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STRUCTURAL ANALYSIS OF HELICOPTER ROTOR COMPONENTS BY MEANS OF FINITE ELEMENT PROGRAM SYSTEMS

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STRUCTURAL ANALYSIS OF HELICOPTER ROTOR COMPONENTS BY MEANS OF FINITE ELEMENT PROGRAM SYSTEMS

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Summary

Components of hingeless rotor hubs are complex and highly loaded structures. The stress analysis is treated by means of a threedimensional finite element method. Idealisation of the model and results of the analysis for rotor hub and rotorshaft are presented and compared with test data. Special problems with the analysis are discussed. The overall stresses are illustrated. This structural analysis is a reasonable method for optimizing complicated structures by parameter variation.

1. Introduction

The static calculation of complicated structural members subjected to threedimensional stress conditions is usually performed by means of the displacement method. In connection with a large scale computer and appropiate software the finite element method (FEM) offers an economically acceptable way of solving this kind of problems.

In the following explanation it will be shown with some rotor hub components as example that the finite element method can be a significant assistance in developing highly loaded structures. It will also be shown, how to perform such computations and how much effort is to be expended. In addition it will be demonstrated how to avoid the often critisized overproduction of data and thus to acquire useful knowledge for the further development. It should also be pointed out that the components used here as example are an intermediate stage in the development of a system.

In the examples presented small deflections and linear material properties may be assumed.

From the available software the program system NASTRAN was selected for all calculations.

2. Premilinary Investigations

In a preliminary investigation the quality and the properties of several types of elements were checked with regard to the element shape and the topological position by means of simple structures such as a cantilever beam. Among the threedimensional element types available in the program system NASTRAN an isoparametric hexahedron (a solid with six sides but not necessarily a cube) with 8 nodes appeared to be the most efficient one.

To get a general view of the effort required, the efficiency and the problems occuring, a component with a well-known stress distribution in a limited range was computed before starting calculation of larger problems.

The object of this preliminary computation was the rotor shaft flange of the helicopter BO 105 (fig. 1 and 2) which was subjected to a rotating bending moment acting as an antisymmetric load.

Already in the definition of the model (fig. 3 and 4) attention had to be given to the reduction of the amount of data to be evaluated. In the presented example only the stresses in the web between the countersunk holes were of interest. Thus the idea of applying strain gauges in the mathematical model was used. These strain gauges can be simulated by a chain of very thin rods fastened along the edges of the web. Because of their low tensile stiffness they do not influence the carrying behaviour of the model itself, but they are capable of indicating the strains.

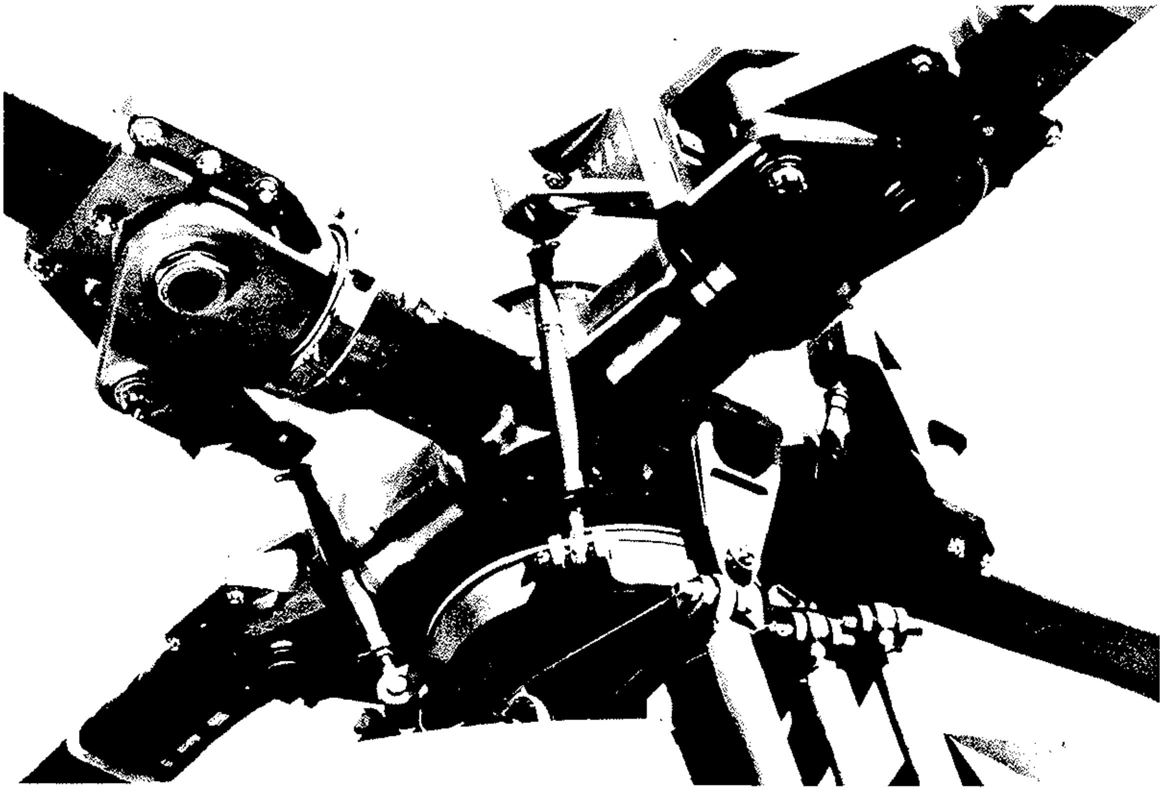

Fig. 1: Rotor Hub of the Helicopter BO 105

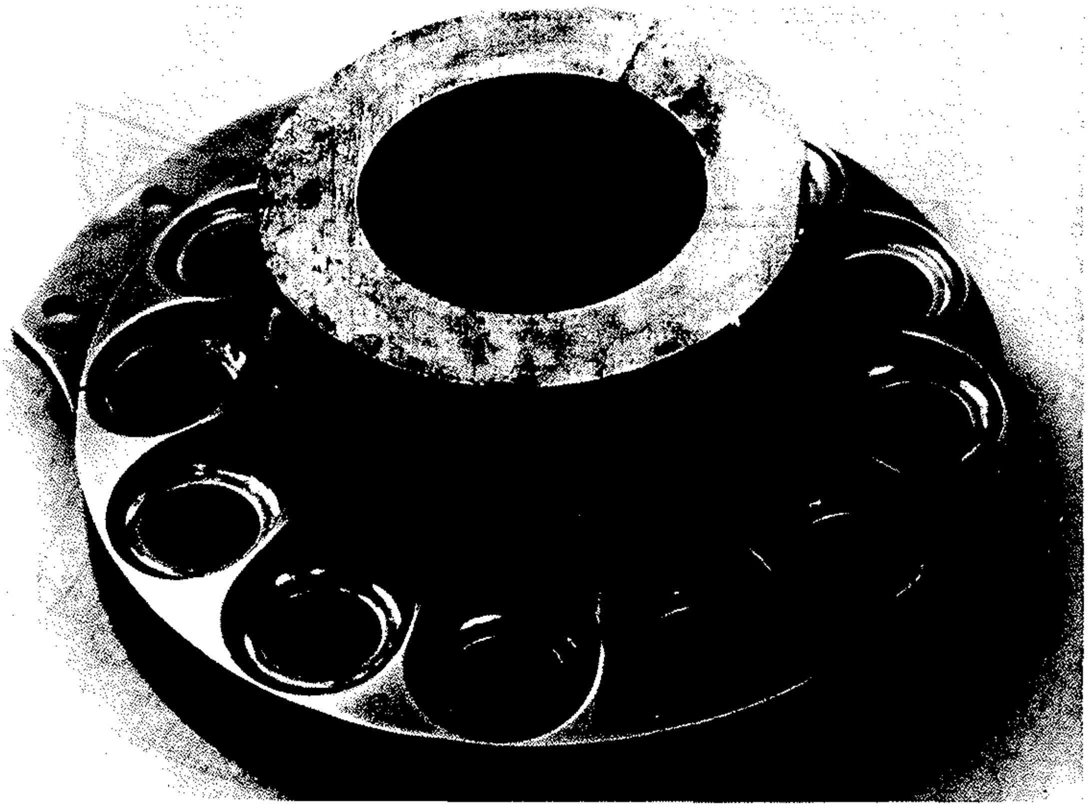

Fig. 2: Rotor Shaft Flange of the Helicopter BO 105

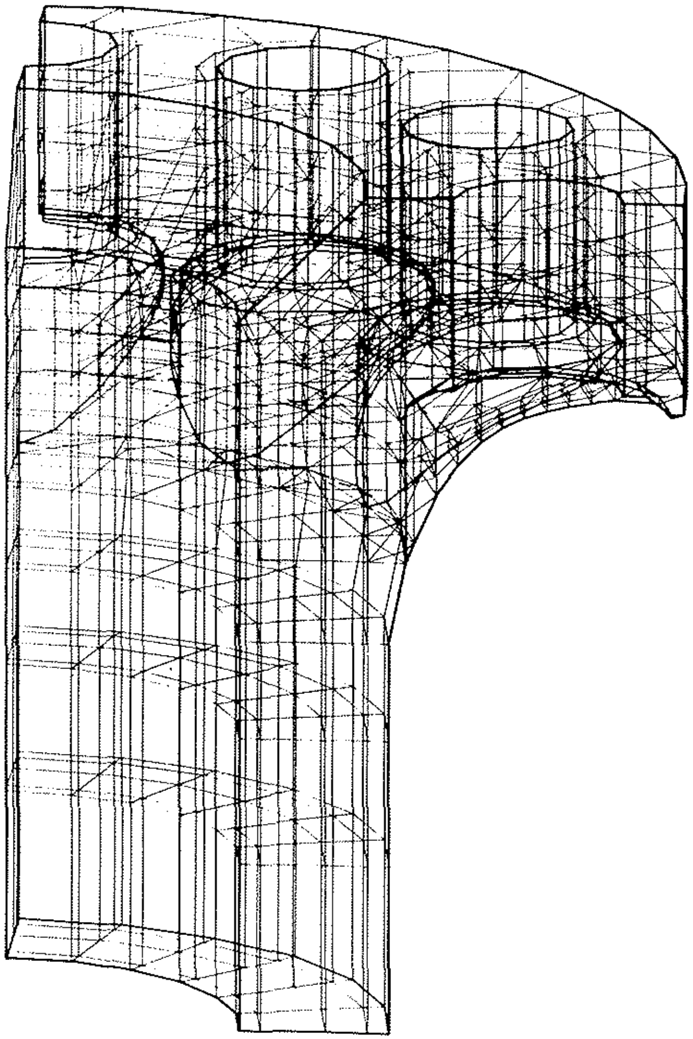

Fig. 3: Idealisation of a 90°-Section of the Rotor Shaft Flange

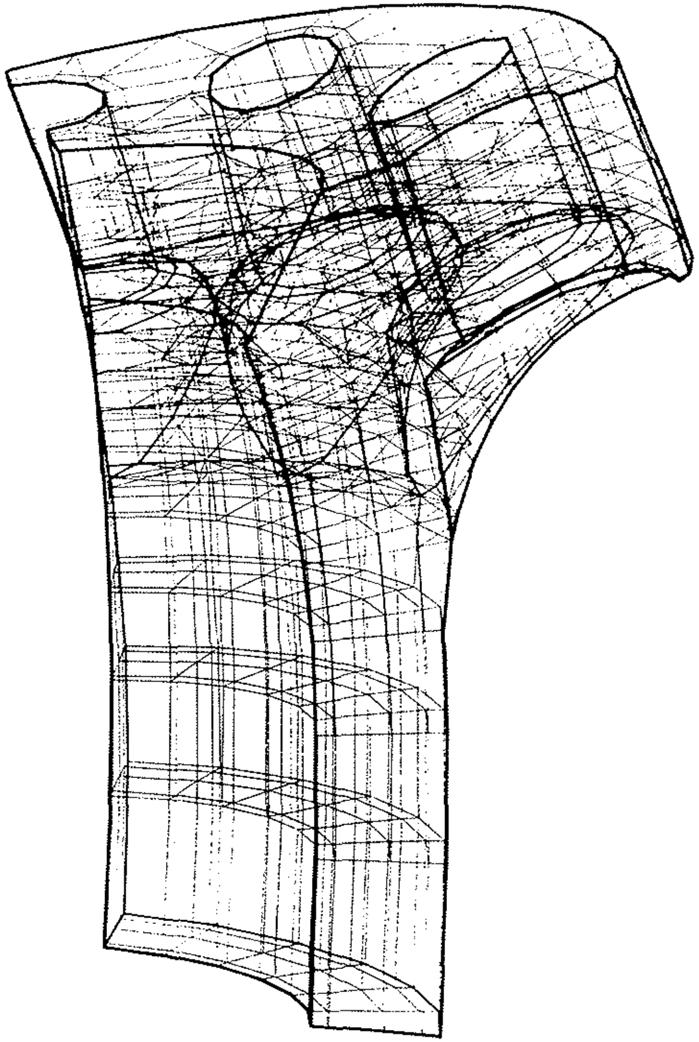

Fig. 4: 90°-Section of the Rotor Shaft Flange after 200-fold Deformation

Since in the range under consideration no stresses other than those effective in the direction of the edges of the web are to be expected these thin rods also indicate the real stresses. Taking into consideration the finite length of these rods as well as the finite length of the strain gauges a good correlation of results calculated with the rods to experimental results with strain gauges was achieved (fig. 5).

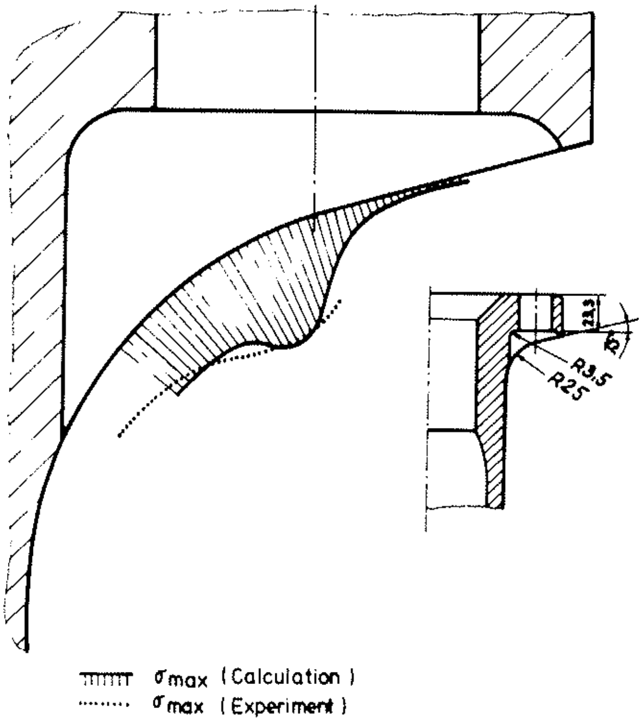

Fig. 5: Stresses in the Web of the Rotor Shaft Flange

3. Computation of a Rotor Hub

Based on the experiences thus gained the static analysis of a complex rotor hub (fig. 6) could now be performed.

The task was to calculate the stress distribution over the complete body and to determine the carrying behaviour of the component under several load conditions.
Due to the one sided placement of the cutouts for the control lever outlet on each axle tube the body itself is antisymmetric.

The component is subjected to symmetric as well as to antisymmetric loads (fig. 7). In the following only the basic load is used as an example; that is the lift of the vehicle and the torque of the drive shaft.

Under consideration of the offset cutouts an idealized 45°-section (fig. 8) was extended to a 180°-section by reflecting and cyclic

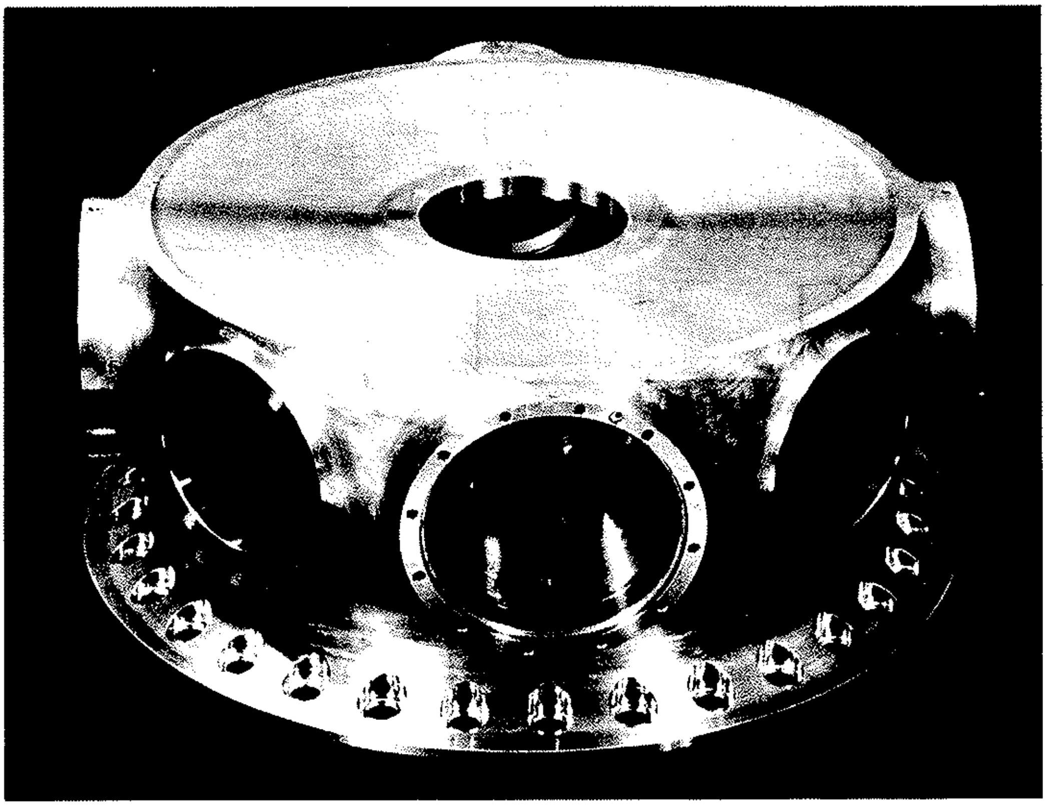

Fig. 6: Rotor Hub, 1st Configuration

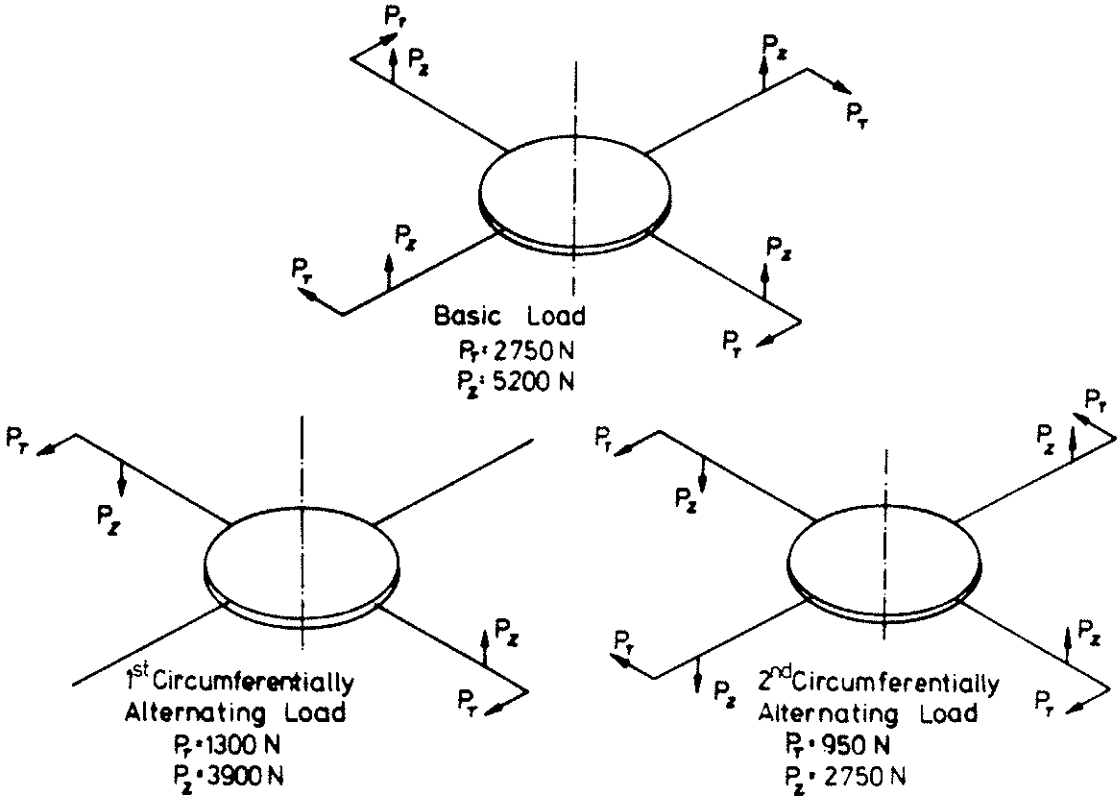

Fig. 7: Load on the Rotor Hub

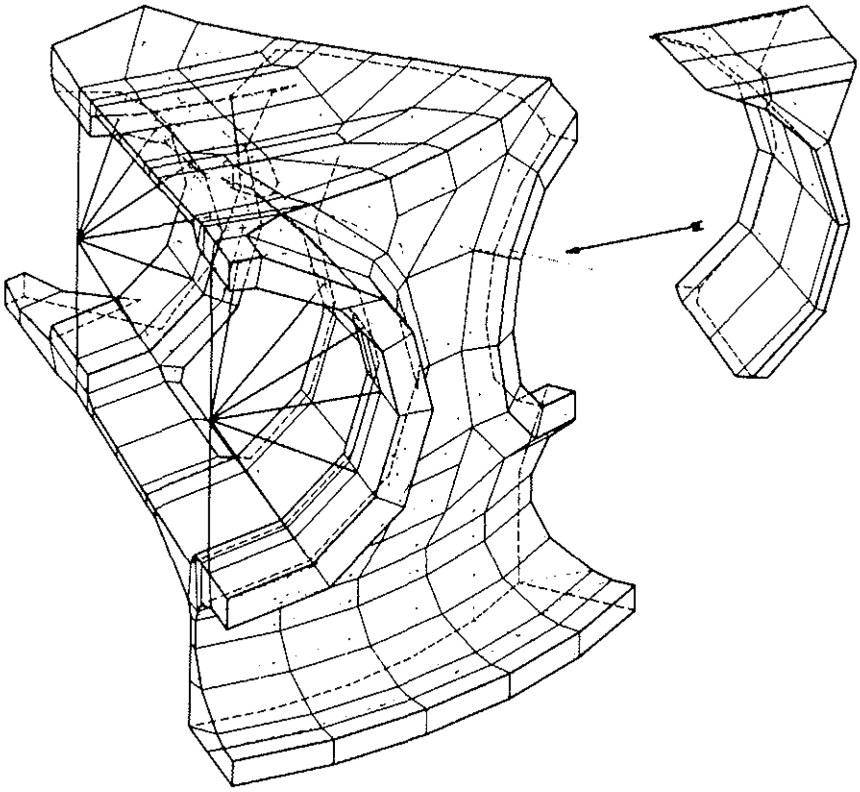

Fig. 8: Idealisation of a 45^{o}-Section of the Rotor Hub

duplication (fig. 9). This size is sufficient for all possible load cases, because on the one hand the body itself is antisymmetric and on the other hand any load can be divided into a symmetric and an antisymmetric component.

Taking these facts as a basis the appropiate laws for the boundary conditions can be formulated by relating the displacement of a point to the displacement of it's opposite point.

The loads are fed in through very stiff radially arranged rods, on which the pressure induced by the press-fit bearing could be adequately simulated by thermal expansion. The flange at the bottom of the body was assumed to be fixed.

By superposing excessive deflections to the original coordinates (fig. 10) some important insights can be acquired. Thus the severe bending of the joint screen between the outer axle box and the bottom flange can easily be recognized. Obviously this deformation is the result of the radial stiffness of the coverplate in connection with the inflexibility of the outer axle box and the fixing of the bottom flange.

Also the extremely high strain of the axle tube can be seen which is caused by the fact that the inner axle box tries to move downwards and thus the inner and outer axle box are forced to misalign.

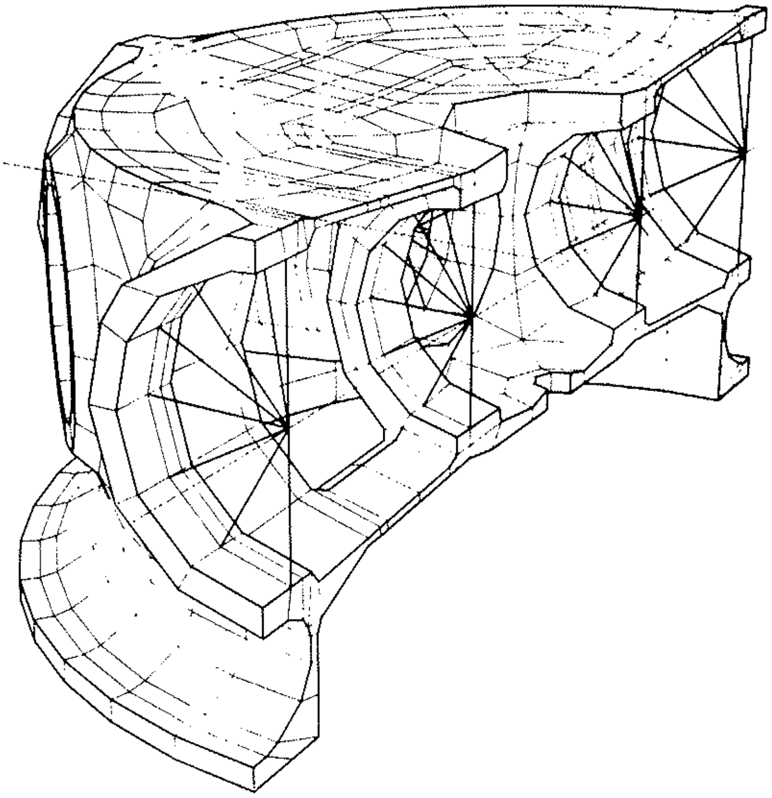

Fig. 9: Idealisation of a 180°-Section of the Rotor Hub

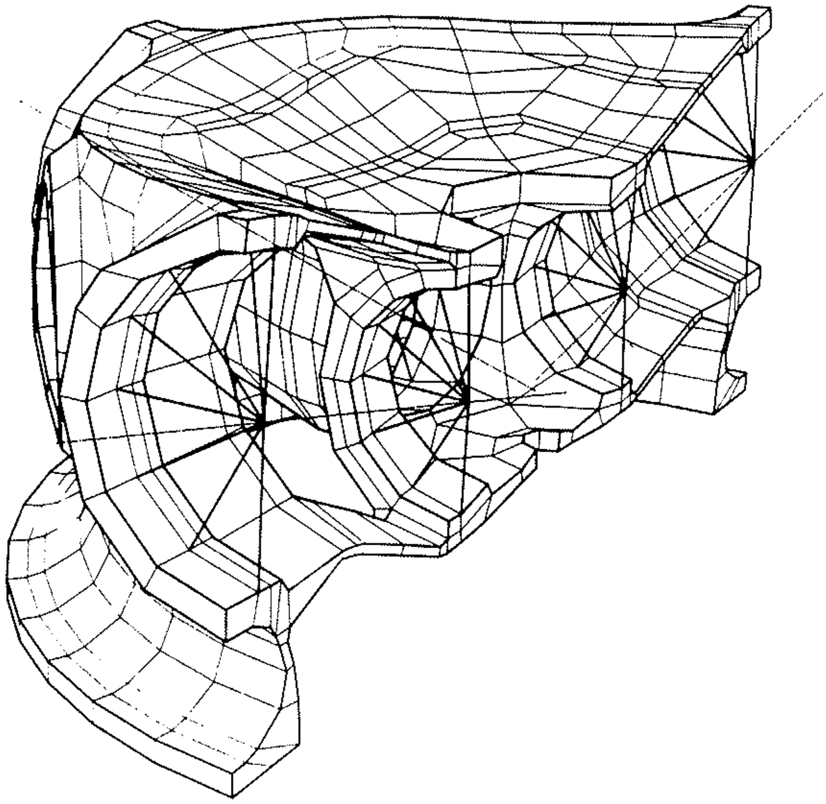

Fig. 10: 180°-Section of the Rotor Hub after 200-fold Deformation Due to Basic Load

Due to the large amount of output data a special and really important problem was the interpretation of the stress results.

For preliminary statements it was sufficient to print out the stresses in a prescribed order whereby the v.Mises-Hencky equivalent stresses were used as key for the order of data printout. However this method does not enable one to determine the global stress distribution.

To obtain a general view it is better to plot the stresses as a relief over the body surface. This manner of representation is called "contour plot" (fig. 11).

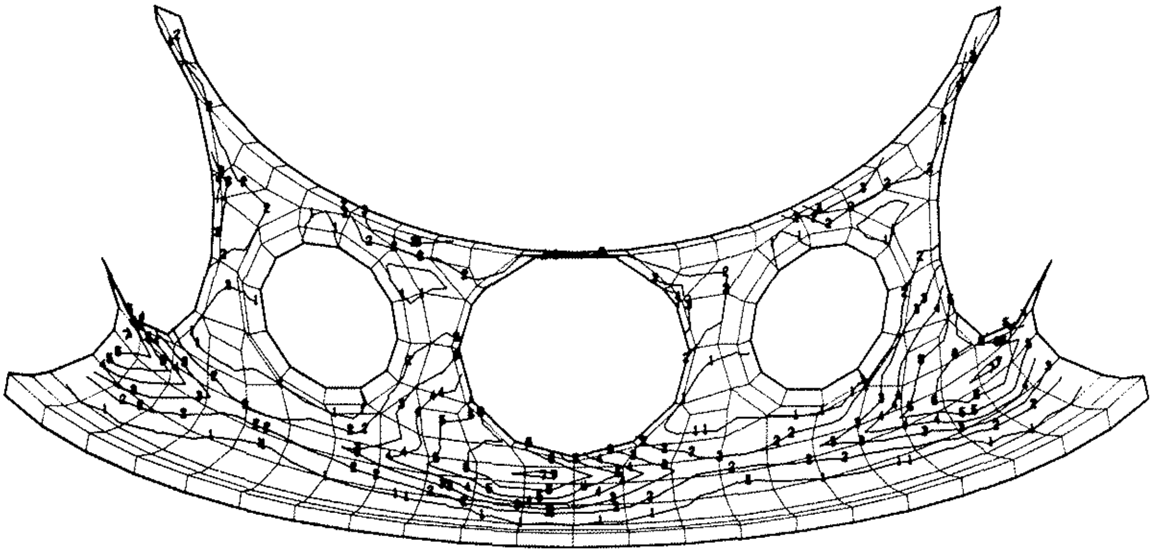

Fig. 11: v.Mises-Hencky Equivalent Stresses in the Outer Jacket of the Rotor Hub Due to Basic Load
Stress Scale: 1 Contour Line Distance ≙ 5 N/mm^2

For this purpose already at the stage of the idealisation the complete model was assumed to be covered with very thin membrane elements. These elements are capable of indicating twodimensional stress conditions as they exist in undisturbed ranges of the surface, and so they are comparable with strain gauge rosettes.
If these stress conditions are plotted the resulting picture is similar to photoelastic varnish.

Thus the ungainly amount of data is condensed to a few pictures, and a real possibility to present the stress distribution and the carrying behaviour of the structural member is created.
What remains is to find appropiate projections and parts of the surface.

At the boundaries of the closed surfaces the stresses are indicated only up to the middle of the external elements. To make the stresses still visible up to the plane of division the membrane elements were extended beyond this plane. The overhanging nodes of these elements were connected to the opposite node points belonging to the initial 180°-section.

4. Protection from Data- and Idealisation-Errors

In practice it appears that those complex bodies shown before do not allow an idealisation at the first attempt without error. Since a correct idealisation is the necessary condition for useful results it is essential to reach the best possible reliability in the idealisation by means of effective test methods even though the checks require more effort than the idealisation itself. With some reasoning it is possible to find suitable methods that guard against almost every occuring error.
These methods can be roughly devided in:

a) simple syntactical checks (formats of data fields)
b) simple structural plots and display pictures
c) visualisation of the third dimension on display pictures by varying the line thickness
d) stereoscopic projections
e) hidden lines representations
f) automatic geometrical and topological tests
  - checking for completeness by plotting the model after separation of the element boundaries by shrinking the elements (fig. 12)
  - checking for completeness of the model by plotting the outlines or surfaces
  - checking for deformity of the elements by calculating the ratio of circumscribed to inscribed circle (at triangles) or of circumscribed to inscribed sphere (at tetrahedrons)
  - checking for positive sense of rotation of the corner arrangement in threedimensional elements by calculating the volumes
  - checking for permissibility of each corner angle by testing the sign of the volume of each tetrahedron resulting from partition of a hexahedronal element

g) input data generation by means of debugged computer programs
h) critical supplementary inspection of the results.

In the discussed case of the rotor hub just the overhanging membrane elements gave a chance to check the boundary conditions and the antisymmetry of the model by means of congruence tests of the contour plot of the considered load case with that of the load case acting on the other half of the model at this instant.

The elements of the compliance matrix which refers specifically to the origins of the loads and which also considers the fixity of the body, are the average values of the NASTRAN-calculated displacements resulting from symmetric and antisymmetric unit load cases.

Since any stiffness matrix concerning a linearly behaving static system is naturally symmetric, the generated compliance matrix must be symmetric too, because it is an inverted stiffness

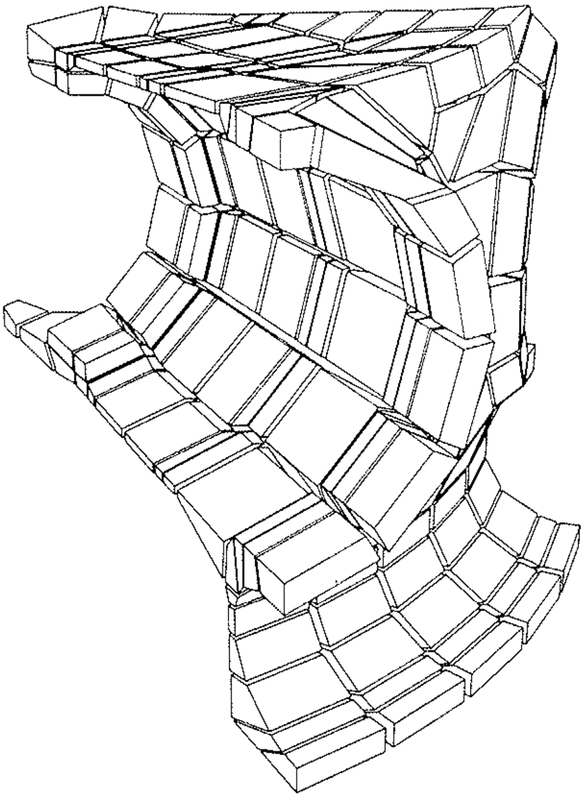

Fig. 12: 45°-Section of the Rotor Hub with Shrunk Elements

matrix. The described compliance matrix can be used as an input for dynamic calculations. The symmetry of this matrix is an important criterion for the correctness of the calculation. Finally the understanding of the global carrying behaviour of the component is also an important chance to check the model. A very good way to understand the carrying behaviour is to inspect the pictures of the deformed structure as well as all the contour plots.

5. Coding Details

In working on the problems described numerous computer programs concerning these types of models have been coded, and a great deal of experience in coding periprocessors and service programs was gained. Some modules were coded from which programs suitable for these duties can be consecutively assembled in a simple way.

Such modules are made for example for all kinds of the usual NASTRAN coordinate transformations and all character handlings.

It appeared that one of the procedures with the highest demand in periprocessors is sorting data sets because properly arranged data offer an economical way to solve many different problems. Therefore a sorting routine with a very fast merging strategy was precoded which can be easily adapted to the actual sorting problem.

Further modules are coded for several repeatedly occuring specifications and thus an easy method to code new appropiate problem dependent periprocessors is established.

The expenditure for solving the global stiffness equation system is dependent to a considerable extent on the distribution of nonzero matrix elements. For most of the FEM-computer programs the characteristic criterion for the computation time is the bandwidth of the stiffness matrix. In NASTRAN however it is only desirable to get clusters of nonzero matrix elements, because NASTRAN works with the "active columns technique". Most FEM-models have a good relation between geometrical and topological arrangement. Moreover, compared to an arbitrary order any systematical order is advantageous for forming clusters of nonzero matrix elements. So the idea was obvious not to use an ordinary bandwidth-optimizer but to arrange the gridpoints depending on the coordinates by means of a simple preprocessor.

A very important facility for the computation is the restart capability of NASTRAN. It allows to solve the problem step by step. In the presented examples the most advantageous way was to divide the calculation into two steps. The first one includes the expensive portion - that is the generation of the stiffness matrix and the solving of the equation system whose right hand side is a unit load vector. In the second step the stress distribution for several load combinations can be calculated by restarting and using the expensive precomputed displacement output from the first step. This step may be repeated for different load combinations as often as desired.

6. Subsequent Estimation of the Costs

The effort to be expended for the calculation of similar structural members is a function of

- the complexity of the shape of the structural member
- the accuracy desired
- the know-how in idealizing similar components
- the availability of periprocessors and precoded modules.

To enable one to estimate the costs arising some data for two different rotor hubs are given in the following table:

7. Conclusion

By means of some examples it was shown how to perform the static analysis of complex threedimensional structural members and how much effort is to be expended for this analysis.

Two problems turned out to be essential, both arising from the large amount of data:

a) the correct generation of input data

b) the evaluation of the results.

With both problems the possibility of automatic graphic representation proved to be the fundamental aid to allow an economical use of the FEM.

A wise application of the aids of the modern computer techniques makes the FEM a powerful and economical tool in the development and optimisation of highly loaded structures.

ITEM	Rotor hub 1 (fig. 9)	Rotor hub 2 (fig. 13)
number of hexahedronal elements	697	290
number of membrane elements	1420	700
number of degrees of freedom	4764	2364
number of input data cards	6281	3355
number of load cases evaluated	13	13
CPU-time for cold start [sec]	4455	1157
CPU-time for each restart [sec]	230	80
total CPU-time [sec]	14000	7200
total manpower [men months]	9	3

The given data for "manpower" and "total CPU-time" contain all tasks from the problem definition up to the documentation including the development of necessary periprocessors and program modules, as well as all miscarried computer runs. CPU-seconds are related to the IBM 370 computer.

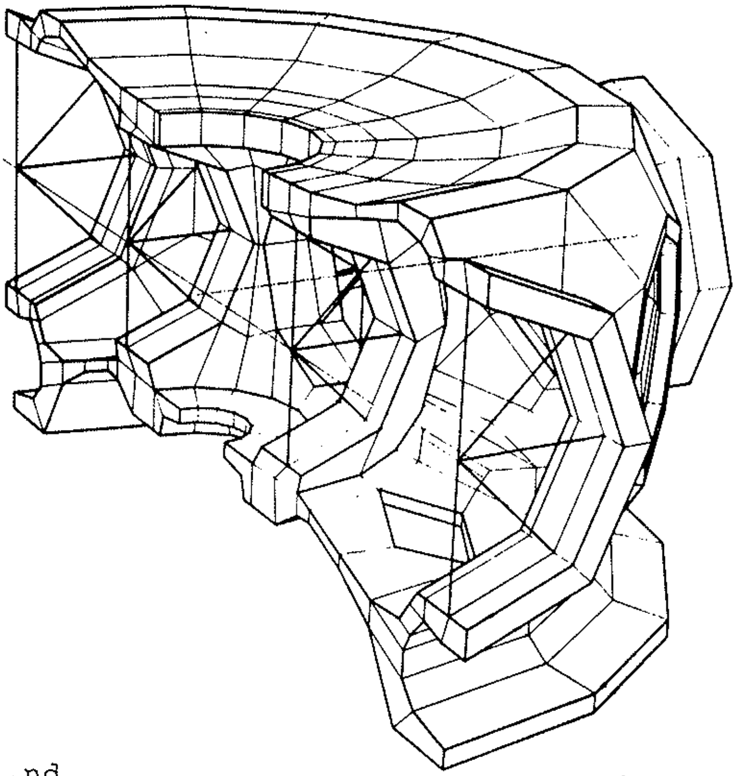

Fig. 13: 2nd Configuration of the Rotor Hub