROELASTIC EFFECTS OMITTED

DISCUSSION

Mr. Leslie said that although he agreed with much of Dr. Pope's paper, he parted with him in his summary of the current situation regarding Sketchpad-like devices. Dr. Pope had said that none of the present applications is likely to be sufficiently useful in the aircraft design office to merit the investment of capital in the equipment. It is exactly this attitude that has got the British aircraft industry where it is today! All the major aircraft companies in the United States are already evaluating this kind of equipment by using it, whilst we are still sitting back and saying that it will be a long time before we will even consider whether we might spend some time and money to see whether we might be able to use it. We will get nowhere this way. There is no doubt that Sketchpad-like devices, if they can be proved economical, are exactly the type of device that Dr. Pope and some of the other speakers have been looking for in their search for a universal computer language for designers. You only have to look at a technical paper in a foreign language to appreciate how much can be conveyed by a diagrammatic or graphical source of information. You only need to look at a drawing to see that you do not need to know the spoken language of another engineer to understand much of what he is telling you about his design.

Mr. Leslie then went on to say that he did not think that enough serious attention was being paid in this country to demand processing with a typewriter console. It is not true to suggest that this is an expensive way of using a computer. A Telex machine plus the communication facilities on the computer are less expensive than a card punch. It should therefore be within our economic reach to buy equipment to find out what the problems really are. As engineers we know that you do not understand a problem until you get to grips with it in reality; if we attempt to assess these facilities on a purely theoretical basis we will inevitably miss a critical point. Demand processing is well suited to engineering design where a large number of decisions have to be taken in series, each dependent on the consequences of many of the preceding decisions. To do a design in an acceptable time, hours rather than days can be allocated to individual decisions and to the calculations and information retrieval on which the decisions are based. Until the advent of demand processing the time scale for digital computing has been a turn round time of a day per step - enough to discourage designers from taking all but major calculations to the computer.

A problem that is liable to cause trouble in the initial stages of multiple-access working is the shunting of information from one special design analysis programme to another. A lot of effort must therefore be put into the systematisation of data to avoid unnecessary manual editing of data between subroutines.

Mr. Leslie also mentioned that he visited the Boeing Aircraft Company two years ago where he was shown what they were doing at that time with the seven computers installed at their Seattle factories, each of which was of the size of an IBM 7090. He understood that Boeing is just one of a number of American aircraft companies, each of which has more computing power than we still have in the whole of the British aircraft industry. It is against this background that one becomes appalled at the situation here. The difference in scale of the available computing capacity leads to the situation where the 727 design is initiated a couple of years later than the Trident and finishes up on the market at the same time. Boeing attributed one of the two years that they caught up purely to computer-aided design, although they were only using graphical output at that stage. This was the first civil aircraft on which they employed geometric computing and computer lofting, and it was also their first aircraft in which the pieces fitted together without persuasion. This ease of assembly was partly a consequence of omitting the lofting and template stages altogether in many parts of the design. Computed cross-sections of the parts which had to mate together were fed directly to a numerically-controlled machine tool which manufactured the parts. Computer-aided lofting is also very valuable in communicating design modifications quickly to the whole design team, so that up-to-date information is available to anyone who requires it.

In conclusion Mr. Leslie mentioned that a bibliography of computer-aided design had been compiled at N.E.L. A copy would be sent to anyone that requested it.

Mr. Atkinson (Royal Aircraft Establishment) commented that Mr. Leslie's powerful plea for increasing the use made of digital computers had to be supplemented by Mr. Hall's comment that you have to convince someone else who holds the money bags. It seems as if our public relations on the computer side are not as good as they should be.

Mr. Hitch (British Aircraft Corporation, Weybridge) said that he too had visited Boeing at Seattle, but he had obtained a rather different impression of the extent to which master-dimensioning was used on the 727. He understood that this scheme was not used seriously in design or production, but that it had been employed experimentally on the back end. It was, however, being employed consistently on the 737.

Mr. Hitch also commented that although the computer power of the British aircraft industry was far below what it should be, he could not see what the American industry did with all the extra computing power it had available.

Dr. Pope said that he had also visited Boeing at Seattle and he had gained much the same impression as Mr. Hitch. He was somewhat surprised to hear Mr. Leslie's remarks on the use of Sketchpad-type devices. Lockheed was the only aircraft firm at which he knew of any work on graphical input devices. He understood, moreover, that the Boeing Airplane Group could not yet foresee any commercially advantageous applications of graphical input devices in the aeronautical field.

Mr. Leslie commented that both North American Aviation and Boeing were experimenting with Sketchpad-like graphical input/output now. They may not expect the initial applications of these devices to be economic, but they will be gaining orders at our expense in a few years' time because of them.

Dr. Pope replied that his remarks were concerned with two-way communication facilities. Would Mr. Leslie agree that there is a far shorter term profit to be made from graphical output devices than from two-way facilities such as Sketchpad?

Mr. Leslie replied that the U.S. Aerospace firms would be demonstrating the commercial value of two-way graphical facilities in a year or two just as they had demonstrated the value of graphical output over the past three years. Presumably once they had done this we would appreciate the value and try to catch up again.

Mr. Atkinson said he did not think that anyone would disagree with Mr. Leslie when he said that there appears to be a general unwillingness to try things out in this country. Plenty of people are willing to try things, however, if someone else will only put up the money.

Mr. Armstrong (Atomic Weapons Research Establishment, Aldermaston) said that although he was not an engineer he would like to make four points briefly.

Firstly, you should not find it difficult to make a cost-effectiveness case to the bankers because they are far ahead of you in the field of computer applications.

Secondly, with regard to graphical input and output, it was very surprising that there had been no mention whatever of graphical input, using devices which are already available. This seemed particularly surprising because these devices are already manufactured in this country. A device of this kind, made by D-mac Ltd., which is being used at Aldermaston would probably also be valuable in the aircraft design field.

Thirdly, it was said earlier that you could not possibly get the amount of information required to describe an airframe into a computer. What order of magnitude is involved? Very large stores (of order 500 million characters) are becoming available quite cheaply now with computers such as the ICT 1900 series.

Finally, we have been discussing whether we should use Profiledata, or Short Cut or a new N.E.L. language as a standard engineering design language. It would, however, be utterly unrealistic to choose any standard language which is not acceptable in America. The construction of software is very expensive so it is important to get everything one can free, whether the viewpoint adopted be that of an individual establishment or firm, or that of the British nation as a whole. Now, taking into account the absolute numbers of computer programmers in the U.S.A. and the U.K., respectively, it seems highly probable that the total effort put into developing high level languages suitable, for example, for application to engineering design, will be greater in the U.S.A. than in the U.K. in any stipulated period of the future. It is therefore most important for Britain to put herself in a position to reap the benefit of this U.S. effort by ensuring that the engineering design language adopted as a British standard is not incompatible with that accepted as standard in the U.S.A.

THE COMPUTER AND THE STRESS OFFICE - TEN YEARS' EXPERIENCE

by

W.G. Heath
(Hawker Siddeley Aviation, Manchester)

1 A BRIEF HISTORY OF THE COMPUTING FACILITIES AT H.S.A. MANCHESTER

In 1950 the aeroelastic section of the Stress Office realised that automatic computation could be of great assistance in the solution of their flutter problems. A small analogue computer was designed and built by a consultant electronics engineer for this purpose; this was a four-degrees-of-freedom machine from which the critical flutter speed could be read directly. It was installed in 1952. The success of this simple computer led other H.S.A. companies to purchase identical models.

In January, 1953, the first use was made of a digital computer. This was the Ferranti Mk.1 at Manchester University. A development of this computer, the Mk.1*, was installed at H.S.A. Manchester in 1955.

This was a 100 kilocycle machine, using a 16000 word magnetic drum for storage, together with a 256 word cathode ray tube working store. The paper tape input was at the rate of 100 characters per second and output at 33 characters per second.

Encouraged by the success of the original analogue computer, the Company built its own six-degrees-of-freedom analogue for aeroelastic work in 1957.

In 1964, the Mk.1* computer was replaced by a Pegasus II 330 kilocycle machine. This has a 9000 word magnetic drum and a 56 word nickel delay line working store, together with four magnetic tape decks. There are two paper tape readers at 200 characters per second, a tape punch at 60 characters per second and two high speed punches at 300 characters per second.

2 INTRODUCTION OF COMPUTER TECHNIQUES INTO THE STRESS OFFICE

When the digital computer was first installed at H.S.A. Manchester, the Stress Office was reluctant to take advantage of its capabilities, yet today it uses more computer time than any other department. This initial reluctance was ascribed to five factors, namely:

(1) The difficulty of communication between stressmen and programmers, i.e. between practising engineers and mathematicians. This gulf was bridged at management level, since the Chief Programmer was an ex-stressman, but at working level language difficulties frequently arose.

(2) The need for the stressman to define his problem in a precise manner and to express the method of solution in a form suitable for programming.

(3) A lack of understanding of the computer's full capabilities.

(4) The length of time taken in conventional computer language programming.

(5) The rigid nature of the programmes and the difficulty of altering them in the light of experience gained in practice.

Looking through the original index of programmes, one finds that the earliest structural ones have the following titles:

Solution of Simultaneous Equations
Schuerch Wing Stressing Programme
Normal Modes of Vibration
Flutter Determinant
Flutter Coefficients
Williams' Method of Structural Analysis

The stressmen thus made two attempts to analyse large units of structure by the methods then available (1955), but neither method proved very popular and was soon abandoned. On the other hand, the small, but more mathematical, aeroelastic section of the Stress Office initiated programmes which have continued to be used extensively during the past ten years.

During the first three years after the installation of the computer the Stress Office was responsible for only 20 programmes out of a total of 67. Of these 6 were concerned with aeroelastic problems, and a further 7 with the preparation of data sheets.

3 THE INTRODUCTION OF TIS

In 1958, a tremendous step forward was made which overcame most, if not all, of the difficulties listed above. This was the introduction of an autocode known as the Tabular Interpretative Scheme (TIS). This scheme, used now by all the technical departments at Manchester, was evolved primarily for the Stress Office.

The basis of the scheme was a careful study of the way in which a stressman made systematic calculations before the advent of the computer. The traditional method is to take advantage of the repetitive nature of many calculations and to reduce the analysis to the filling of a table consisting of rows and columns.

Steps in the calculation then consist of operations on certain columns, the result being written in a further column. For example, one column might list stations along a wing, a second might contain the weights of wing sections, and the operation of multiplying corresponding elements of these columns together would give increments of bending moment.

Quite large and complex problems have been solved in this manner which seems quite obvious and natural - more natural indeed than the programmer's talk of "programme loops" and "conditional transfers". The purpose of TIS is therefore to represent the computer as a table divided into 50 columns and 40 rows.

The columns are numbered 00, 01, 02 ...... 49 and there are some 45 functions similarly numbered. Each instruction contains a function code and three addresses, e.g. 01, 07, 08, 25, where the function code 01 specifies the addition of the two columns 07 and 08, the result being placed in column 25.

The various functions provide for the usual arithmetic operations, the evaluation of trigonometric ratios, input from and output to punched tape, etc. Provision is also made for the storage of a set of 42 single numbers, and some of the function codes operate on these separately. A block of single numbers may be transferred into a column and vice versa.

Many programmes can be written with the facilities described above, and as the stressman gains experience he can progress to a simple repetitive type of programme. For this purpose, a "jump" instruction can be used to jump back to the beginning of a programme, where the input instructions take in more columns from tape and the whole programme is repeated using another set of initial data.

For more sophisticated programmes, there is a "conditional jump" instruction which will test values of calculated quantities and select one of alternative paths in the programme. The facility of modification is also provided so that a repetitive loop may contain a systematic variation in the coding.

Success in practice is partially due to standardisation. The initial data and the instructions are written on standard pre-printed sheets, together with titles and reference numbers. The tape editing and computer operating staffs follow a standard procedure, and consequently the whole process is remarkably free from trivial snags.

The other main reasons for success are due to the personal control which the stressman has in preparing programmes, the speed of preparation, the ease of altering programmes, and the stimulation to seek other applications.

The utilisation of the scheme on the Mk.1* computer is illustrated in Fig.1 which shows that by 1964 it was being used, on the average, more than once per working day.

An unforseen bonus came when the computer at Manchester was changed, which meant that all the standard programmes needed re-writing. By re-writing just one programme - that for TIS - practically the whole of the Stress Office work was transferred to the new machine within a fortnight.

4 THE INTRODUCTION OF MIS

Although TIS was the first autocode to be used by personnel outside the programming staff, an earlier autocode had been developed centred on the formulation of problems in matrix terms. Matrices offer a convenient form of calculation for a computer and the autocode was developed from a rudimentary processing system into a very useful Matrix Interpretative Scheme (MIS).

This scheme was introduced to the Stress Office a year after TIS and is still one of the mainstays of Stress Office computation, especially in the analysis of large pieces of structure, and in aeroelastic calculations. Fig.2 shows its utilisation, which now exceeds that of TIS.

5 WIDER UTILISATION OF THE COMPUTER

The Stress Office originally saw the computer as an aid to the more rapid solution of its problems by existing methods. Thus the first programme was "Solution of Simultaneous Equations" - a useful tool, but the equations had to be derived by hand, put onto tape, the solutions read from the output sheet and used in some further calculation. No attempt was made to complete the preceding and succeeding stages within the computer.

The earliest attempt at the computer analysis of a closed ring required the input of the shear force, bending moment and end load in the "cut" ring;

the stressman calculated these by hand. Later he realised that the computer could calculate these for him, and the present programme only requires the input of the applied loads and the ring geometry; the computer does the rest.

Later still, the stressman began to realise the potentialities of the computer for the solution of problems by new methods. He began to think in terms of matrices, and the development of MIS enabled him to manipulate his matrices without having to wait for a special programme to be written for a particular job.

6 THE ADVANTAGES AND DISADVANTAGES OF COMPUTER ANALYSIS

Speed is the prime advantage of the computer. A modern machine is capable of performing 100 000 operations per second and of printing out results at the rate of 2700 characters per second.

Secondly, the computer removes the tedious arithmetic from structural analysis, freeing the brain for more creative work.

Thirdly, the computer gives the ability to use methods of analysis which were previously impossible.

These advantages are all well known and often quoted. However they bring certain less-publicised disadvantages in their train which must not be overlooked. These are discussed below.

The speed of the computer is offset by the time taken in preparing the initial data in a form suitable for ingestion by the computer, i.e. in punching and checking the input tapes and possibly writing or modifying the programme (Fig. 3). Again, no commercial undertaking can afford to use its computer solely for one type of work such as structural analysis, and often there may be a queue of programmes waiting to be processed.

When the results are obtained, there still remains the often tedious job of sifting the output to determine, for example, the design case which produces the highest shear stress at a given point in a spar web.

Now it may be argued that this kind of work - searching for maxima amongst a mass of data - is in itself an ideal job for the computer. This is true, but by allowing the computer to play too big a part in analysis, the stressman can very easily lose his appreciation of the physical meaning of the problem (Fig. 4).

The aircraft structure differs from most other engineering structures in one important aspect - it is continually being developed to withstand ever-increasing loads. A bridge is designed to carry a given density of traffic and to withstand a given wind velocity; one or two cases provide all the essential design parameters. Once built, the structure is not modified to carry more traffic; once completed, the structural analysis may be filed away and forgotten.

A bridge may therefore with advantage be analysed by an "all-in" computer programme, but the aircraft designer is not merely concerned with the ability of his structure to meet the original type specification. He will wish to know, from time to time, what modifications will be necessary for a particular development such as an increased payload or a more powerful engine. Moreover, he will not be prepared to wait while the data is prepared for the computer, processed, and printed out. He will expect a competent stressman to make simple, but reasonably accurate, calculations on the spot. For this purpose the stressman must retain the "feel" of the job; he must know the location of the high stresses, the design cases which cause them, and the sensitivity of each case to variations in particular parameters.

This is one reason why methods of analysis which rely entirely on the computer can be as much of a hindrance as a help. Another disadvantage is that no alternative method is available in the event of a computer breakdown - an infrequent, but nevertheless real, eventuality. Again, even results produced by computers are liable to errors, especially errors in programming and input data when new techniques are being developed. When everything is left to the computer, the stressman has no yardstick by which he can judge the accuracy of the results.

Finally, the computer is essentially a tool for analysis, not for design (Fig.5). However complex a structure may be, it must first of all be designed by elementary methods. The computer facilitates the use of refined methods of analysis which define the stress distribution with great accuracy, but the structure itself will only be as good as the crude methods by which it was designed. In the aircraft industry, where drawings are snatched off the board and rushed via the print room into the workshop, refined analyses are carried out too late to permit corresponding refinements to be made to the design.

7 CONCLUSION

Surrounded by the complex requirements for which aircraft are designed today, life in the Stress Office would be impossible without the aid of a computer. It is however a tool, not an automaton, and the stressman is not a data-processing clerk. Although feasible, it would be unwise to feed the computer with all-embracing programmes which would enable it to digest the aircraft specification and print out the Type Record.

Rather it should be used to take the toil out of each of the three stages of analysis; loading actions, structural data, and stress distribution. In this way each stage can be checked, the analysis has meaning, and structural development is facilitated.

The usefulness of the computer is further enhanced if the stressman is able, by means of a simple autocode, to write his own programmes.

ACKNOWLEDGEMENT

The author is indebted to his colleagues at H.S.A. Manchester and especially to Mr. J.P. Morton, Head of Computer Services, for their assistance in the preparation of this paper. He is also indebted to Mr. Christopher Storey of Hawker Siddeley Dynamics, Manchester, for drawing Figs.3-5.

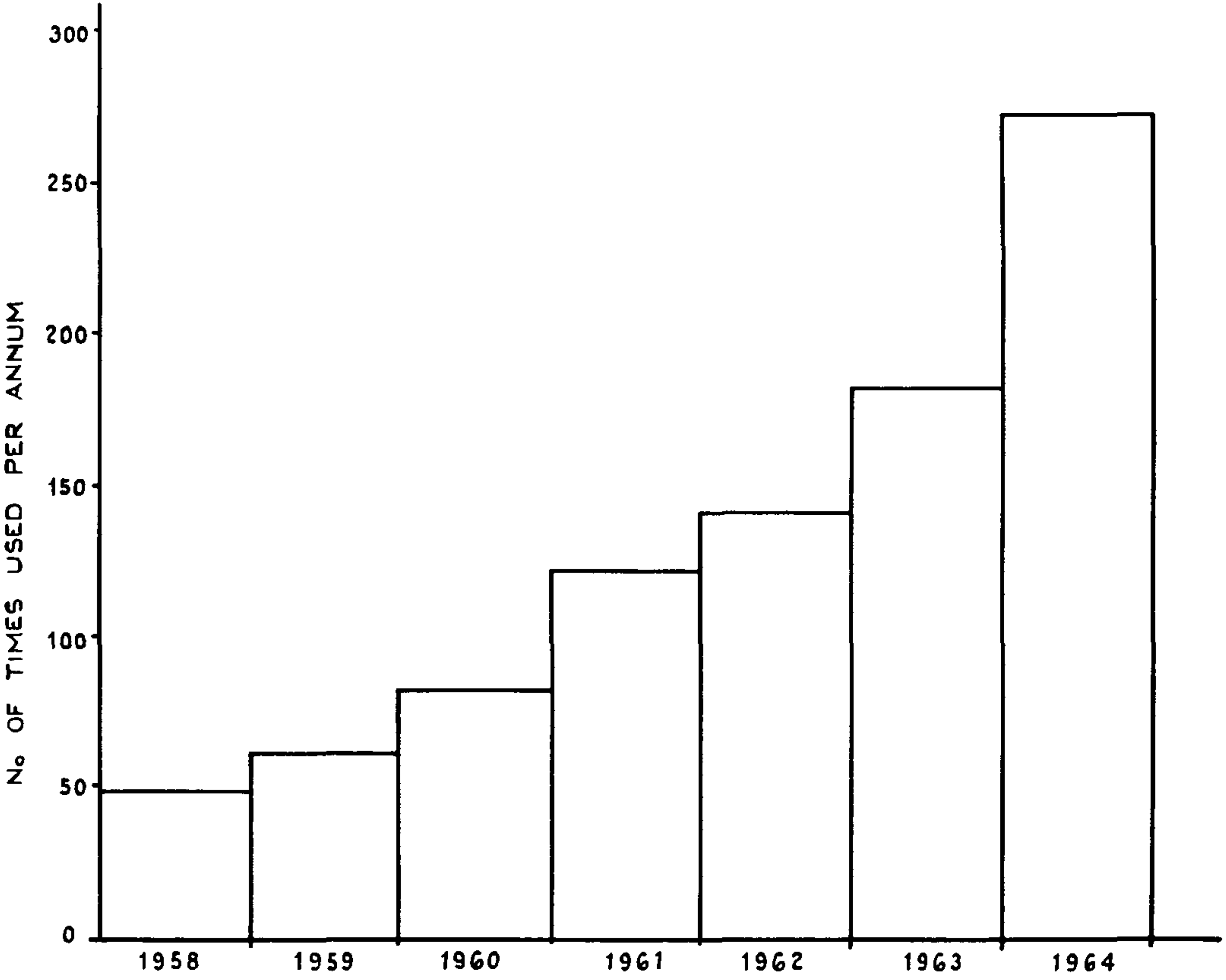

FIG. I T.I.S. ANNUAL UTILISATION

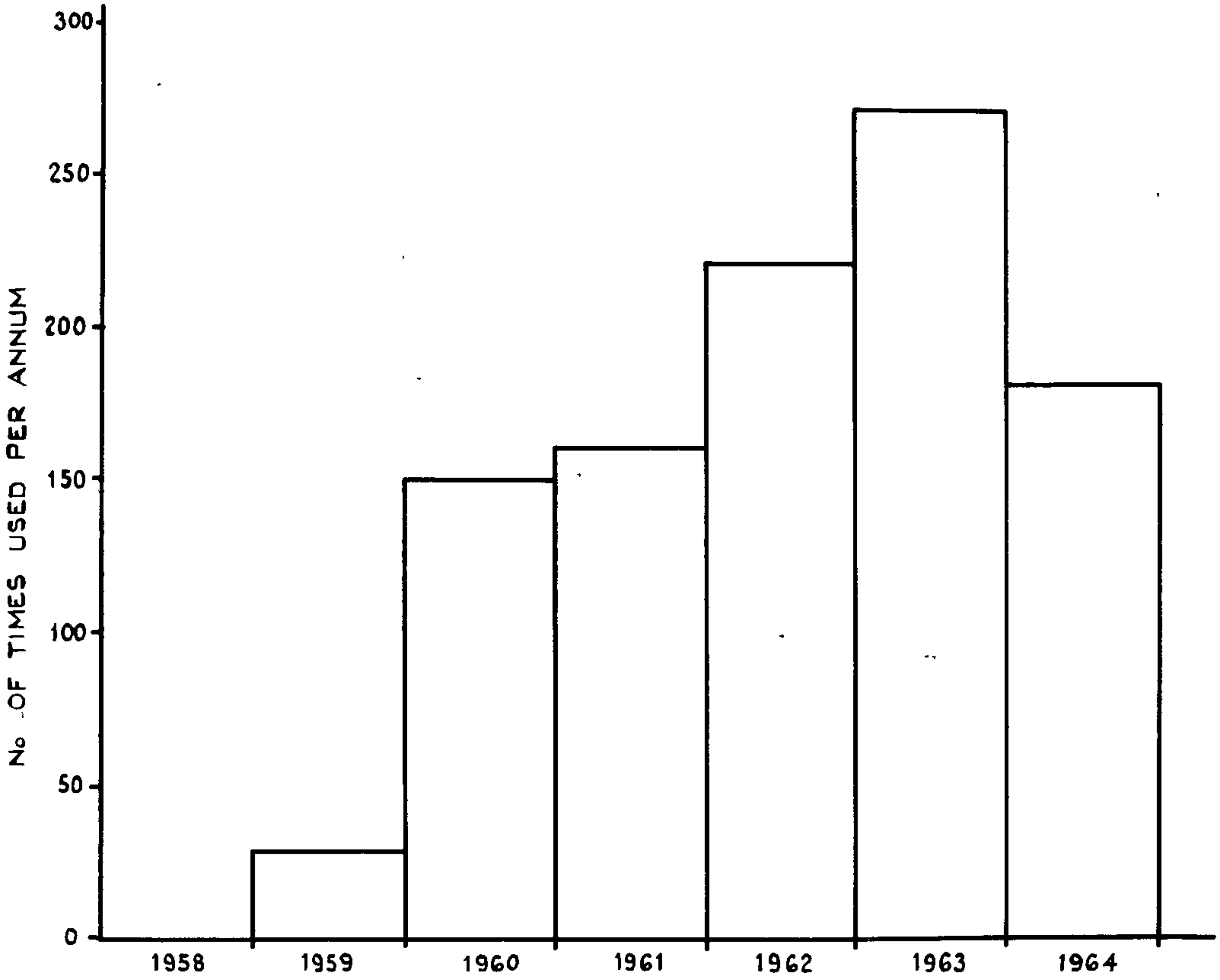

FIG. 2 M.I.S. ANNUAL UTILISATION

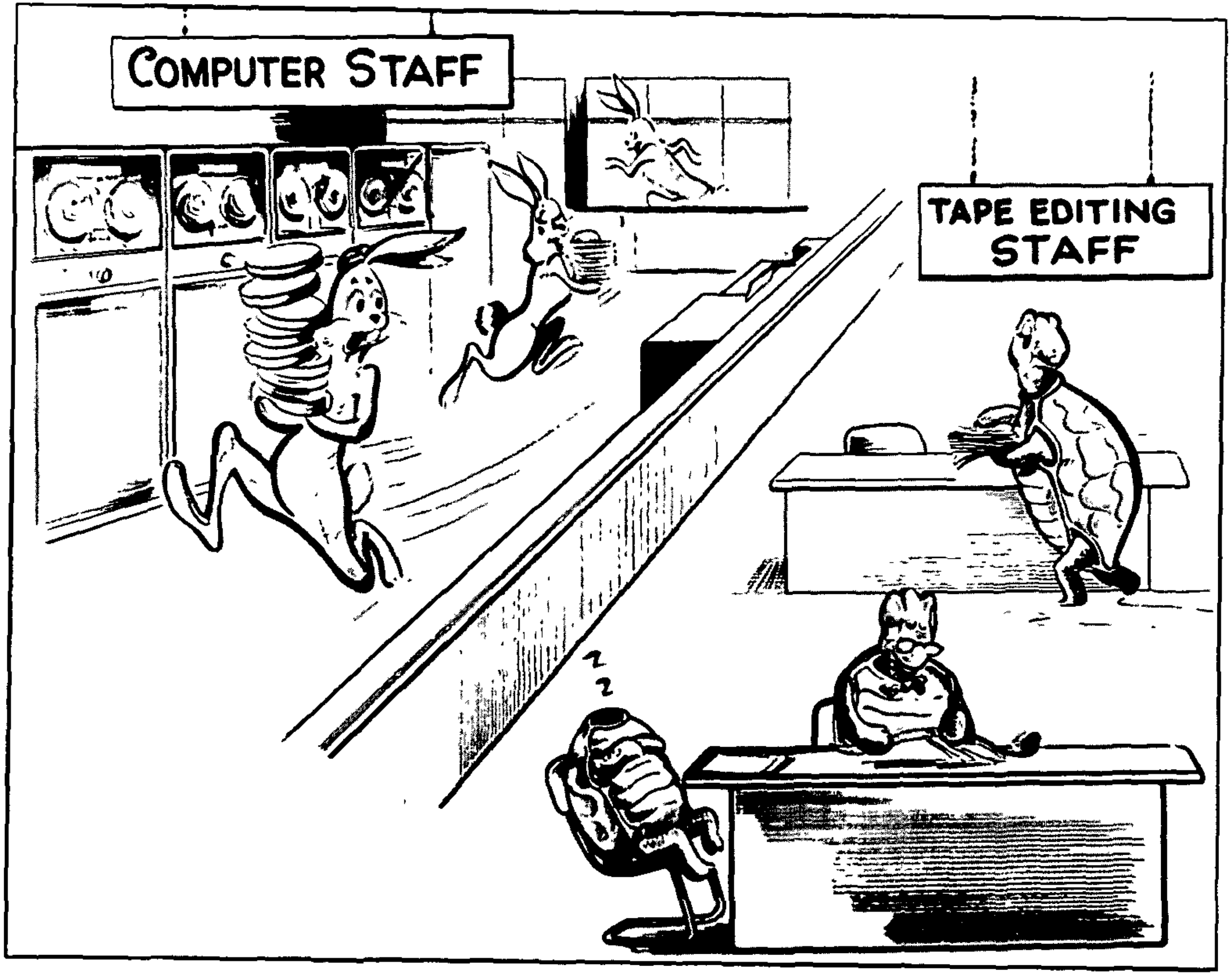

Fig.3 How fast is the computer?

Fig.4 The computer is not a substitute for the stressman

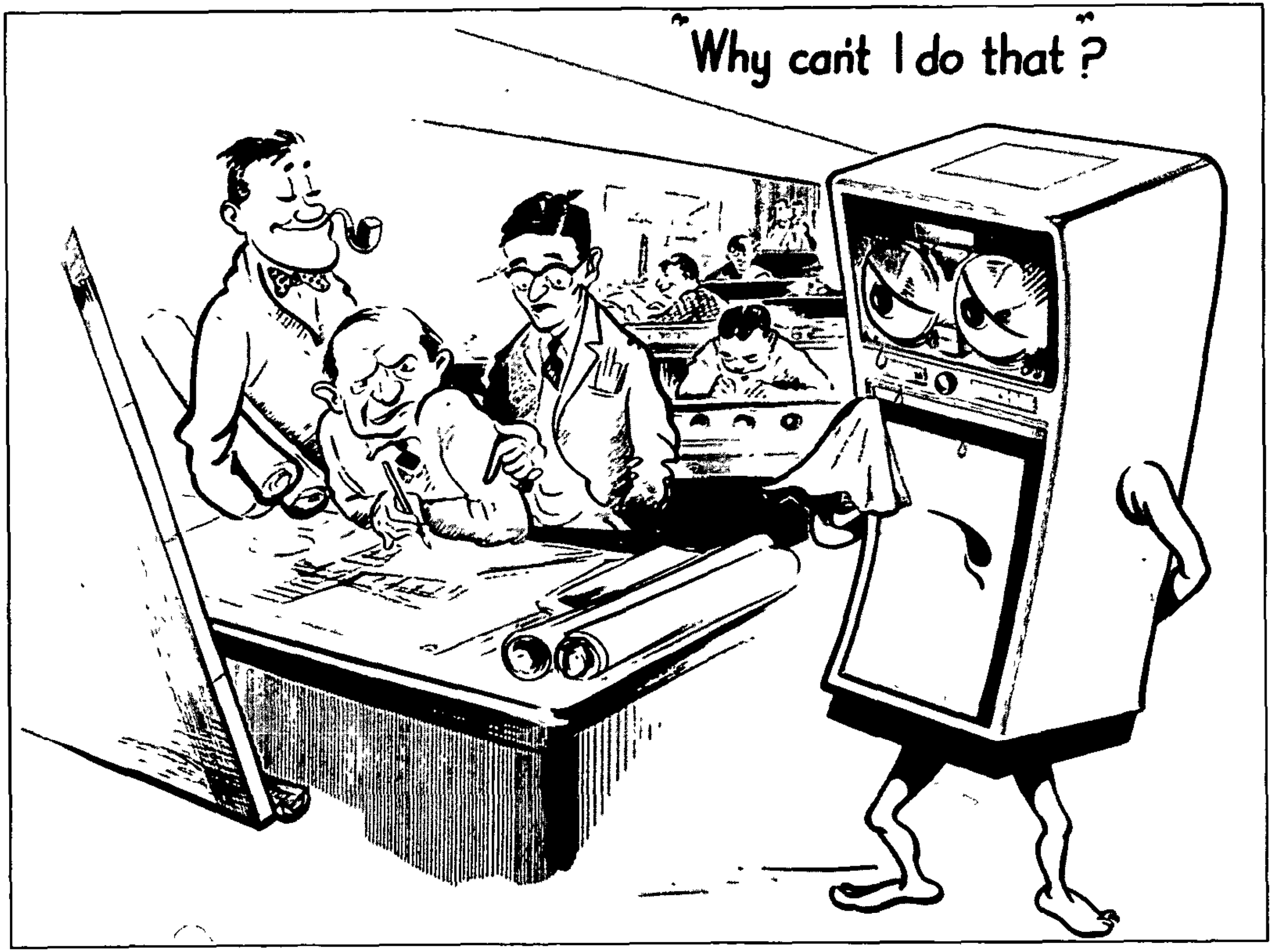

Fig.5 The computer cannot design aeroplanes

GENERAL DISCUSSION

Opening the discussion, Mr. Hitch (British Aircraft Corporation) said that it was quite clear that Mr. Heath had brought the Symposium fairly and squarely down to earth, because the jobs that the Stress Office has to do on a day-to-day basis are essentially those that Mr. Heath had described. It was very appropriate to point out the value of the tabular scheme and the various matrix interpretive schemes that have been employed in the last few years, as well as the wealth of standard programmes that were only hinted at. Nevertheless, there was an enormous contrast between the attitudes of Mr. Heath and, for example, Professor Argyris. Mr. Hitch indicated that he would range himself with Professor Argyris and the more avant garde contributors, but he would not accept their thesis hook, line and sinker. He thought that it should be recognised that there are significant dangers which can arise when the computer is used as a sausage machine. There is, for example, the question of cost-effectiveness raised by Mr. Hall. It is quite clear that the more you invest in sophisticated computer techniques the less return you get per pound invested. Care must be taken, moreover, not to spend time and energy on the structural problem at the expense of other problems requiring equal attention more urgently.

Mr. Hitch next turned to the structural analysis techniques now advocated for use in conjunction with a digital computer. He had yet to see test work on real practical structures compared with this theoretical work to show the justification for the very large expenditure necessary in effort of every sort.

He felt that a stressman must learn to design a good structure using essentially "back of an envelope" techniques. The stressman would nevertheless want to use the more sophisticated techniques, and he would soon learn an order code such as that described by Dr. Kamel if it were available to him. It would, however, be wrong to abandon the "back of an envelope" approach altogether.

We might now ask what further design office processes could profitably be mechanised. The output stages of specialised programmes would certainly repay mechanisation. Mr. Taig mentioned that some poor devil has to look through an enormous volume of computer output to decide what it all means. We should have drawing devices which would draw up the required grids and the corresponding values of stresses, temperatures and deflections to give the engineer a picture directly; it has already been pointed out that the eye appreciates graphically displayed information at a glance but it gets very little from a large quantity of ten digit numbers. Another area which should be mechanised is the specification of aircraft geometry. At B.A.C. we have a very powerful scheme nearing fruition which uses splines and conics to represent surfaces. The output can be in digital form or it can be in the form of numerical-control tapes for machine tools or draughting machines. Such a scheme does, however, raise an inspection problem. How are the inspectors to know that the part which comes out at the end is the right part? How far back should they check the basic data?

Except perhaps for Mr. Taig's contribution on the design of panels, the discussion has so far been restricted to the question of mechanisation; design itself has not been considered. We have explored at Weybridge the problem of choosing the optimum design for a curved beam to transmit load across the gap of a rivet gun. Even this apparently simple problem is very complicated since the position and shape of the neutral axis has to be computed as well as the beam cross-section. It would be interesting to know if anyone has explored true design problems of this kind with the aid of a digital computer. It would also be interesting to know whether any useful work has yet been done with the computer on such problems as the design of the best structure to transmit a given load to a specified wall.

Mr. Leslie has told us about American work in the field of graphics, and he has suggested that we should be doing more in this field. Perhaps it should be mentioned that the Cambridge University Engineering and Computing Laboratories are getting a device of the Sketchpad type which they will be using for research in computer-aided design. Mr. Hitch said he had thought a great deal about such devices but he did not know what he would use them for in the aircraft industry.

On the subject of numerically-controlled machine tools Mr. Hitch said he thought that we should accept that Profiledata is a good language for 2D and $2\frac{1}{2}$D machining; if a higher language is required we should go straight to APT. It may be of interest that ICT plan to have Profiledata available in FORTRAN IV within a year.

Finally Mr. Hitch commented that some speakers had given the impression that structural analysis is the central problem of aircraft design, and that other problem areas such as aerodynamics and aeroelasticity are only of secondary importance, it would, of course, be more realistic to give equal emphasis to all problem areas.

Mr. Macnaghten mentioned that Short Brothers had used the computerised techniques referred to by Mr. Hitch to analyse a cantilever circular cylindrical shell, reinforced by frames and stringers, under a concentrated load at the tip. Results of the analysis which seemed unlikely, and which conflicted with elementary engineering theory, were subsequently confirmed by test results.

Dr. Kamel commented that Mr. Heath looks upon the computer in a completely different way to Professor Argyris and Mr. Patton. Mr. Heath uses the computer as a slave to do his dirty work. Mr. Patton looks upon it as a member of a team who he wants to talk to and get answers from. Sometimes he may tell the computer what to do because he knows best; sometimes he may have to accept what the computer says because it is right. Perhaps the ideal approach is somewhere between these two extremes?

Professor Argyris pointed out that the structural analysis work of his team had been checked by tests on actual structures on more than one occasion. One particular example was the Transaal aircraft which is a joint French/German venture. The fuselage stresses were computed using the force method he had published two years earlier and which he now considered to be overtaken by the finite element developments in the matrix displacement theory. Only 400 redundancies were employed in the analysis but the calculated stresses only differed from those obtained from strain gauge results by 5%, in spite of tremendous cut-outs. The analytical results had been particularly valuable in the vicinity of high stress concentrations.

Professor Argyris then commented that one's attitude to computers changes when one gets access to a larger computer. The outlook of his own team had been transformed when they jumped from Pegasus to the UNIVAC 1107. It is difficult for anyone who has not been through this process to understand the need for sophisticated methods of analysis and corresponding software designed especially to utilise a large computer effectively.

Mr. Taig added that the validity of finite element methods of structural analysis had been proved over and over again and he had thought that this was now universally accepted.

Professor J.B.B. Owen (University of Liverpool) made the point that we must not be dominated by computer programmes and results; we must dominate them. If we want to understand the behaviour of a structure, we must often go back to the basic theory to appreciate what is happening and what ought to be done. A knowledge of Michell structures could, for example, be of great value in reducing a structural optimisation problem to a tractable size in an efficient manner.

Mr. Sadler (Hawker Siddeley Aviation, Kingston) complained that each new paper on finite element methods claims to do something that its predecessors do not do, and yet little is ever said about their deficiencies. He did not think that the general stressing problem had yet been solved and he was not convinced that a large computer was all we need to solve our stress problems.

Mr. Molyneux (Royal Aircraft Establishment) commented that the design process depends ultimately on the accuracy and adequacy of the information which comes into the design office in the first place. Consequently it is worth while considering the role of the computer in the processes that generate the required information. What, for example, is the basis of current market research? What part does the customer as distinct from the operator play in it, and can the computer contribute to the analysis? Gallup and other public opinion polls demonstrate that predictions of astounding accuracy can be made for most human activities if the sample is representative, whereas completely misleading results are obtained if a poor sample is chosen. Are the samples employed in this field constrained to be too small to be statistically significant?

Material selection is another real problem to the designer. The quantity of available material properties is always increasing and new alloys are continually being developed. The designer is not inclined to be venturesome because he does not have information on new materials readily to hand. If this information could be coded and stored in a convenient form in a large computer, the designer would be able to extract quickly the data he requires and the data itself could be updated without difficulty.

Inspection is a further area where the computer has a part to play. Inspection is an integral part, not only of the construction of an aircraft but also of its maintenance and repair throughout its life. Most inspection techniques consist of an examination of a component to find out its condition at a given time without reference to its previous history. There are, however, occasions when the rate of change of some property is more revealing than its current value. For example, the rate of propagation of an already detected crack may be more critical than its actual length. In this particular case the history travels with the component, perhaps simply as a sequence of dated pencil marks, but in the general case a more comprehensive record may be required which might conveniently be kept in an auxiliary store of a digital computer. However, many features looked for by a skilled inspector may be difficult to categorise in a quantitative way, so more precise techniques may be required to specify inspection procedures in digital form. For example, a single X-ray photograph of a component may show little that can be attributed positively to corrosion damage. Comparison with photographs taken under the same conditions at previous inspections may be more revealing, and the digitisation of a single parameter such as the average intensity might prove valuable for comparison purposes.

Finally there is the problem of defects in service. Here the difficulty is to record the defects in a form suitable for a computer analysis, so that rapid surveys can be made at intervals throughout the operating life to detect statistically significant defects as early as possible, and to initiate corrective measures. All too often defects have been well documented in a form which makes statistical analysis impracticable; there is an obvious potential for computer applications here.

In conclusion Mr. Molyneux commented that most speakers seemed to have taken free access to a computer for granted; many people, however, had great difficulty in getting adequate time on a computer suited to their needs.

Professor Argyris commented that there would be no difficulty in getting access to a computer if the industry and the Royal Aircraft Establishment jointly purchased a very large computer with many remote consoles attached to it. Each user would then have virtually immediate access; the facility could be organised in such a way that commercial and government secrecy could be maintained, so that no unscrupulous organisation could tap off the results obtained by a competitor.

Mr. Nicholson said that he accepted that a really large computer is needed for many jobs arising in aircraft design. It seemed, however, that no single design office could use such a facility anything like fully. The sharing of computers is therefore a real issue.

CHAIRMAN'S SUMMARY

Mr. Nicholson, in his summary, said that the Symposium began by considering some very advanced concepts, philosophies and generalities. The examples that had been discussed had, however, been relatively simple in concept if rather large in size. His worry was not that the U.K. is failing to think advanced thoughts about computer philosophy, but rather that it is failing to do the straightforward things quickly enough either through lack of money or through lack of seriousness of purpose. The money involved is not enormous compared to the amounts spent in the aircraft industry, so it may be that people are not making themselves felt properly if they are not getting the money they need. Perhaps, on the other hand, the differences in wage rates and related costs between the U.K. and U.S.A. are great enough for it to become economic to apply certain advanced techniques later in this country. He did not believe this argument, but it was a possibility which had to be considered. The conflicting views which have been expressed often merely indicate the difference between what is practicable now and what will one day be practicable. We are not, however, dealing with a static situation. The things that the aircraft designer is trying to do are changing all the time and so are the facilities that the computer engineer has to offer. This constantly changing situation makes the linking of the aircraft design and digital computer fields difficult, but it would be a great pity if it stopped them linking altogether.

Some of the ideas that have been discussed will prove to be impracticable in the end, but we will only find out which ones are impracticable by trying them out for ourselves. This point requires particular emphasis because we have not always been as quick trying things out as we should have been.

Everybody agrees that "back of an envelope" sums will continue to be valuable. There does not appear to be any real reason, however, why the competent structural engineer should not retain his feel for the job when he makes full use of the potentialities of the digital computer.

This Symposium will have served a useful purpose if it has stimulated a dialogue between the aircraft designer and the computer engineer which will continue elsewhere, and which will help the aircraft designer to use the computer more effectively as a tool and as a colleague. We must not sit back and do nothing; we must all get to grips with the new aspects that are cropping up all the time.

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