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INVESTIGATIONS OF HELICOPTER STRUCTURAL DYNAMICS AND A COMPARISON WITH GROUND VIBRATION TESTS

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Abstract

The paper presents the results of a structural dynamics study for a helicopter. The aircraft is modelled using NASTRAN for a low degree of freedom model (a so-called one shot model) and a more complex one using superelement techniques. The calculation shows that the advantages of the small model - well manageable and clear, moderate storage and low costs - are limited by the accuracy of the results at higher modes.

The large model has the advantages of ease of parameter modification by changing only the effected substructure. In addition higher modes are calculated with greater accuracy. The peculiarity of the helicopter structural dynamic models are discussed: Few distributed structural masses and additionally large concentrated masses result in a concentration of many natural frequencies in the range up to 60 Hz. Hence careful placing of the concentrated masses in the analysis-set and selection of the analysis points is necessary. In order to obtain accurate results, basic understanding of the modal pattern is a prerequisite.

A special ground vibration test was carried out in order to check the finite element model of the helicopter. Problems of ground vibration tests for helicopters are discussed, and the difficult task of correlating the measured modes, especially in the higher frequency range, with the numerical results is treated in detail.

1. Introduction

The analytical methods for studying the vibration characteristics of helicopters based on the finite element programs, such as NASTRAN, have a reliability which enable them, to make accurate predictions of vibration problems even in the preliminary design phase.

This point is significant because of the requirement to minimize the vibration levels of helicopters, which have become of increasing importance.

An essential step towards this goal is to check the technique of modelling by shake tests on existing helicopters. A problem unique to helicopters is that the dynamic behaviour is characterized by the overlay of a light structure with additional large lumped masses, which are responsible for the complexity of modes.

The investigation of these problems is the subject of this paper which describes the analytical methods, the vibration tests and the correlation between these two data sets for the example of a BO 105 helicopter.

2. Modelling of Helicopter

There are two finite-element-models for the BO 105 helicopter (Figure 1). The larger one with 4400 degrees of freedom has been developed to fulfil the stress analysis requirements for a more refined stiffness representation. It has nearly a one-to-one correspondence between the hardware and the model. There are more details than necessary for a dynamic calculation. From this model a simpler model with 13 00 degrees of freedom has been extracted. This was done primarily by elimination of an average each second grid point for the fuselage.

The main saving of freedoms results from the presentation of the tail boom by a chain of bar elements which can obviously be done for this regular structure.

2.1 Reduction of Matrices

For dynamic calculations a rough reduction of the degrees of freedom to an analysis set (A) is required (Figure 2). The selection of this A-set should be based firstly on an estimation of the relative deformations in order to determine all modes of interest in the investigated frequency range.

This is possible, because for many substructures regular vibration behaviour can be expected in the sense of fundamental modes and higher harmonics. Therefore the members of A-Set are uniformly dispersed throughout the structure. The cabin floor is represented by 2 A-grids for each second frame as in the same way the tail boom with 1 A-grid for each second frame. As additional investigations have shown further reductions could have been carried out without essential loss of accuracy for all frequencies in the range of interest. The engine deck is substituted by 3 A-grids for each frame, because here detailed warping modes are to be expected as a consequence of the large lumped masses situated here. Particular considerations are made for the cockpit, where complicated modes due to the curved shape have to be regarded.

And as a matter of course all large mass items such as rotor, transmission, engines, hydraulics are replaced by their own A-grids.

Summarizing the larger model with 733 grids each with 6 degrees of freedom (DOF) = 4398 DOF is reduced to 47 A-grids with 3 translational DOF = 141 A-DOF, in addition to 6 rigid body DOF. This means a reduction to 3% of the original number of freedoms.

The small model has 217 grids with 6 DOF = 1302 DOF. They are reduced to the same analysis set as above, which gives a reduction to 10%.

2.2 Analytical Approach

Finite element models of large order are only amenable to dynamic calculations by special procedures such as the NASTRAN superelement techniques (Figure 3). The aircraft is divided into 7 substructures or superelements. Each of them is handled separately for matrix generation and matrix reduction. By the special process of multi-level-substructuring each superelement has its own rank in relation to the residual structure.

The calculation begins with the superelement of the highest rank in a branch. The last superelement to be processed is the residual structure. This processing sequence has to be taken into consideration in the choice of substructures. For restarts there are great advantages, if elements subject to change belong to the residual structure, or to a superelement of a low rank, because only these parts have to be computed again.

As a consequence of the large amount of organisation needed for the superelement technique a special system has been created, the so-called data base management, where all data blocks are stored on permanent discs with low access times, whereas tape storage is very uneconomic. (For more details see Ref. [1]).

2.3 Computing Time

Figure 4 gives an impression of the NASTRAN program flow. It shows the superelement loops for matrix generation, assembly and reduction, the comparatively small time consuming part for the actual eigenvalue analysis and the data recovery. Most of the cpu-time for the large model as well as for the small one is used by matrix reduction and data recovery. It can be seen that for the small model approximately five separate calculations can be run for one superelement run. Also if there are changes only in the residual structure the restart will be done in the same time as the small model. This has to be taken into account for economic calculation, because in spite of the increasing running time of the computers and the availability of large permanent storage capacity the cost-effectiveness of a program is still an important factor.

Therefore the following comparison between the analytical and experimental modes is made for the small one-shot-model to show that there is a real chance for achieving a good agreement between calculation and measurement up to high frequencies.

The absolute running time shown here depends on the computer. The indicated time of 500 cpu-sec for the superelement model is only valid for IBM 360-370, model 3033. In contrast for IBM model 178 the time will be about 2000 cpu-sec for the same problem.

3. Experimental Investigations

In order to check and improve the analytical finite element model, a special ground vibration test (modal survey test) was performed on a BO 105 helicopter at the DFVLR Institute for Aeroelasticity. The aim of this test was to determine the modal parameters of the structure within the frequency of 56 Hz. These parameters are the eigenfrequencies, normal mode shapes, generalized masses, and damping factors.

3.1 Description of the Test Method

Ground vibration tests are performed at the DFVLR by means of an improved technique of the phase-resonance method (Ref. 2). The individual normal modes are determined by applying appropriate exciter configurations, which result in a phase shift of $\pm 90^0$ between the dynamic displacements u_i of the structure and the external harmonic exciter forces. In this case the inertia and stiffness energies are equivalent, while the external forces compensate the internal dissipation. To isolate a normal mode, the corresponding exciter configuration as well as the eigenfrequency must be found, whereas the response of all measuring points of the structure must be observed concurrently to fulfil the phase-resonance criterion. Due to the great number of measuring points and possible exciter configurations this is obviously a very time-consuming and difficult process, essentially simplified by resolving the response of the structure into its real and imaginary parts with respect to the excitation and by combining all response data within one single value, called the 'indicator function' and defined by

$$(1) \qquad \Delta = \frac{\Sigma_i \; |Re(u_i)| \cdot |u_i|}{\Sigma_i \; |u_i|^2} \qquad (i = 1, 2....N).$$

u_i is the displacement of the i-th measuring point, while N represents the total number of measuring points.

In the case of a normal mode the indicator function Δ, calculated continuously by a process computer, must be equal to zero.

3.2 Determination of the Modal Characteristics

A diagram of the ground vibration test setup is given in Figure 5. The softly suspended helicopter is excited by several (up to six) electrodynamic exciters, which are controlled by a frequency generator. The complete force level as well as each individual force amplitude can be varied.

The dynamic response of the structure is measured by means of small inductive accelerometers. All response signals are amplified and resolved into their real and imaginary parts with respect to the exciter forces by means of vector component meters. An A/D-converter feeds the data into a process computer.

The process computer continuously calculates the indicator function and shows the real and imaginary deformations of the structure on a display screen. Peripheral equipment is available for the output of the results. The execution of the ground vibration test can be separated into three parts:

- identification of the normal modes
- isolation of the normal modes
- measurement of the modal characteristics.

To identify the normal modes, numerous frequency sweep runs with different exciter configurations are performed. For each run the indicator function is plotted versus frequency. The more or less significant peaks in these plots indicate the existance of a normal mode.

For the isolation of a mode, the particular exciter configuration is used which produces the most significant peak in the sweep plots. By variation of the force amplitudes and the frequency and, if necessary, by addition of exciters the indicator function is optimized. The best location of the exciters can easily be found by visual observation of the in-phase and out-of-phase deformations of the structure on the display screen.

When the indicator function is optimized and the in-phase deformations are small enough relative to the out-of-phase deformations, the modal characteristics can be measured: the eigenfrequency, mode shape, and damping. The generalized mass is calculated by pre-and-aft-multiplication of the analytical mass matrix with the measured mode shape vector.

By means of this test process about five to ten modes can be measured per day.

3.3 Test Structure and Suspension

The ground vibration test was performed on a BO 105 C helicopter owned by the DFVLR. The four rotor blades were dismounted and replaced with mass dummies. In order to simulate a mean take-off weight, mass dummies were placed at the pilots seats and in the cargo room. Total weight of the helicopter during testing was about 1800 kg.

A very soft suspension of the helicopter was provided by an air spring vessel, which was supported in a frame. The suspension frequency was 0.6 Hz, which is very low compared with the first elastic eigenfrequency of 5.5 Hz. Thus, the free-free flight conditions of a helicopter were simulated realistically. Figure 6 shows the helicopter and the suspension facilities during ground vibration testing.

3.4 Test Results

To measure the dynamic response of the structure, the BO 105 helicopter was equipped with 229 accelerometers, 63 for the lengthwise direction, 69 for the lateral direction, and 97 for the vertical direction. This large number of measuring points, distributed uniformly throughout the structure, assured a reliable determination of the structural displacements. All grid points of the analytical finite element model were included in the measuring points, in order to facilitate the correlation of analytical and test results. Figure 7 gives some details of the test facilities, showing an exciter and some accelerometers.

The frequency range of interest was up to 60 Hz, including the 4/rev and 8/rev (28 Hz and 56 Hz) of the four-bladed BO 105 helicopter. In this frequency range 30 elastic normal modes were found, the lowest of which were the fundamental bending in vertical and lateral direction at 5.52 Hz and 6.63 Hz, respectively. The modes are listed and correlated with the analytical modes in Figure 9. For the damping, measured by the halfpower method, values between 1% and 4% of critical damping were found for most of the modes.

The mode shapes were normalized by setting the greatest amplitude value equal to one unit. Then the generalized masses were calculated by pre-and-aft-multiplication of the analytical mass matrix with the measured modal matrix:

$$(2) \qquad [M_{MM}] = [\Phi_M]^T [M_{AA}] [\Phi_M].$$

The generalized masses are given by the diagonal elements of M_{MM}. This matrix can be used not only to determine the generalized masses, but also to check the accuracy of the measured mode shapes by means of an orthogonality test. For this purpose M_{MM} is normalized, so that the diagonal values are equal to one unit. Because of the orthogonality relation of the normal modes the off-diagonal elements of M_{MM} should be zero. Thus, the actual values of the off-diagonal elements are a criterion for the accuracy of the measured mode shapes.

Figure 8 shows the normalized matrix M_{MM}. It can be seen that nearly all off-diagonal elements are less than 20% of the diagonal ones; most of them are even lower than 10%. This fact indicates a satisfying accuracy of the experimental measurement.

The results show the ground vibration test to be a powerful tool for experimental investigations of helicopter structural dynamics. As opposed to an airplane, the airframe of a helicopter has only a small distributed structural mass compared with the large additional concentrated masses, e.g. rotor head, gearbox, engines etc. Consequently, there is a high modal density, i.e. a concentration of many closely spaced normal modes, the shapes of which cannot be estimated in advance in many cases. In addition, an appropriate exciter configuration cannot always be applied for all modes, due to poor accessibility of several structural points. In spite of these difficulties the applied technique of the ground vibration test yielded a reliable determination of the dynamic behaviour of the helicopter with satisfying accuracy.

4. Correlation of Analytical and Test Results

An important task for each analytical investigation of the dynamic behaviour of a structure is the correlation with experimental results. While it is no problem to assign visually the lower normal modes, e.g. fundamental bending, this becomes more difficult in the higher frequency range, especially for the initial calculations, as the analytical model is not yet refined by experimental results. Due to the complexity of the higher mode shapes of a complicated three-dimensional structure like a helicopter, the visual classification is seriously aggravated. In addition, by visual observation of the mode shapes the displacements of the structure cannot be weighted with the corresponding mass distribution. Thus, the energy distribution of the made shape is not taken into account.

There are several methods to correlate two sets of data, not all of which are applicable to mode shape comparison. A rather easy but nevertheless most adequate method is to combine both analytical and measured mode shape vectors and to calculate the generalized mass matrix:

$$(3) \qquad [M] = [\Phi_A \,\vert\, \Phi_M]^T \cdot [M_{AA}] \cdot [\Phi_A \,\vert\, \Phi_M] = \left[\begin{array}{c|c} \bar{M}_{AA} & M_{AM}^T \\ \hline M_{AM} & M_{MM} \end{array}\right]$$

Figure 8 shows this matrix normalized to 10. $\bar{M}_{AA}$ is a diagonal matrix, while M_{MM} is identical to the normalized generalized mass matrix of Eq. (2).

A very reliable quantitative correlation of the analytical and experimental modes can now be performed by using the matrix M_{AM}. In the case of close conformity of an analytical and a measured mode shape, the corresponding value of M_{AM} will be close to 10, while independent modes will result in a value close to zero. Thus, the modes can be assigned most easily by looking for the largest elements of M_{AM}. If there is a good correlation between analysis and experiment, each row or column will have one value close to 10, while all other values will be rather small.

Figure 8 shows the results for the BO 105 helicopter. The first six analytical modes are not correlated, because these are rigid body modes with zero frequency. The elements of M_{AM}, whose corresponding analytical and measured mode were correlated, are marked by a box. Obviously, most of the modes can be correlated easily. In general, there is a large correlation factor; only for some higher modes this value becomes rather small.

5. Classification of modes

Figure 9 shows the result of the correlation between the vibration tests and the FEM.-calculation. Firstly it can be shown that almost all measured natural modes have a corresponding analytical mode. (An exception is the mode of 22.50 Hz, yet this mode is very similar to the next mode of 23.54 Hz, which has an excellent calculated equivalence). There were 30 measured natural modes up to 60 Hz. 40 modes including the 6 rigid body modes were calculated. Only 5 modes in the high frequency range from 50 to 70 Hz have no equivalence by measurement.

According to figure 9 most of the frequencies show very good agreement between measurement and calculation. Less than perfect correlation can be seen for the pitching modes, which are influenced mainly by the tail boom. Obviously the stiffness in the vertical direction of the bar model is somewhat high . It is considered, that these results could be improved further.

The modes are identified by their dominating component, bearing in mind, that these short descriptions often concern modes with high couplings with adjacent modes. Nevertheless the descriptions follow from visual comparison and separate investigations in respect to the vibration behaviour of special components like pylon,engines and tail boom.

The following modes can be distinguished and are recorded by measurements:

1., 2., 3.	pitching	
1., 2., 3.	lateral	mode of fuselage
1., 2., 3.	torsional	
1., 2., 3.	pitching	mode of tail boom
1., 2., 3.	lateral	

(where the first mode of fuselage and the first mode of tail boom are identical).

1., 2.	pitching mode of rotor + xmsn (pylon)	
1., 2.	pitching	
1., 2.	lateral	mode of engine
1.	long.-yawing	
1.	long.	
1.	torsional	mode of cockpit
1.	pitching	
1., 2.	flapping mode of tailplane	
1.	flapping mode of tail rotor shaft	
1., 2., 3.	warping mode of engine deck	

With this scheme of modes the vibration behaviour of the BO 105 helicopter is covered up to 60 Hz. This is the first step towards achieving a survey of the complexity of helicopter modes with the aim of studying the influences of parts of the structure on certain modes and for modified restarts.

As examples of the classification of modes some comparisons of measured and calculated natural modes will follow.

Figure 10 shows the lateral fuselage modes with good correlation in frequencies as well as in mode shapes. Only in the high frequency range (from 50 Hz upwards) some differences can be seen.

Figure 11 gives the corresponding lateral modes of the tail boom, where the first frequency of tail boom is identical to the first frequency of fuselage. Up to 60 Hz a good correlation may be stated.

Figure 12 shows the torsional mode of fuselage. The analytical and measured modes harmonize with each other which is also shown clearly by the high calculated correlation factor.

The natural modes in figure 13 concern the cockpit; the remaining fuselage is relatively inactive. The model of the cockpit only contains structural masses without additional lumped masses. In these cases the NASTRAN-calculation has an excellent correspondence to the vibration test both in mode shape and in frequency.

The mode shapes of Figure 14 showing strong warping of the engine deck are examples for a poor correlation between measurement and calculation. Although a certain visual agreement may still be seen the correlation factor is quite low. These modes show the difficulties which arise, if a structure of comparatively low stiffness like the engine deck is loaded by large masses. Obviously the engine rubber mounting springs used in the calculations are the cause for the large differences in the modes. Thus any inaccuracy in mounting stiffness of the engines will result in a poor correlation of some helicopter modes because of the high engine masses.

6. Conclusion

Basis of the finite element calculation for BO 105 helicopter is a large model with an almost one-to-one relation between the hardware and the model. For structural dynamic requirements a somewhat simpler model has been extracted with high cost-effectiveness in handling.

The ground vibration test procedure has been proved to be very efficient in experimental investigation of helicopter dynamics. The result of the correlation method performed for the analytical and experimental data show, that the analysis has achieved a high degree of reliability.

All essential natural frequencies and mode shapes of a complex aircraft like a helicopter can be detected by finite element calculation based on the constructive data set. Thus, possible vibration problems can be recognized in an early stage of design and modifications may be carried out.

Acknowledgment

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7. Referencies

[1] MacNeal, R.H. The NASTRAN Theoretical Manual, Los Angeles, 1977

[2] Breitbach, E. A Semi-Automatic Modal-Survey Test Technique for Complex Aircraft and Spacecraft Structures. Proc. Third Testing Symposium, Frascati, 22-26 October 1973, ESRO SP-99, pp. 519-528.

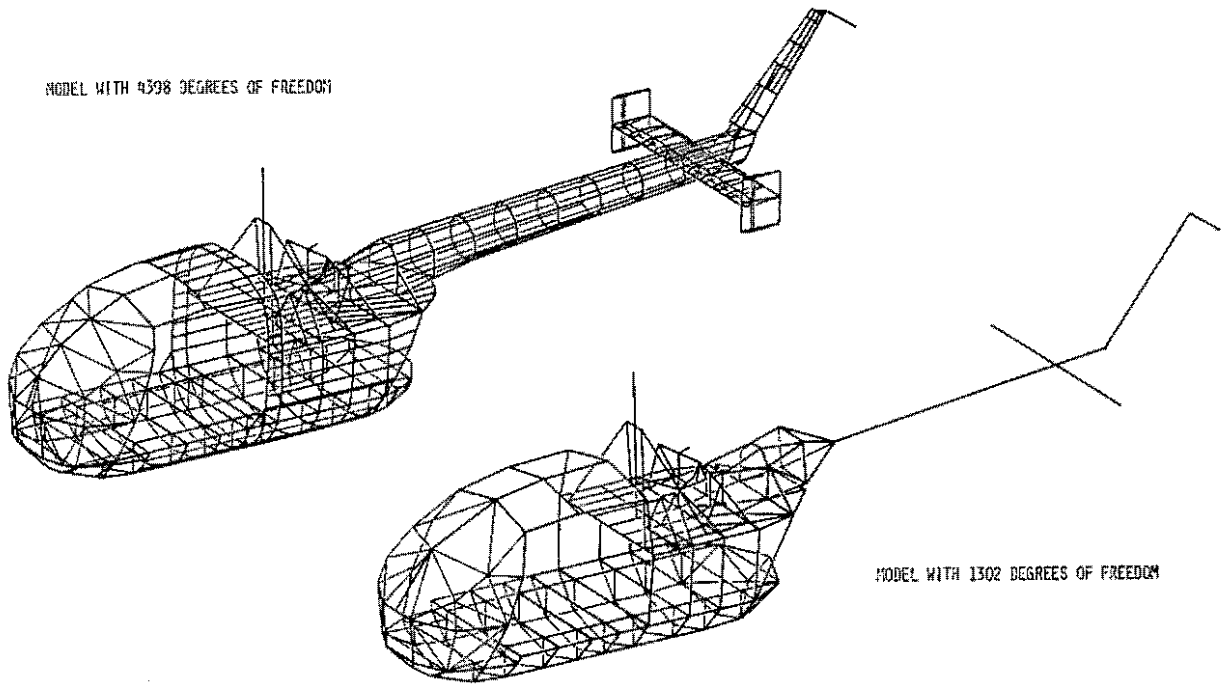

Figure 1: Modelling of helicopter BO 105

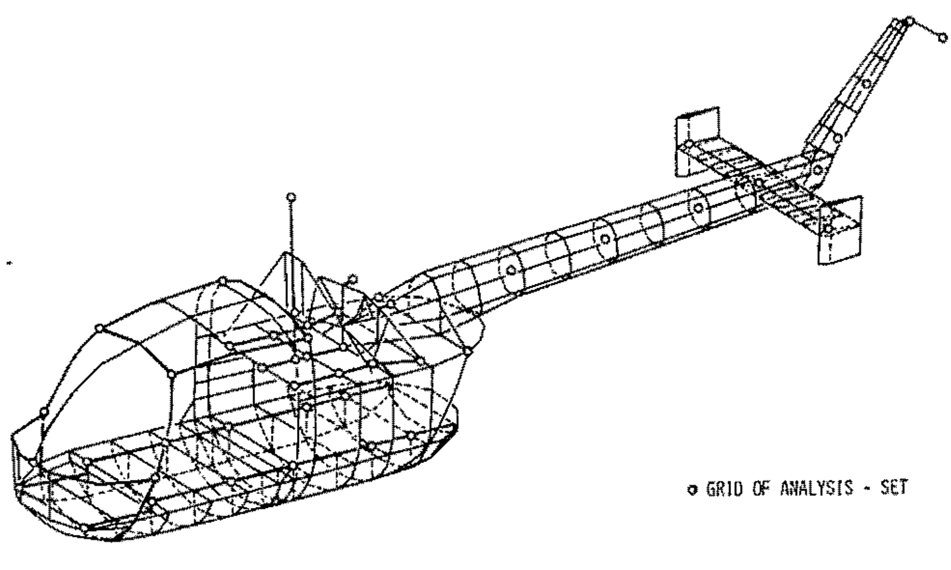

Figure 2: Analysis - set of model of helicopter BO 105

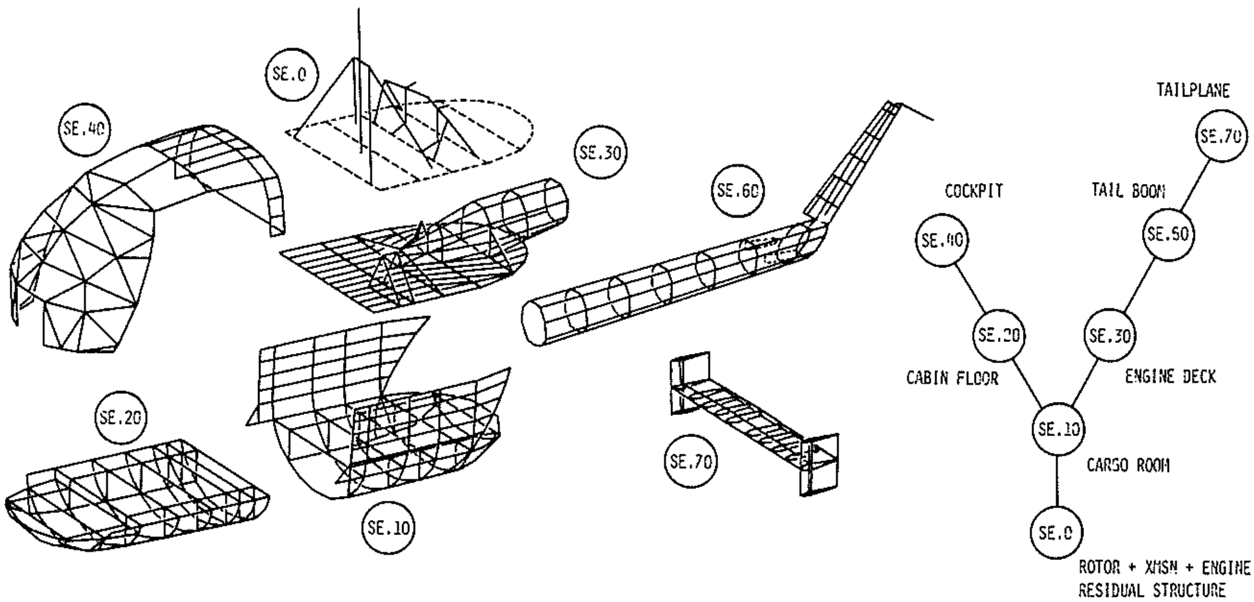

Figure 3: Idealisation of helicopter BO 105, multi - level - substructuring

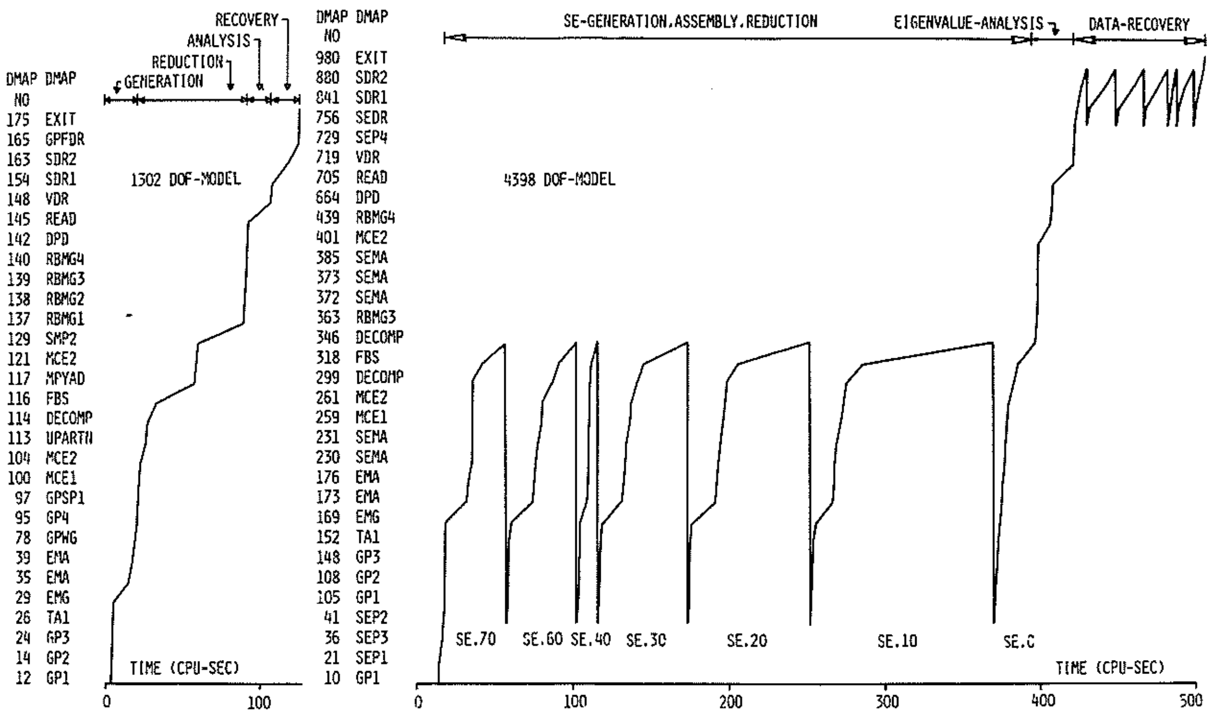

Figure 4: CPU - time for fem.-calculation with NASTRAN, version 60 on IBM 360-370, model 3033, comparison "one-shot-model" - "superelement-model"

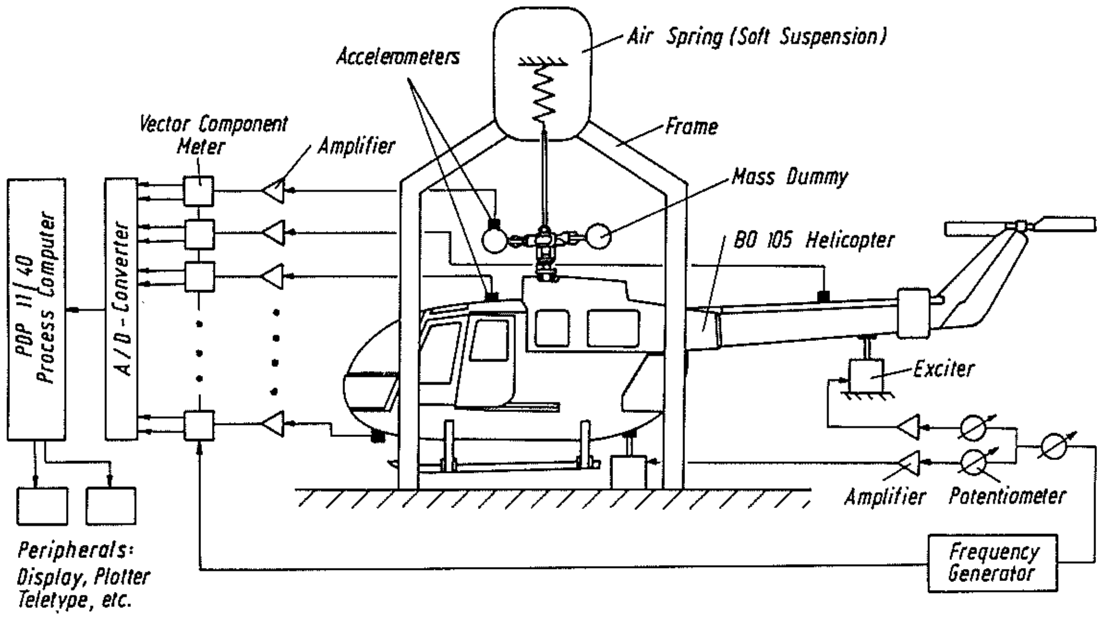

Figure 5: Diagrammatic test setup

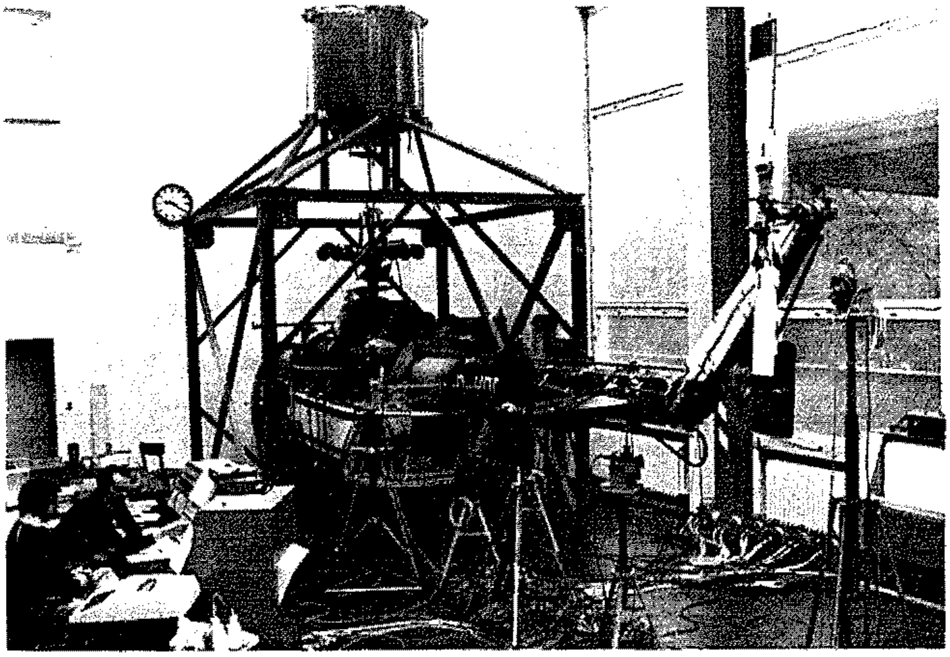

Figure 6: Test rig with helicopter

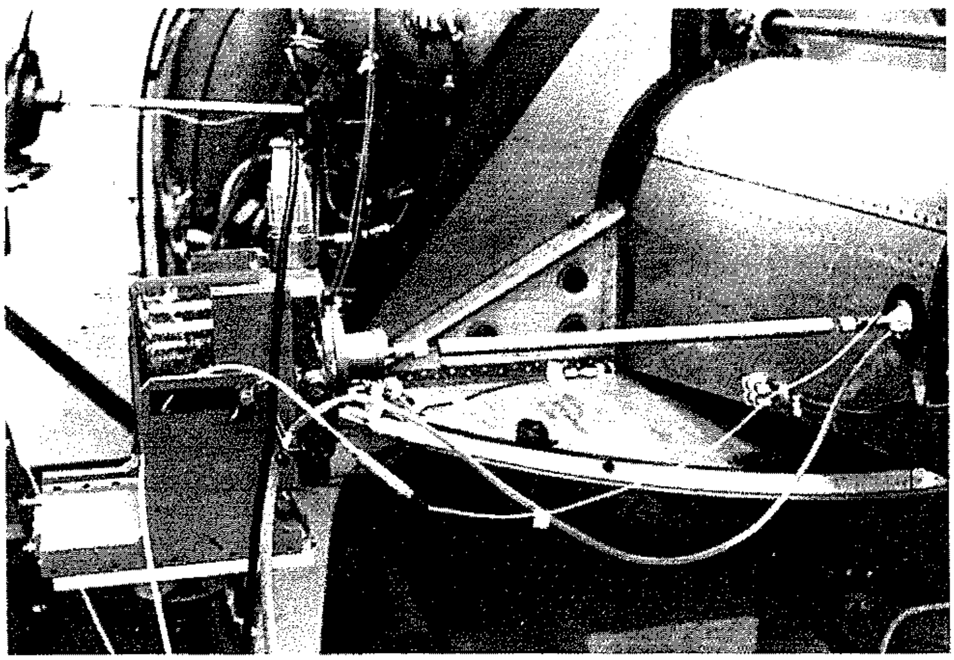

Figure 7: Exciter and Accelerometers

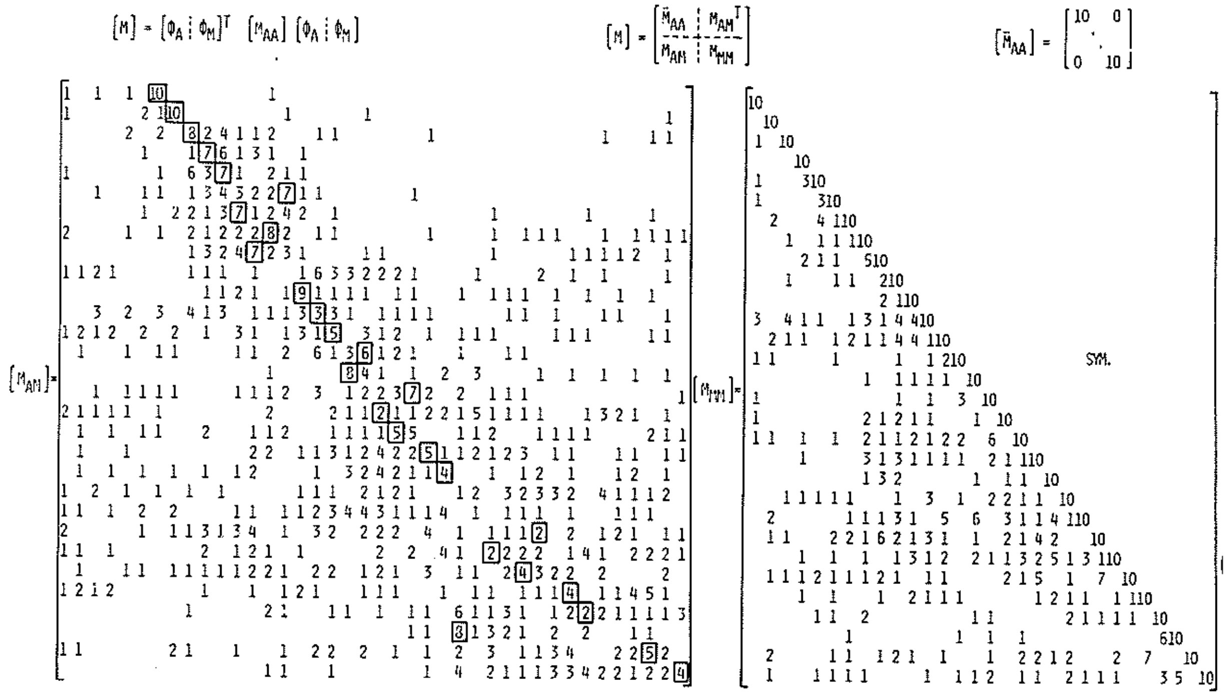

Figure 8: Generalized mass matrix (normalized to 10)

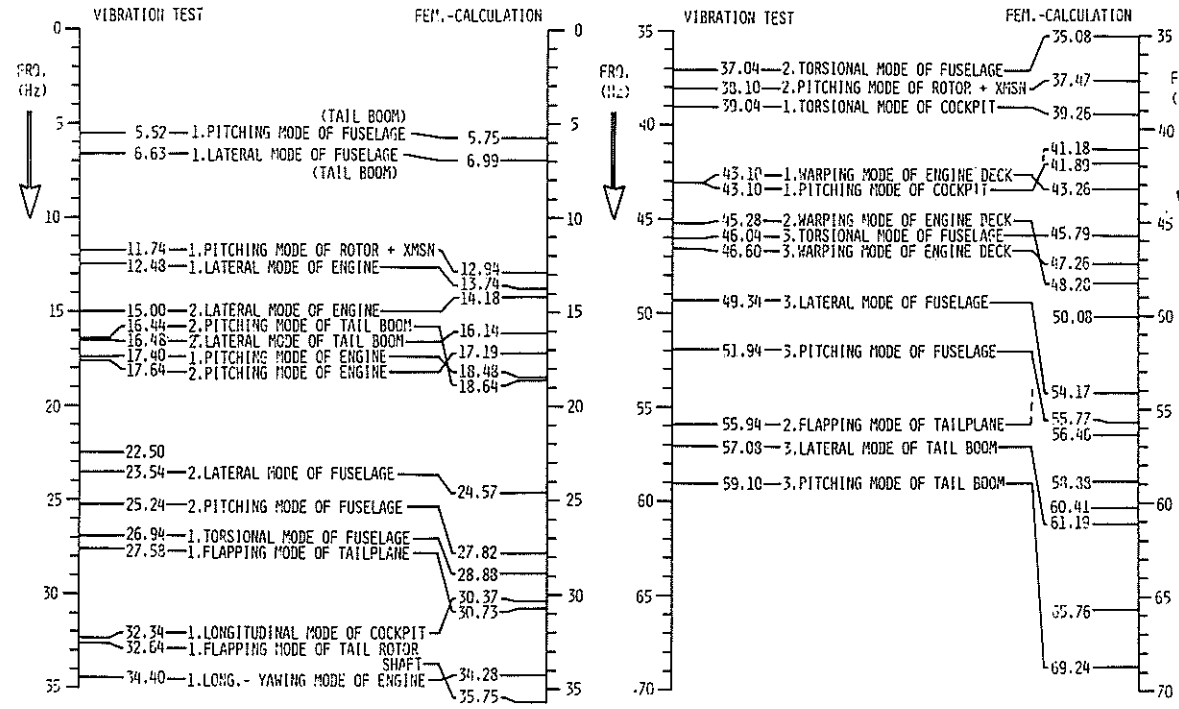

Figure 9: Natural frequencies and modes of helicopter BO 105, comparison vibration test - fem.-calculation

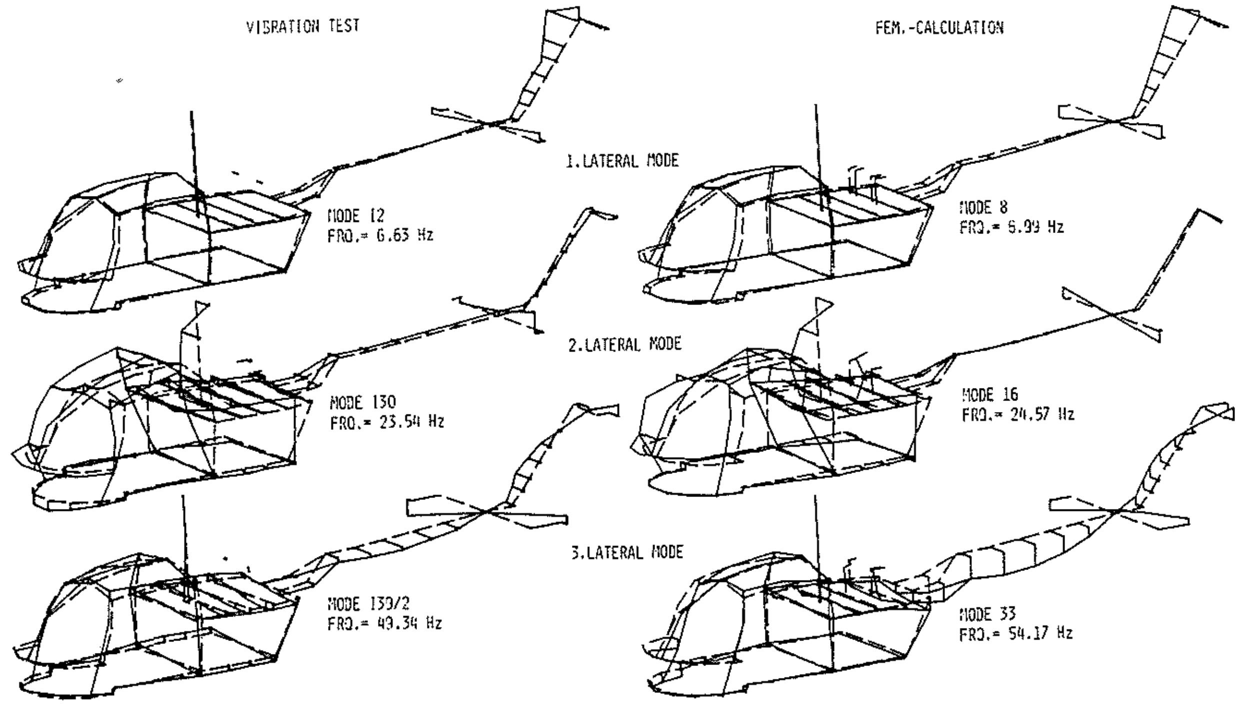

Figure 10: Lateral modes of fuselage of helicopter BO 105, comparison vibration test - fem.-calculation

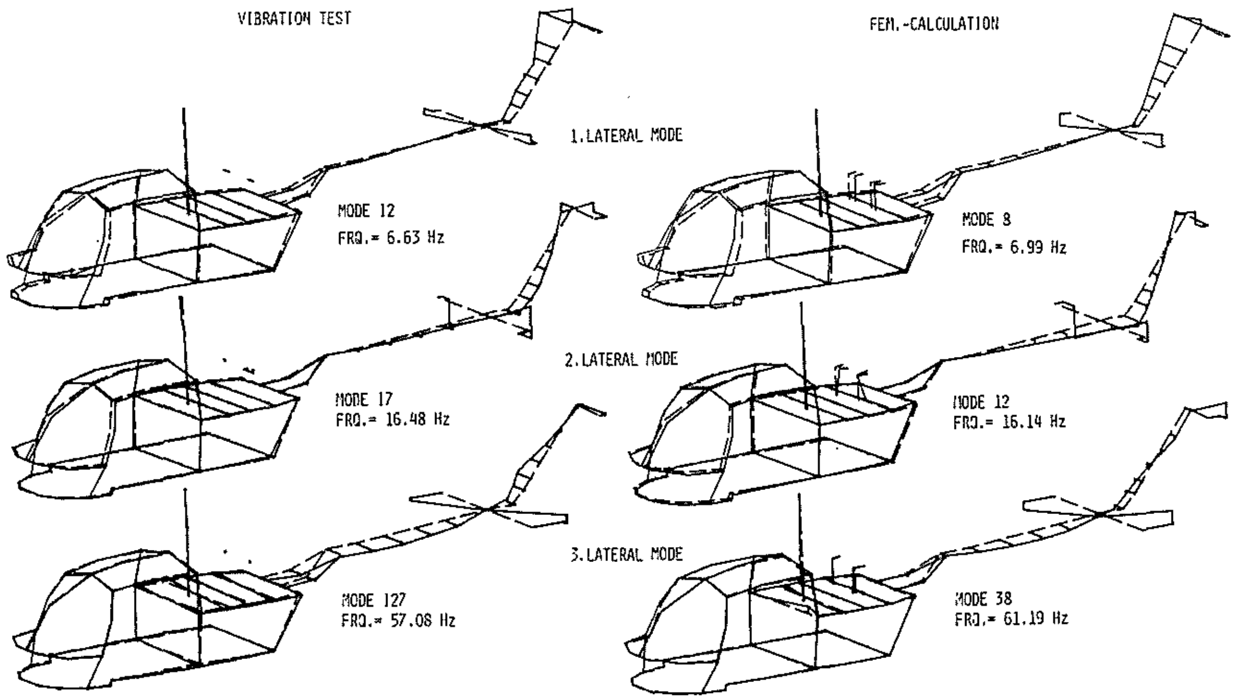

Figure 11: Lateral modes of tail boom of helicopter BO 105, comparison vibration test - fem.-calculation

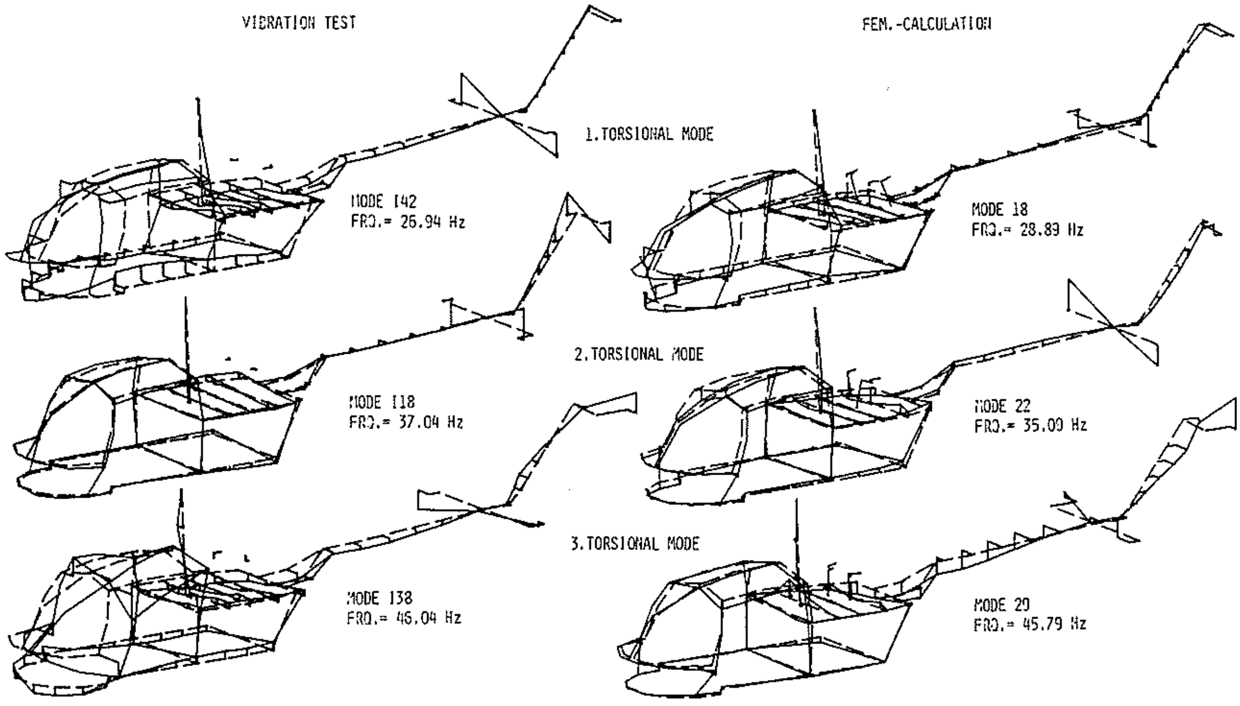

Figure 12: Torsional modes of fuselage of helicopter BO 105, comparison vibration test - fem.-calculation

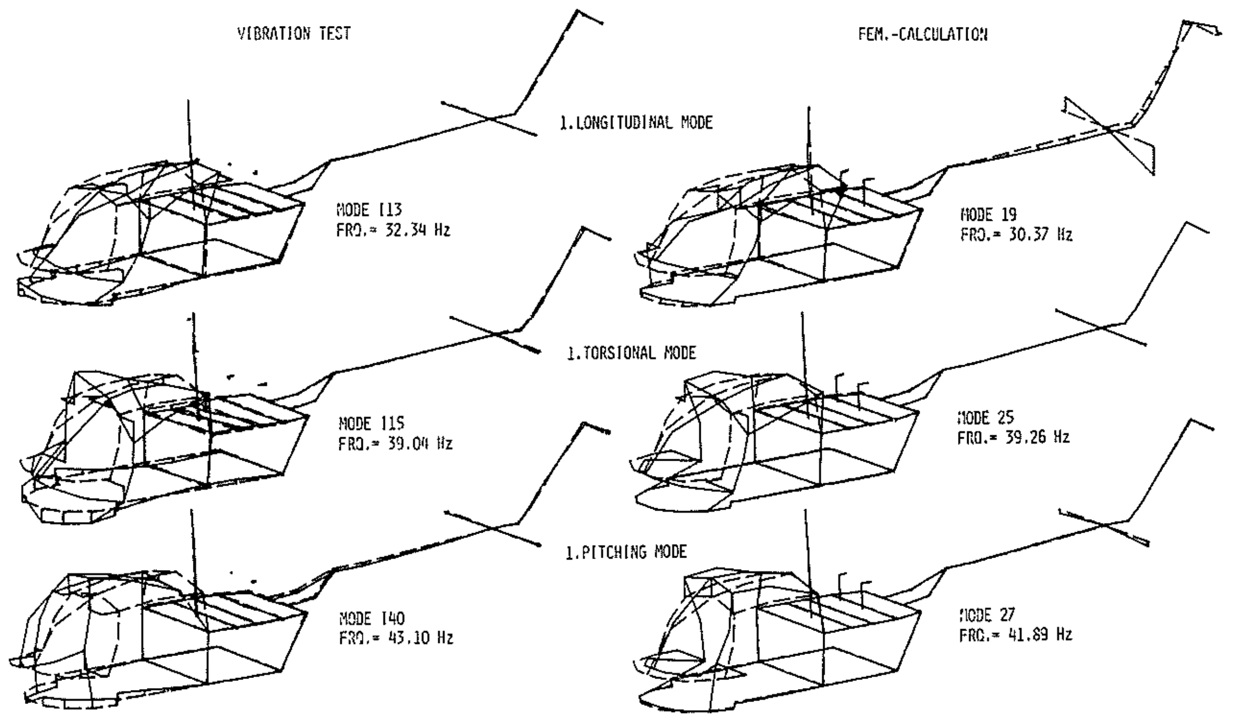

Figure 13: Natural modes of cockpit of helicopter BO 105, comparison vibration test - fem.-calculation

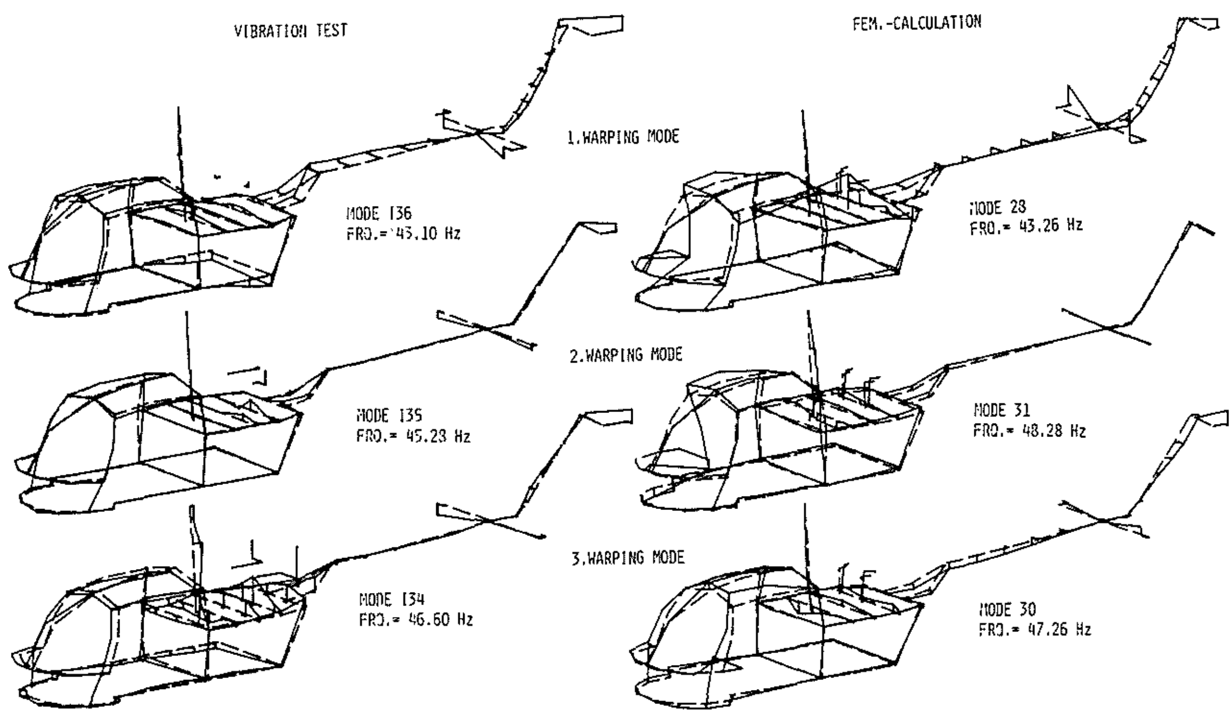

Figure 14: Warping modes of engine deck of helicopter BO 105, comparison vibration test - fem.-calculation