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THE PLACE OF KNOWLEDGE BASED SYSTEMS IN HELICOPTER DYNAMIC SYSTEM CONDITION PROGNOSIS

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ABSTRACT

The application of knowledge based systems to the power plant, transmission and rotor of a helicopter has been made by Stewart Hughes Limited.

The various applications are discussed and the problems and successes reviewed.

The ability of the engineer to think numerically modifies the traditional view of the value of the knowledge based system. The representation of the data in the most suitable form is important and this reflects on the data gathering and processing system. These topics are addressed.

The place where the engineer can interact with profit with the knowledge based system is considered. One example is in the research/development phase of scientifically based discriminators when the knowledge based system is used as a hypothesis tester.

The ability to allow a system to 'self learn' from a data base is exampled.

1.0 INTRODUCTION

Stewart Hughes Limited have always considered that presenting a busy and often harassed field engineer with a complicated signal which must then be interpreted is both unreasonable and potentially dangerous. One way of avoiding this problem is to process the signal and to produce non-dimensional parameters which are therefore independent of the particular system under test. These parameters, from a particular test or series of tests, can then be assessed against numerical criteria which can give a diagnosis of the machines health. This technique has been exploited very successfully in the determination of gearbox faults which has been described in Reference [1].

The development of non-dimensional parameters is based on an understanding of the underlying scientific principles behind the diagnostic. In the more complex cases the understanding may be qualitative but this is much better than no understanding. It is, however, recognised that there is a further important area of knowledge which is based on experience of the system. In the method which relies wholly on non-dimensional parameters it is very difficult to incorporate this knowledge. The claims for artificial intelligence in general and expert systems in particular led to the Stewart Hughes' interest in that technology in 1982/3. Stewart Hughes have developed several expert systems for helicopter rotor head track, balance and fault diagnosis, gas turbine fault identification by module and an extension to the transmission technology. Some examples of this work will now be discussed.

2.0 EXAMPLES OF EXPERT SYSTEMS

2.1 The specification of the problem

Engineers have developed considerable skills in processing data and producing very selective information. The FFT and the cyclic average are two common examples. It was clear that an expert system would not supersede the need for such processing but could greatly enhance the result. It was, therefore, natural that one should start by hosting the expert system in the computer system which did the signal processing. In the case of Stewart Hughes this was our own PDP based Mechanical Systems Diagnostic Analyser. Due to the inadequacies of shells, all work has been done, until relatively recently, in Prolog or Lisp. The disadvantages of linking the expert system to the analysis facility are obvious, so three years ago it was decided to use a PC to host the expert system, which could then control any slave computer which would perform all specialist analysis (Figure 1). This allows great flexibility in application of particular expert systems.

The problems which were tackled lent themselves naturally to a rule based structure with forward and/or backward chaining inference. More recently, the application of classifier technology to engineering problems has become of increasing interest.

2.2 A rotor head expert system

A requirement to produce a rotor head track and balance technology involved Stewart Hughes in a fundamental review of the methods available and the requirements of the users. Since this has been extensively documented elsewhere (eg References [2] and [3]) only a very brief summary of the technology will be given here.

The requirement to avoid any instrumentation in the rotating components of the rotor, plus the need to make the measurement accuracy independent of the skill of the operator led to the development of a simple, light, but highly accurate, device to determine the position of the rotor blade in space. This device uses the principle of triangulation to determine the track height of the rotor and is accurate to ±1mm. The original tracker was required for military reasons to work entirely passively (ie without any emissions), and while it is able to adapt to considerable changes in light illumination, it cannot work if there is no contrast between the blade and the background. Active tracking systems have been developed which have comparable accuracy. One tracker is shown in Figure 2.

Since accurate measurements are taken on each passage of each blade through the tracker field of view, this has permitted the use of variable rotor speed on the ground and measurements during entry into manoeuvers in flight as diagnostic tests. This increases data and knowledge bases but at the same time may make the unaided decision process more difficult. It was also clear at an early stage that no sooner had the relatively simple and well practiced techniques for rotor track and balance become systematically used than there would be a need to provide more extended procedures to trouble shoot the "Hanger Queens". It was against this background that expert systems were examined.

A recent Expert System for track and balance (Figure 3 (a), (b), (c)) is configured as follows. The data is taken by the Rotor Analysis and Diagnostic System (RADS), the output of which is the vibration of the rotor and the track and lag of each blade either averaged over many rotor revolutions when the rotor speed is constant or provided rev by rev for varying rotor speed cases. This information is transferred to the Expert System machine (IBM AT or compatible) and with the header files, giving aircraft specific information, forms the data base.

The first part of the program (Figure 3(a)) involves identifying to the Expert System the test cases which have been taken. The Expert System has a list of three letter codes which identify all flight test states used in the rules. RADS, however, allows complete freedom for the flight test crew to name their tests as they wish for subsequent identification. The Expert System, therefore, attempts to match the given designator with its list of recognised flight tests. It confirms with the operator that its matching is correct and asks for guidance when it is unable to determine a match. It also allows human intervention to comment on reliability of data, to enter scaling changes required to allow for attenuator settings if the data has been obtained by a different system.

The next step is entirely algorithmic, being the comparison of the vibration (and track if applicable) results against mandatory limits for flight. If the limits are not exceeded then the need to take remedial action is removed. However, if the minimum vibration of the helicopter is required then a further level of the expert system can be initiated.

If the helicopter does not pass the exceedance test then the Expert System diagnostic test is initiated (Figure 3(b)). The philosophy behind this version of the Expert System is to identify tab errors as early as possible and then "adjust" the flight data to allow for the identified corrections. The remaining faults are then determined by "forward chaining" through the rule base. The process stops when either the diagnosis remains unchanged within a predetermined window or after a fixed number of passes through the rule set.

A final set of rules is then entered, which rationalise all the fault facts and produces the "agreed" diagnosis.

There are rules which note apparently contradictory evidence and these facts are weighted accordingly. Such contradictions are also noted for reference by the user at a later stage if required.

An algorithmic procedure then completes the expected vibration and track levels on the basis of the proposed corrections and advises if the limits are less than demanded.

Currently the program now gives the user the options shown in Figure 3(c). These options are reasonably self explanatory. The manual intervention at this stage is there for two reasons. The first is to allow an expert actually using the procedure to understand what has happened, why, and if necessary to impose additional constraints on the solution. The second is to allow the manual actions to be replaced by further rule based sets when a direct comparison between human and machine expertise can be made.

The system has been successfully tested against existing flight test data.

2.3 Gas turbine expert systems

Two expert systems have been developed to aid engine module fault identification in gas turbines. One used performance monitoring through the engine and involved matching engine data with that obtained from a thermodynamic model of the engine to identify the likely faults. It again was rule based and used forward and backward chaining to assert the faults which were presented with a likelihood factor attached. In addition to using performance trend data, heuristic information was included from simple observations made by the tester. The system behaved satisfactorily and saw some service in a limited trial. Favourable comments on its performance were received but insufficient faults were diagnosed and confirmed by engine strips to make an assessment of the system robustness.

The second system had the objective of determining if a module was out of balance using two vibration sensors on the engine carcase. The data base consisted of a limited number of trials in which a known out of balance was seeded in particular modules. The engine was then run up to maximum speed and back to idle conditions relatively slowly and the vibration recorded. The overall and the once/shaft levels were then recorded against shaft speed. An example is given in Figure 4. During the run up and run down, various modes in the engine were excited and the vibration curve showed characteristic shapes depending on the position of the out of balance in the engine. The characteristic shapes were then defined in terms of features eg peaks at frequencies, shape of peak etc and this information becomes the data base for that particular engine type. A forward chaining rule based system was employed to match the pattern of the seeded faults to that obtained from the test engine which had undergone a similar test.

The system had only limited success because other faults could contaminate the analysed signals. Not only that but the out of balance could occur in other planes in each module than that in which the mass had been placed in the seeded trial. This clearly affected the modal response. The knowledge available to differentiate between the various cases was insufficient.

The conclusion was that the system showed promise but that the knowledge base needed extension. Progress has since been made in significantly expanding the knowledge base.

3.0 FURTHER DEVELOPMENTS

The cases mentioned above have shown that Expert Systems have value in prototyping and evaluating diagnostic techniques using rule based architectures. We are extending our investigations in the following directions.

3.1 Gas turbine diagnostics

The very simple vibration imbalance expert system application described above is being extended as part of a joint project with Rolls Royce plc. In an effort to assist the vibration engineer to "see" faults a plot of spectra against time was developed. This is known as the ZMOD, because the modulus of the signal is shown by colour. Figure 5 is a black and white representation of the plot. The skilled vibration expert is able to interpret many faults from such a plot. An expert system is being developed which acts in the same way. The problems of constructing such a fault diagnosis system can be summarised under three headings:

(i) Transforming the incoming data into a representation appropriate to the problem. This is done by devising discriminators and applying them to the data.

(ii) Associating the transformed data with the faults which need to be detected, and constructing a mapping between the two.

(iii) Analysing the devised mapping by comparing its performance with previous known cases, and considering its 'physical reasonableness'.

Techniques to meet (i) which are being utilised range from simple line matching routines to methods used in spectrogram interpretation and speech recognition work.

Methods applicable to (ii) include interpretation of the designer's knowledge gained from mathematical analysis and experience of allied engines. A technique of interest here is the 'speech sketch' developed at the University of Sheffield, England. This may be summarised as follows:

The first stage of Speech Sketch production consists in converting a conventional spectrographic representation of speech into a list of fragments describing the time evolution of spectral peaks corresponding to formants or harmonics. The technique for producing these fragments is as follows:

(a) A multi-scale representation of spectral edges is created.

(b) A probabilistic relaxation algorithm, employing a spectral continuity constraint seeks out the most likely labels for each spectral peak (from the set onset, offset, noise part of a track and continuation at a finer scale) and identifies the most likely links between peaks in adjacent time frames and scales.

(c) A deterministic procedure integrates information across scales driving from onsets in the coarsest scale, continuing at a finer scale where necessary (seeking always to return to a coarser level) until an offset is reached.

The similarity between this technique and that required to interpret a ZMOD is self apparent.

Part (iii) above is often particularly difficult because:

(a) Knowledge of the relationship between discriminators and faults is very scarce.

(b) Large (>100K) quantities of data can be involved. This data can be noisy and incomplete. Much knowledge lies buried in this data.

It will be obvious that the number of seeded fault tests that can be afforded is small and hence much of the "proven" knowledge has to come from the field. It cannot be too strongly stressed that an accurate data base of signatures and correlation with faults is an essential to the development of such diagnostic systems. This is an easy statement to make in the comfort of a lecture theatre but much more difficult to get implemented in the sometimes arduous and at other times boring times in the field. Every assistance which can be given to the operators must be provided and Stewart Hughes are actively working in that field.

However, when a data base exists it is then possible to assess the usefulness of the discriminators to identifying the faults. This is to some extent a purely algorithmic procedure, and can therefore be performed by the classifier system. In this respect, the classifier acts as a 'hypotheses tester'. The classifier operates by making a search of the chosen mapping space, driven by specified examples, hints, problem specific constraints and general heuristics, and produces a mapping consistent with what it has been told. This mapping then needs to be tested to assess its usefulness.

Stewart Hughes have developed a classifier which is being given a trial on small but important fleet of engines which are well data logged. There is also considerable knowledge available from a range of sources. The classifier developed is based on the general heuristic of minimising entropy as used in the ID3 algorithm of Quinlan.

The results of using such a classifier allows the engineer to clear up inconsistencies, reduce the incompleteness, discard redundant or irrelevant descriptors and obtain guidance on the need for new hypotheses.

The classifier tree as developed by the program may be used immediately to assess new data and obtain advice on the faults contained. Once it is decided that the quality of the classification is acceptable then it can be embedded in either an off-line data analyser or an on-line fault monitoring system.

3.2 Rotor head

The obvious extension of the simple rotor track and balance is to the adjustment of the rotor and fuselage dynamics to reduce higher harmonic vibration. It is worth noting that reducing 1R vibration does not necessarily minimise higher order vibration.

Higher than 1R order excitation in the rotor may arise from two main causes. The first is that the excitation forces and moments at the rotor head are increased due to either the condition of the rotor blades, hub etc and/or the way in which the helicopter is operated. This increase in forcing function will give rise to an increase in levels at all points in the fuselage pro-rata to the original forcing. Alternatively, the forcing in the rotor may be unaffected, but the level at the accelerometer position chosen for the standard measurement may be increased due to a change in transmissibility of the vibration through the structure. The aerodynamic excitation generated in a rotor is discussed in an attempt to understand how increased vibration levels arise. A simple finite element model of a helicopter has then been used to obtain the response from the rotor at various points in the fuselage. The model has also been run with "faults" in the structural components and the response in the helicopter recalculated. The mathematical model is extremely simple, for example, it contains no damping and it is two dimensional giving only forces in the vertical and fore and aft direction and the response to pitching moment. It has 30 nodes so the representation of the structure is limited. Nevertheless, it is considered entirely adequate to demonstrate a principle.

3.2.1 The aerodynamic excitation due to a rotor

A main rotor provides lift and control of a helicopter by means of a near vertical force. The control of the rotor is obtained by cyclicly varying the angle of attack as the blades rotate using constant and first harmonic inputs only. The simplest theory of helicopter response shows, due to the aerodynamic forces on the rotor blades in forward flight, harmonics higher than the first rotor order. It is therefore quite impossible to cancel out all the vibratory loads even in the most idealised case by the 1R cyclic input. The actual response is considerably more complex than the simple model predicts. The aerodynamics of the rotor blade involve significant penetration into the transonic flight regime principally on the advancing side. On the retreating side the area of reversed flow increases roughly as the square of the advance ratio To maintain control retreating blade incidence progressively increases and at some stage, the tip section will stall giving rise to a marked increase in vibration. These two boundaries are shown in Figure 6 which is taken from Reference [4]. That reference confirms that the compressibility barrier, indicated by the number 1, is a soft barrier meaning that large penetrations can be made, particularly in transient flight. The effect of advancing blade compressibility can be seen in terms of increased power consumption as well as in vibration. Any effect which causes the blade compressibility effects to occur at a lower Mach number will clearly move this boundary. The retreating blade stall boundary (2) is described in Reference [4] as being a much harder limit. Penetration into that region results in a rapid rise in vibration in the helicopter as the blades begin to stall flutter. There is also a rise in required power and the handling degrades more than due to a similar penetration into the compressibility region. In both cases there is an increase in required power and therefore if the helicopter is equipped with torque meters it should be possible to show that the rotor has degraded because increased power is required for a given flight condition. While this is possible, and in extreme cases will be noticeable, it will still be a difficult technique to apply due to changes in helicopter configuration in operational service. It must therefore be regarded very much as a piece of secondary evidence.

One obvious way in which the retreating blade stall limit can be seriously compromised is due to blade leading edge erosion. Figure 7 is taken from an MSc thesis of A E Ahmed. He obtained a piece of a Mil 8 helicopter rotor blade, which was time expired in the Sudanese Air Force and this section was tested in a low speed wind tunnel. Its performance was compared with an equivalent piece of a rotor blade which was in pristine condition. The differences between the two and their obvious significance to the onset of vibratory levels are clear from Figure 7. Profile degradation also affects compressibility effects.

Consider then the blade vibratory levels that might be expected on a helicopter in first class order. Reference [5] provides a very useful survey of the relation between rotor vibratory loads and airframe vibration. Data from six sources was collected and copies of some of the results are given in Figure 8. The data which is identified on each of the diagrams, includes full scale flight testing from four, five and six bladed main rotor. In addition, there is the full scale four bladed S76 Ames wind tunnel data and the two sets of data on model rotors which both had four blades.

Figure 8 shows the 3 per rev loads in hinge based co-ordinates. The axial forces are in the lift direction and it will be noticed that there is a good condensation irrespective of model or full scale data for the amplitude. The phase, as might be expected shows a much greater variability. The inplane data is smaller in magnitude and less well defined, although there is a trend with the bulk of the data. The radial moment has considerable scatter.

Niebanck concludes that the values of the 3, 4 and 5 rotor order vibration is largely independent of the number of the blades. While the trend of level with advance ratio has been noted, the scatter should not be overlooked. Niebanck also shows some correlation between the vibration level and the natural frequencies of the blades relative to the various harmonics. The differences between the various rotors is not always consistent from speed to speed. This variability could clearly be important in tuning a particular helicopter. Information which may help to elucidate this variability is next considered.

The airloads on the rotor depend on the incidence, its rate of change and the local velocity at every point on the blade. For much of the rotor disc steady state aerodynamics is acceptable but non-steady aerodynamic forces should be considered on the retreating blade. The effective local incidence can only be calculated when the induced flow field due to the rotor is known. The complexity of this flow has been demonstrated in many papers including Reference [6].

Explanations and calculation of these flows have been given in terms of the vorticity associated with the rotor. The effect of these vortices may be considered in terms of macro and micro structure of the inflow. The macro structure may be likened to the actuator disc approximation where the momentum balance and mass conservation predict the inflow without reference to the blades at all. This is called the non-wake induced flow. The second or micro structure is the modification to this flow by the vorticity patterns - the wake induced effects. This effect is on blades following the one that is generating the vortex pattern. The effect of these vortices will depend on the closeness of their passage to the following blade, the degree to which the vortex is rolled up, the effect of the shed vorticity etc. These macro and micro effects are examined.

Non-wake vibratory loading arises from the time-varying velocity encountered by the blade sections rotating around the disc and by blade dynamic motions. A mathematical model has been constructed by Dr M M Soliman of the University of Southampton for a typical rotor. This model includes blade bending in the flap direction and the correct aerodynamic data for the rotor blade sections used. The induced velocity has been approximated by the simplest possible model for forward flight, namely that due to Glauert, although the value of the constant used to give the gradient of the velocity from front to rear has been adjusted in the light of later evidence, eg Reference [6]. For an advance ratio of μ = 0.4 the results are shown in the following figures. Figure 9 shows the local incidence distribution around the disc. Figure 10 shows the variation of the vertical hub force for one blade. A harmonic analysis of Figure 10 has been made and the results are presented in Table 1. The value for 3/rev normalised to be relative to unit lift on one blade is plotted on Figure 8 (marked University result). The axial force amplitude falls within the scatter of the results but phase is more variable. Figure 11 shows the corresponding 4 and 5/rev vertical force comparisons. The calculated values for 4 and 5/rev cases fall increasingly below the experimental data. Since this model of the rotor downwash was extremely simple it suggests that details of the wake are of little importance for the lowest harmonics which appear to depend on correctly representing the detailed aerodynamic performance of the blade section and blade flapping motion. This result is confirmed by Figure 12, which is taken from Reference [7], and which shows the contribution of the free wake, compressibility and rotor blade bending to the third, fourth and fifth harmonics for an H34 test. Thus the third harmonic appears to be most influenced by the detailed aerodynamic performance of the blade and the macrowake structure. For the fourth harmonic the effect of blade bending compressibility effects and free wake approach equal importance. For the fifth harmonic the wake induced effects are most significant. This is an important conclusion.

COMPONENT	VERTICAL	
Harmonic	Mod	Phase°
0	1.058	-
1	0.159	295.5
2	0.530	99.5
3	0.612	9.4
4	0.006	76.4
5	0.047	262.1

TABLE 1

Harmonic analysis of the vertical, inplane and side force and hub torque associated with a single blade

For higher harmonic rotor vibration sourcing the reasons for the individual frequency component changes are important. The above has shown that third harmonic is predominantly affected by microscopic wake effects, eg by the detailed aerodynamic performance of the blade profile. Thus changes here would be important. By contrast, the 5th harmonic is very much affected by the microstructure of the wake which is strongly influenced by the blade spanwise loading. An obvious contender to cause a change between nominally identical rotors is the blade twist which is influenced by chordwise (or product) mass balance and tab adjustment. If all the blades behave in the same way then the normal 1/rev track and balance condition will be satisfied in both cases above but the particular solution achieved will affect the level of the higher harmonic content. This is particularly appropriate to the advancing side.

Retreating blade stall also affects higher harmonic excitation. After stall takes place flutter occurs which builds up over a limited number of cycles. Since this occurs on each blade this will give rise to a lift and drag variation at the number of flutter cycles times the number of blades. One therefore expects the vertical force transmitted to reflect these harmonic components.

It must be remembered that in addition to the lift and drag forces the pitching moment may be affected. The resulting forces in the control system will couple together to put inputs back into the blade pitch, so modifying the lift distribution.

The forces and moments transmitted through the hub and control mechanism are subject to the well known laws of combination which are directly related to the number of rotor blades. When hub cancellation occurs, this information is lost in going from the rotating to fixed co-ordinate system.

It is however unlikely that all blades will be affected equally and therefore the difference in individual blade harmonic forces and moments relative to the mean for that harmonic will be transmitted to the fuselage and these give a clue to the reason for any increase in aerodynamic excitation.

3.4 The response of the fuselage to inputs from the rotor

The forces and moments at the rotor head are transmitted through the structure and undergo change of amplitude and phase depending on the modal behaviour of the structure. It is possible, but difficult, for any structure to measure the response at any point for a force/moment input at any other. The various finite element models have been developed to allow such a response to be calculated. The stage reached was reasonably summarised in Reference [8] which compared Black Hawk shake test results with Nastran finite element analysis. The two pertinent conclusions were:

- Methodology for obtaining and analysing shake test data has been made significantly more efficient and accurate

- Correlation of the Black Hawk modal parameters and frequency response functions has been significantly improved over previous efforts. The steadily improving ability of the Nastran model to predict vibrations, particularly in the 4 per rev region, should make the analysis a more credible tool for use in the design process. Close co-operation between the design, stress, mass and dynamics organisations is essential in developing an accurate vibration model.

It is therefore reasonable to use finite element analyses to indicate methods of tackling the higher order vibrations. A very simple model was available at RAE Farnborough and some calculations were made with the help of Mr D Davies. The outline of the two-dimensional model is shown in Figure 13. This is a spring-mass system without damping. Knowing the modal response of the model the eigenvectors can be utilised to calculate the response at any point due to forcing at any other point. In this instance the rotor forcing is at station 3 in the diagram, ie the top of the rotor mast. Using the eigenvectors, the transmissibility of the input forces and moment to the output point is found. Using typical vertical and inplane harmonic forces the appropriate bR scaled forcing functions at the rotor head have been calculated. Figure 14 shows the vertical and horizontal accelerations predicted at several positions throughout the helicopter. Because there is no damping in this model the phase change from the origin to the response is conserved. The results shown in Figure 14 are for the standard helicopter with no structural defects. To try and assess the possibility of finding accelerometer positions where the response will change with faults in the fuselage, three cases with changed individual stiffnesses were re-run. It was appreciated that these changes do not necessarily have a direct correspondence to a real fault in a helicopter but they were chosen in parts of the helicopter where problems are known to occur. As this is a feasibility investigation only three cases have been examined. These cases deal with a stiffness between points 6 and 9 at the front end gearbox feet where the stiffness has been reduced by 10%; at points between 11 and 10 where the stiffness has been reduced by 10%, and finally between positions 27 and 28 where the stiffness has again been reduced by 10%. It must be stressed that these were arbitrarily chosen. Each of these cases was analysed in the same way as for the standard helicopter and a figure comparable to Figure 14 was produced. These figures were examined to see if there were any obvious changes in the vibration pattern which might suggest an area for further examination. The area which seemed to indicate most promise was the region from point 11 forward to the nose at 23. The accelerations corresponding to the same forces and moment input at the rotor head, have been plotted in Figure 15. Since the values have only been obtained at discreet positions, no attempt has been made to put a curve through them, but they have been joined by straight lines so that the eye can easily relate values together. It is not difficult to see that distinct patterns for each of the four conditions result and can be easily described, so providing a possible method of identifying structural defects.

It is appreciated that the number of faults as well as their magnitude will vary. The faults may not occur singly and will vary in severity. It is in this situation that the application of artificial intelligence starts to show to advantage.

3.2.3 The application of artificial intelligence

In Section 3.1 the value of a classifier was indicated as were some of the steps which have to be made to obtain a successful result.

The data for the diagnosis that is obtained at each flight speed is the level at each harmonic of the rotor speed at each accelerometer position. Signal averaging has already been used to improve the signal to noise ratio.

A reference location is chosen (probably the one at which the bR level is judged for exceedance) and all results normalised relative to those values in the appropriate directions.

Mathematically the problem can be expressed as a number of simultaneous equations relating the forcing functions, the transmissibility coefficients between forcing and measurement position and the response. These equations are not linear but if expressed in terms of deviations from a datum state then they become linear in the deviations. If it is assumed that the transmissibility coefficients are unaffected by speed then the equation can be solved using data from several speeds and accelerometer positions. This gives the change from the assumed loading and changes in the transmissibility coefficients. Thus the fault can be divided into rotor or fuselage originated. From the particular transmissibility coefficients which have changed the location of the fuselage faults may be located.

The classifier can be used to assist in this respect. If the best finite element model is used to give an estimate of the transmissibility coefficients between the rotor head and the accelerometer sites selected and data such as that shown in Figures 8 and 11 is used to assess the rotor blade forcing functions, then deviations from these values of real data can be used to calculate the changes in aerodynamic forcing and tranmissibility coefficients. This means that for the acceptable helicopter there will also be deviations from the assumed and these have to be determined. The use of a clustering algorithm condenses the data. Deviations from the condensed data are then entered into the classifier together with the "faults" and automatic fault trees are generated. These fault trees are then used to provide a diagnosis with data from cases where the cause of the increased vibration is unknown.

The step of solving the simultaneous equations can be eliminated. If the data is normalised with respect to a reference accelerometer location for each deviation as mentioned above then the values at all other measurement positions can be clustered together for the "acceptable" helicopter. Deviations from the cluster value are then used as the attributes on which the classifier makes its decision. An example of such clustering is given in Figure 16. In some cases noise may result in an increased scatter in which case the limits of the cluster are set to include the majority of the points - this was discussed in Reference [9]. Deviations outside the cluster can now be determined and used in the classifier for fault identification. The level of the bΩ vibration in each direction at the reference position relative to the acceptable level must also be included as this is fundamental to the differentiation between aerodynamic and structural sources. Phase information may also be used but this is inclined to be more variable than amplitude and must be applied with care.

Stewart Hughes have engineered a general database facility which takes data from any of the vibration gathering equipments. This versatile system is described in Reference [10]. It already incorporates a classifier in the software. AI facilities to increase the power and use of this database are being continually updated.

4.0 CONCLUSIONS

(i) The application of rule based prognostic programs to several diagnostic problems associated with helicopter rotor head, transmission and gas turbine problems has been made. These have proved extremely useful in allowing hypotheses to be tested. It has also been relatively easy to accommodate the wide ranging quantities and quality of data which is available in the field.

(ii) All of the programmes have involved considerable data processing and analysis. For program efficiency this code has been written in Fortran or C. A powerful interface between these languages and Prolog or LISP is an essential feature of the development system.

(iii) Commercial shells have proved disappointingly slow to run. For service operation it has been necessary to recode in Fortran or C, which has resulted in the loss of the development facility.

(iv) Classifier techniques have been tried with success. The response of the general mechanical or aeronautical engineer to them has been much more immediate and positive than to the rule based systems.

(v) Stewart Hughes Limited are continuing and extending the application of AI techniques to helicopter, aircraft and general machinery management. A powerful general database facility with an integral AI facility to allow hypothesis testing, diagnostic upgrades as data is gathered and automatic warnings and cautions is about to enter service.

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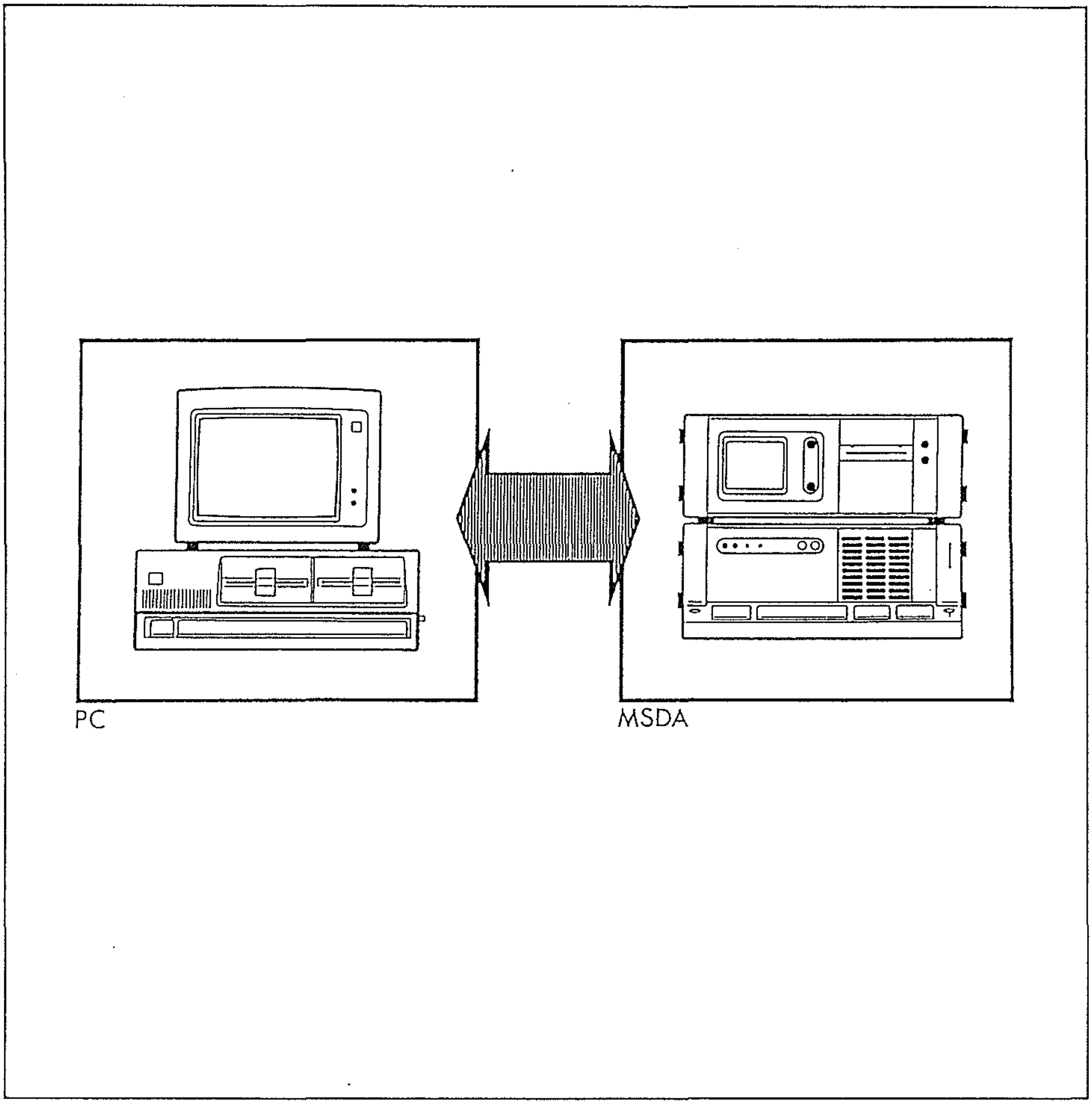

FIGURE 1 : Stewart Hughes Expert System for Data Analysis

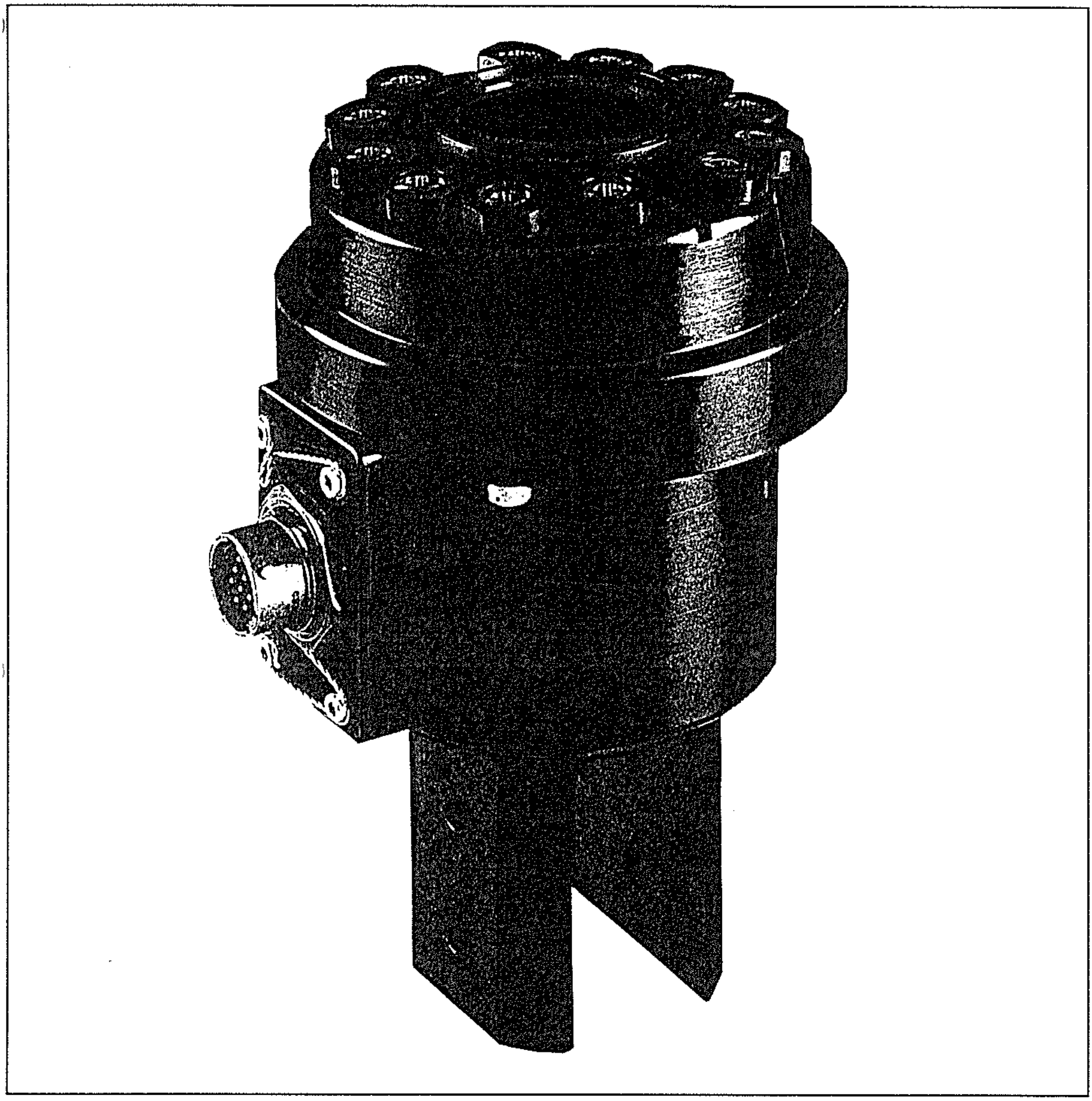

FIGURE 2 : Active Tracker

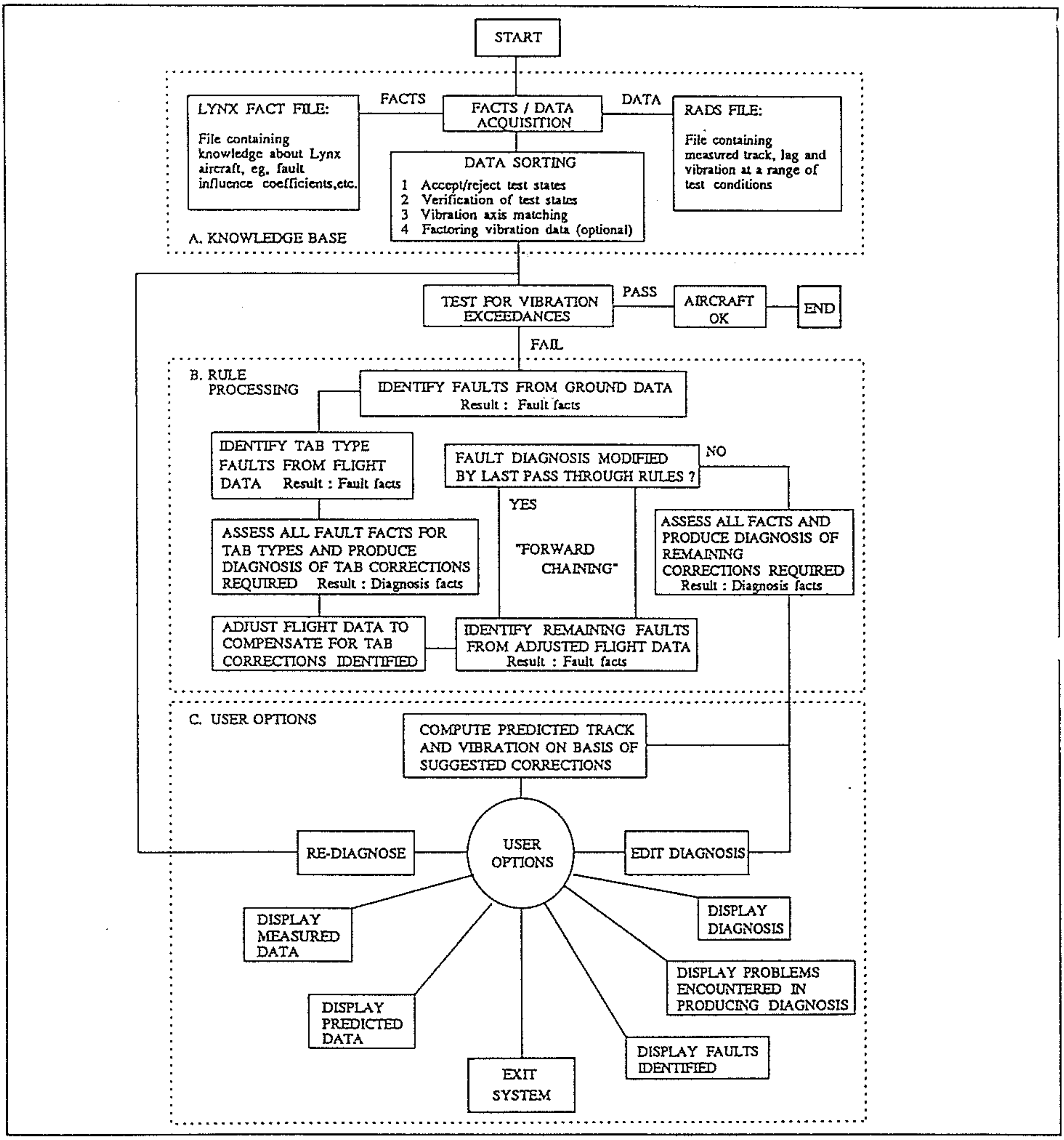

FIGURE 3 : The Structure of PC-EXPROT

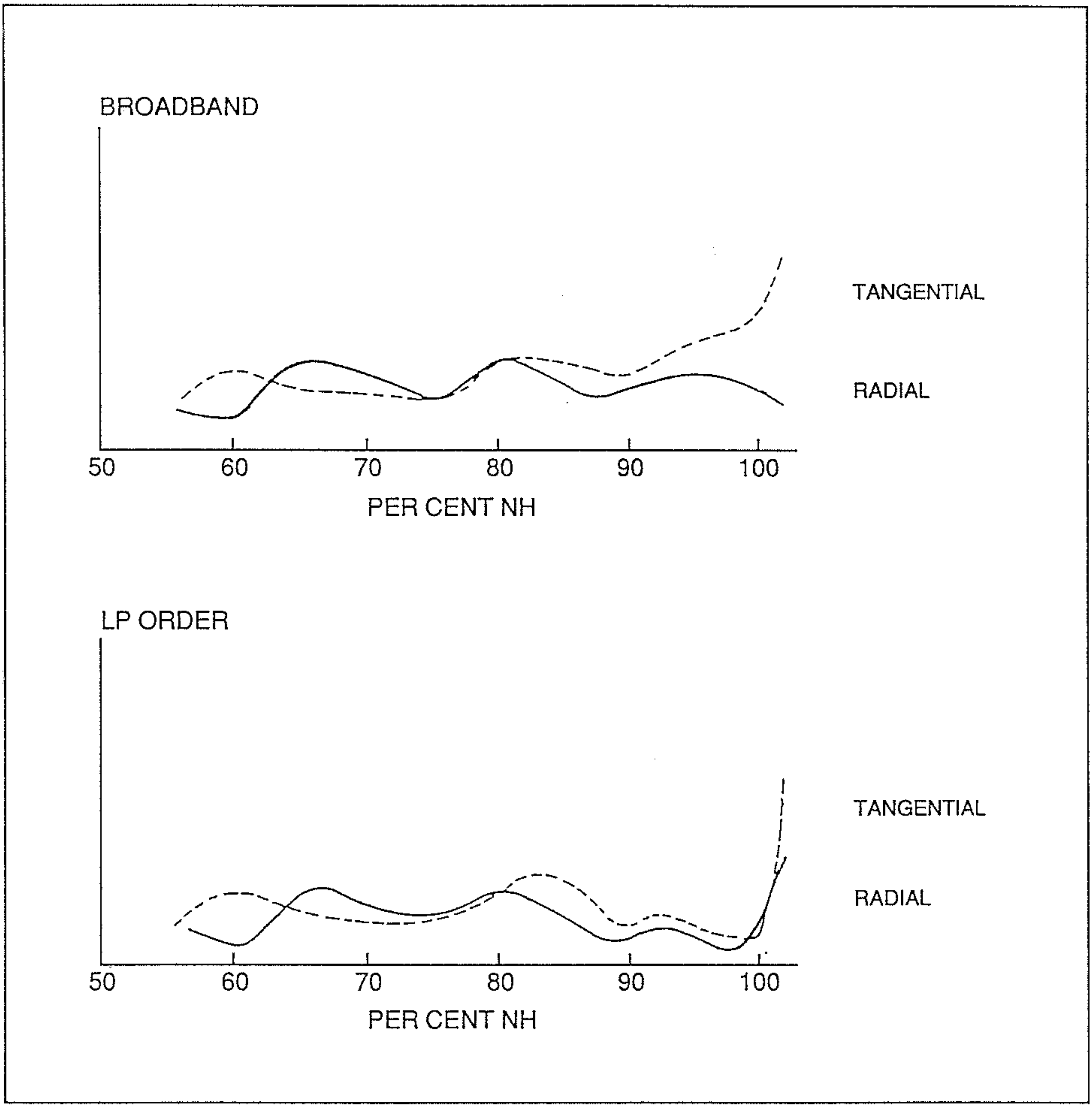

FIGURE 4 : Effects of LP turbine imbalance on vibration

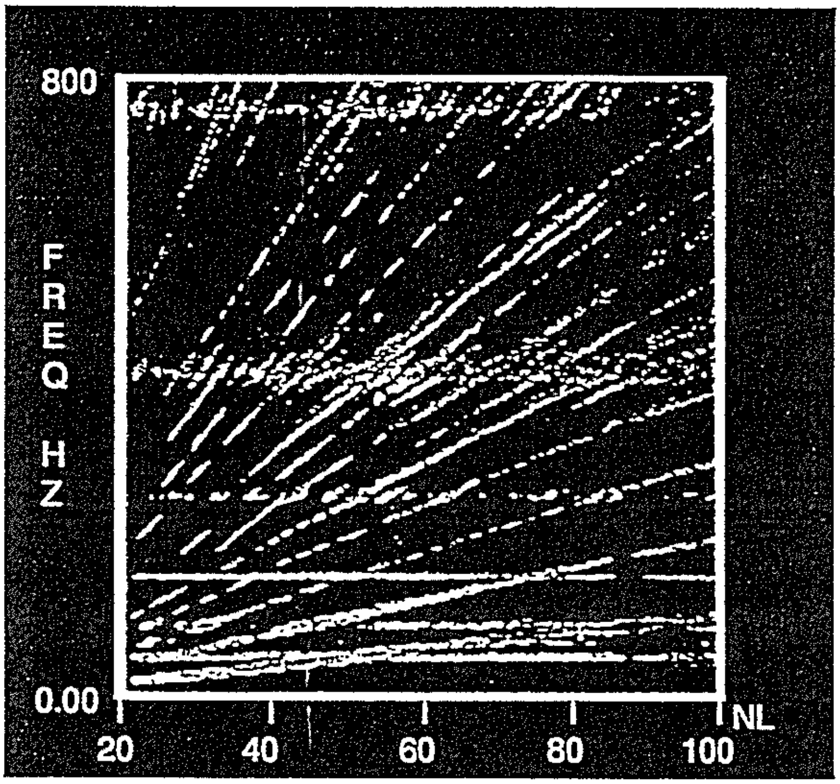

FIGURE 5 : Typical ZMOD for acceleration of two spool gas turbine

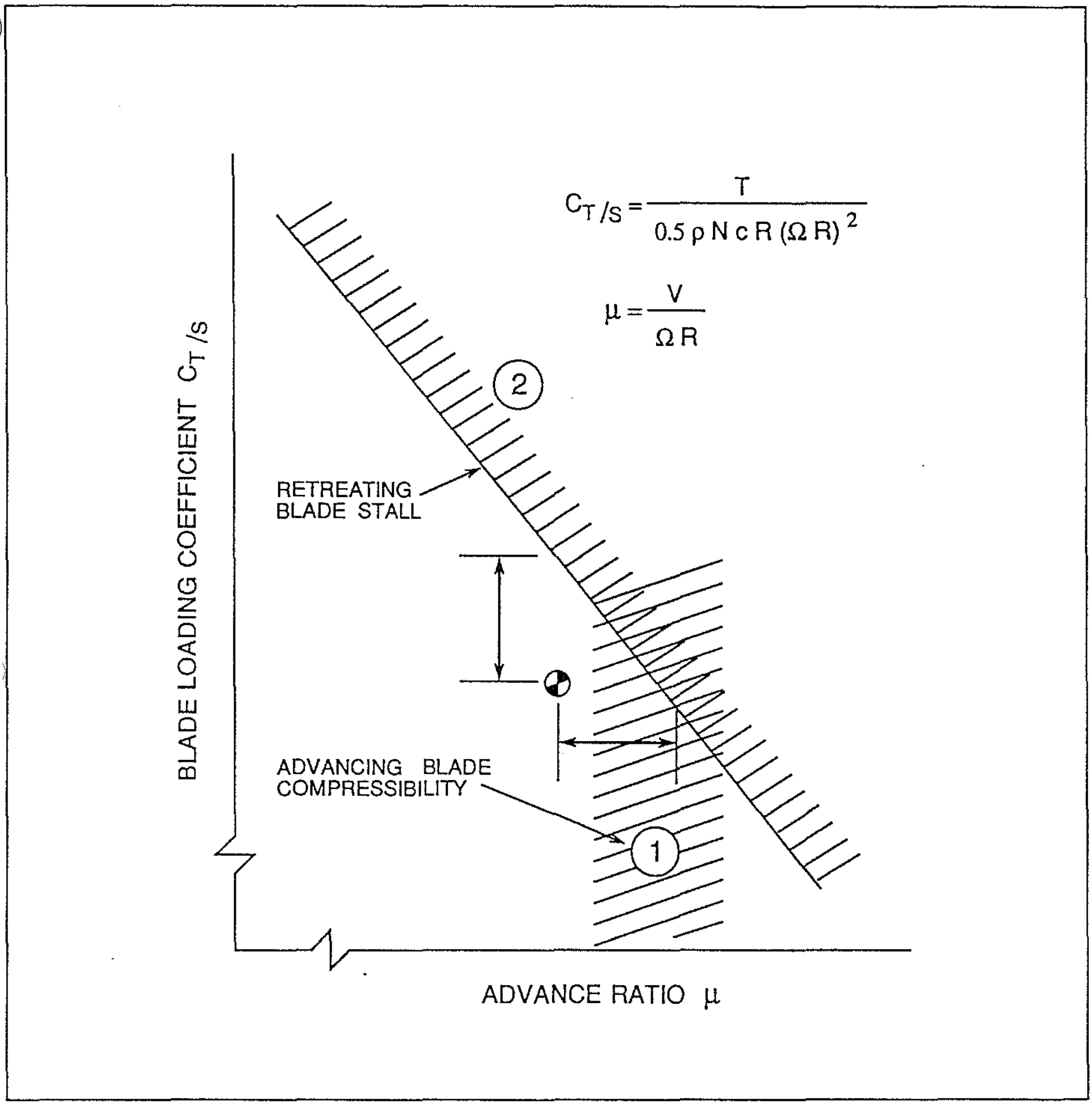

FIGURE 6 : Rotor Design Point and Aerodynamic Limits for LYNX Helicopter

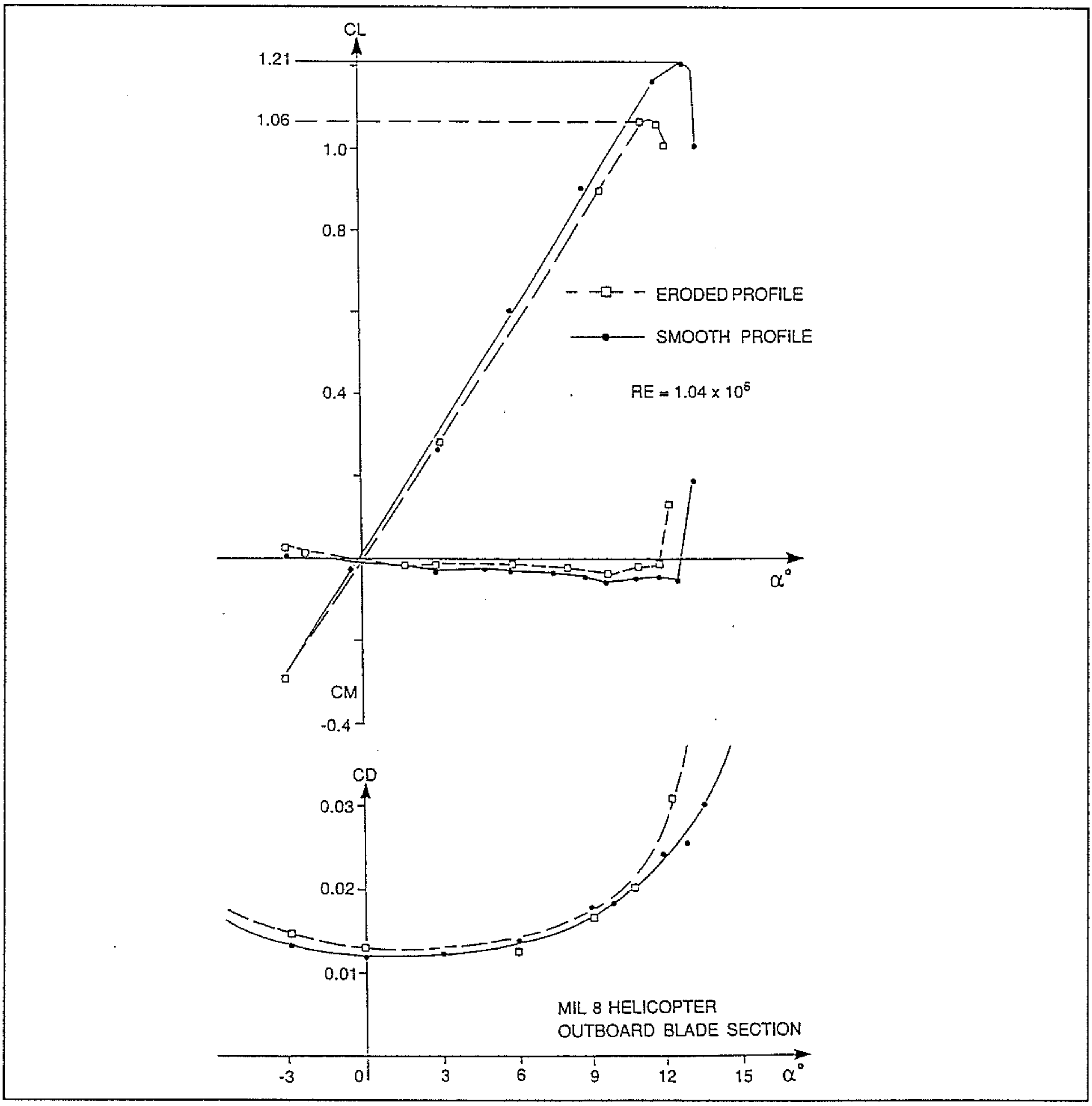

FIGURE 7 : C_L, C_M, C_D vs $\alpha°$ - Data from Wind Tunnel

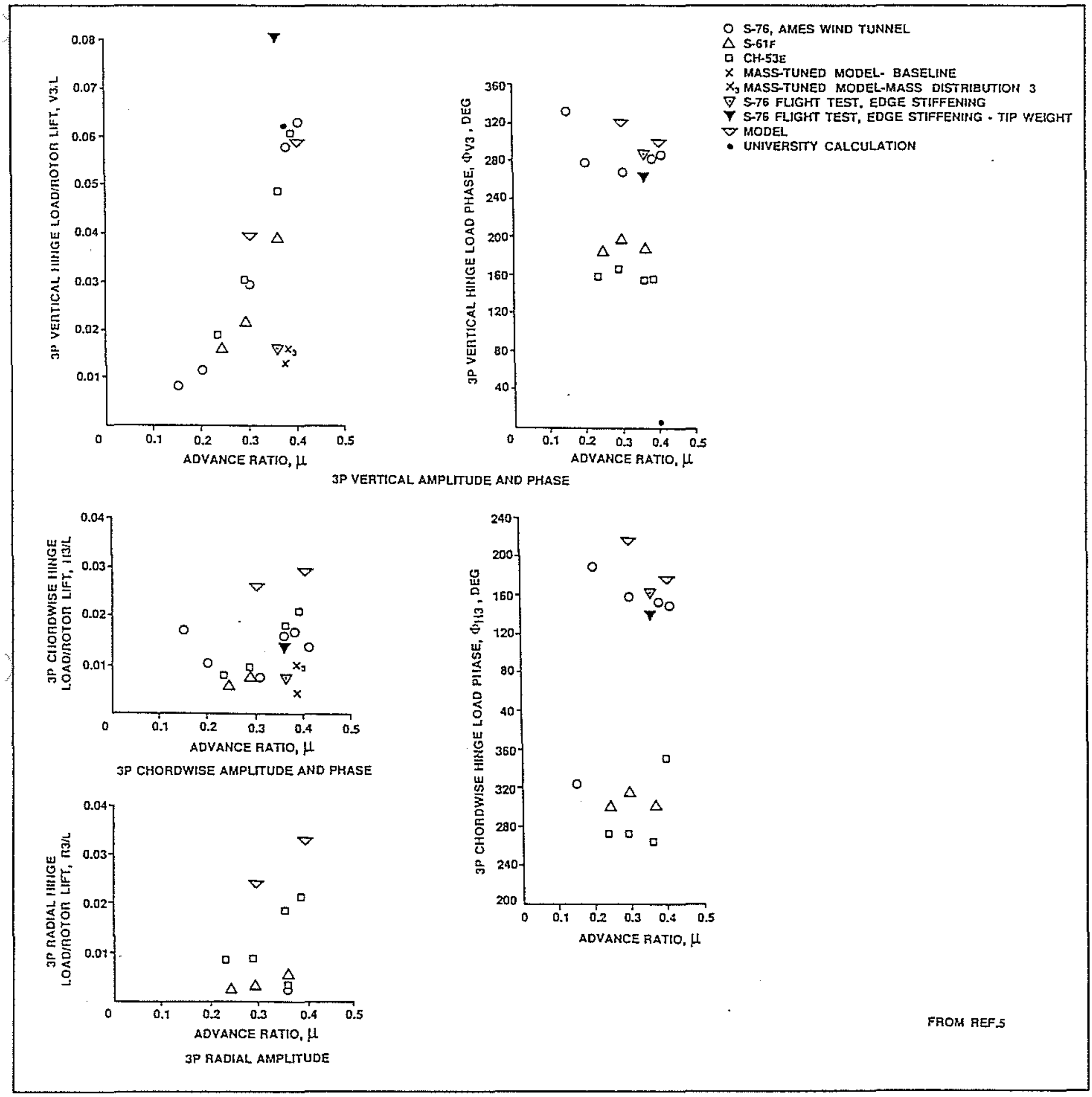

FIGURE 8 : Curves of Harmonic Hub Load Test Data

FIGURE 9 : Calculated Local Incidence Distribution

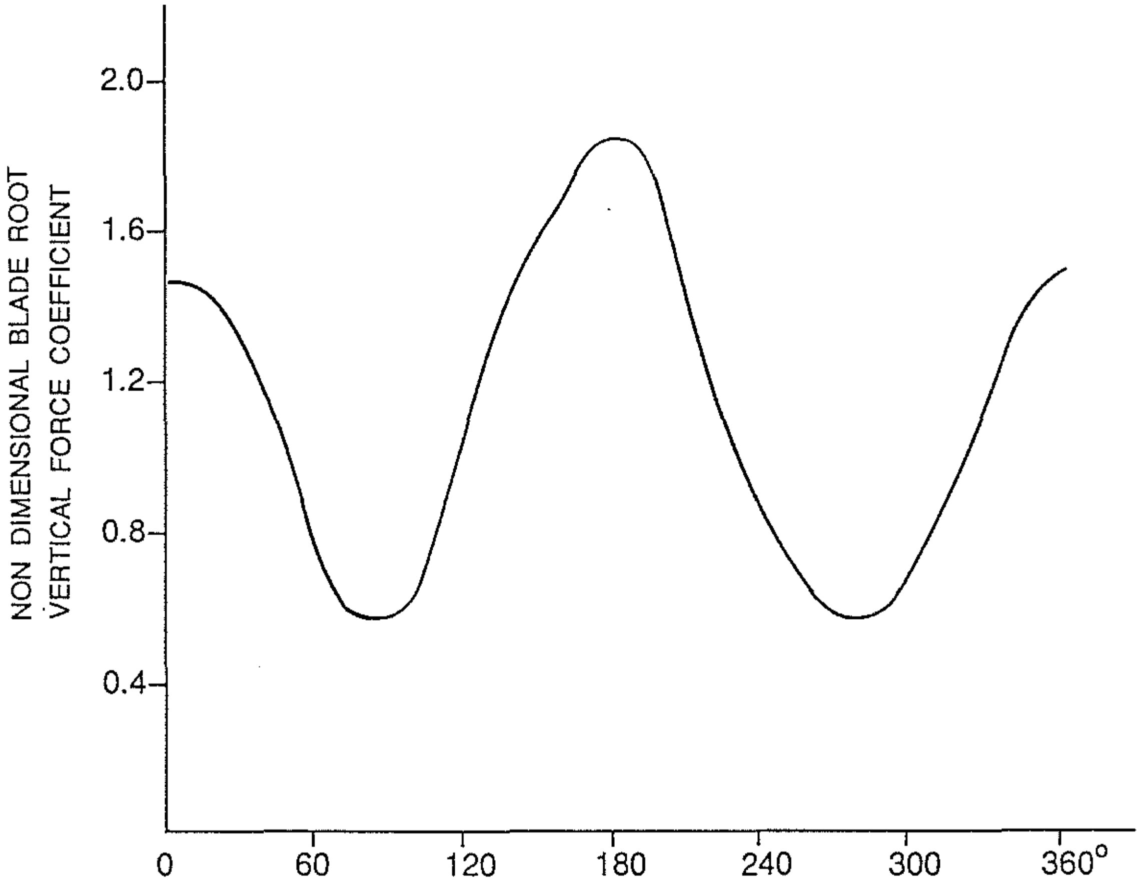

FIGURE 10 : Azimuthal Variation of Blade Vertical Force Coefficient

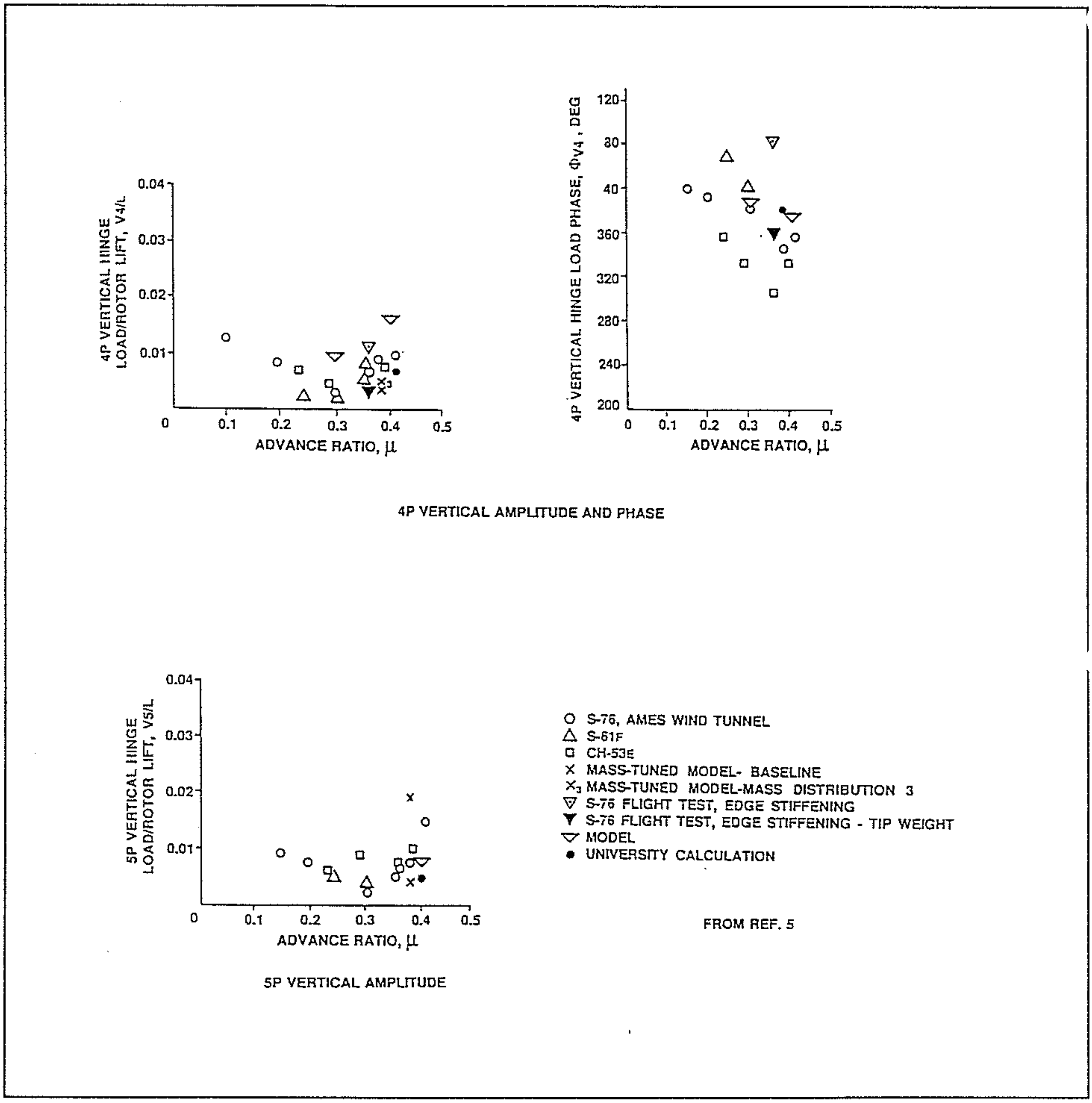

FIGURE 11 : Survey of Harmonic Hub Load Test Data

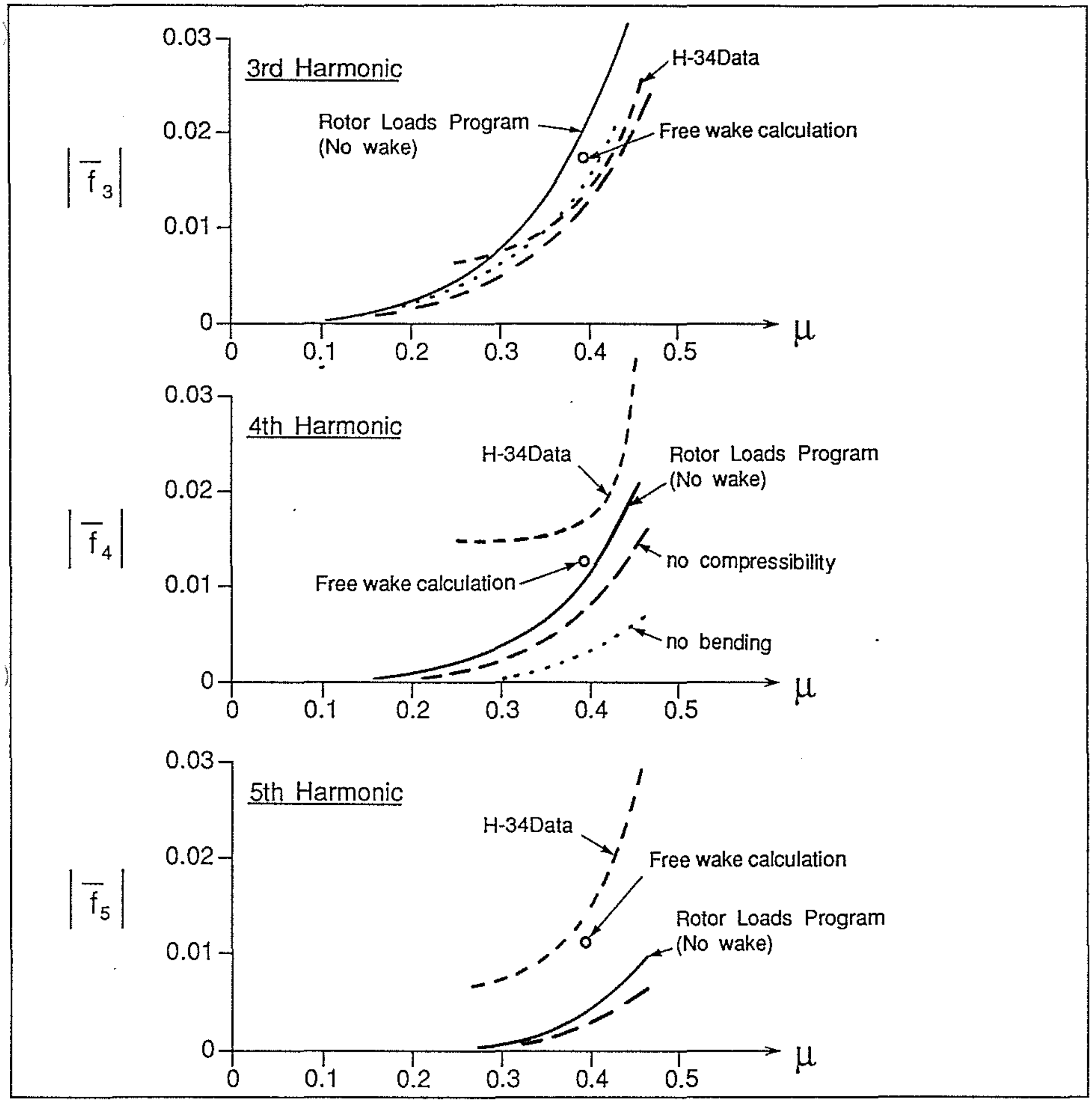

FIGURE 12 : Non-wake airloading harmonics at r/R=0.9 versus advance ratio, calculated for H-34 test parameters.

Note the effects of compressibility or bending.

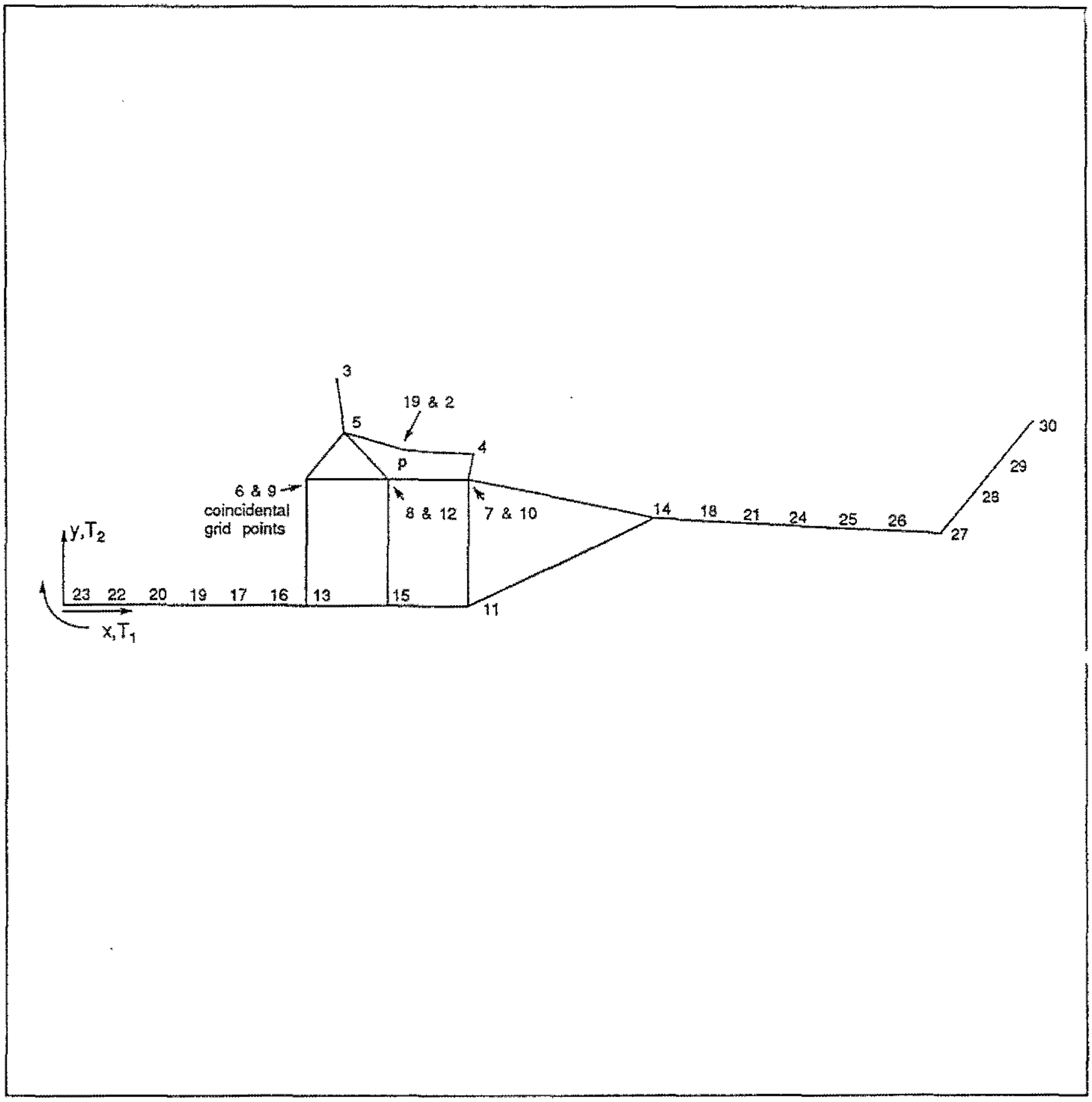

FIGURE 13 : Stick Model of Idealized Helicopter

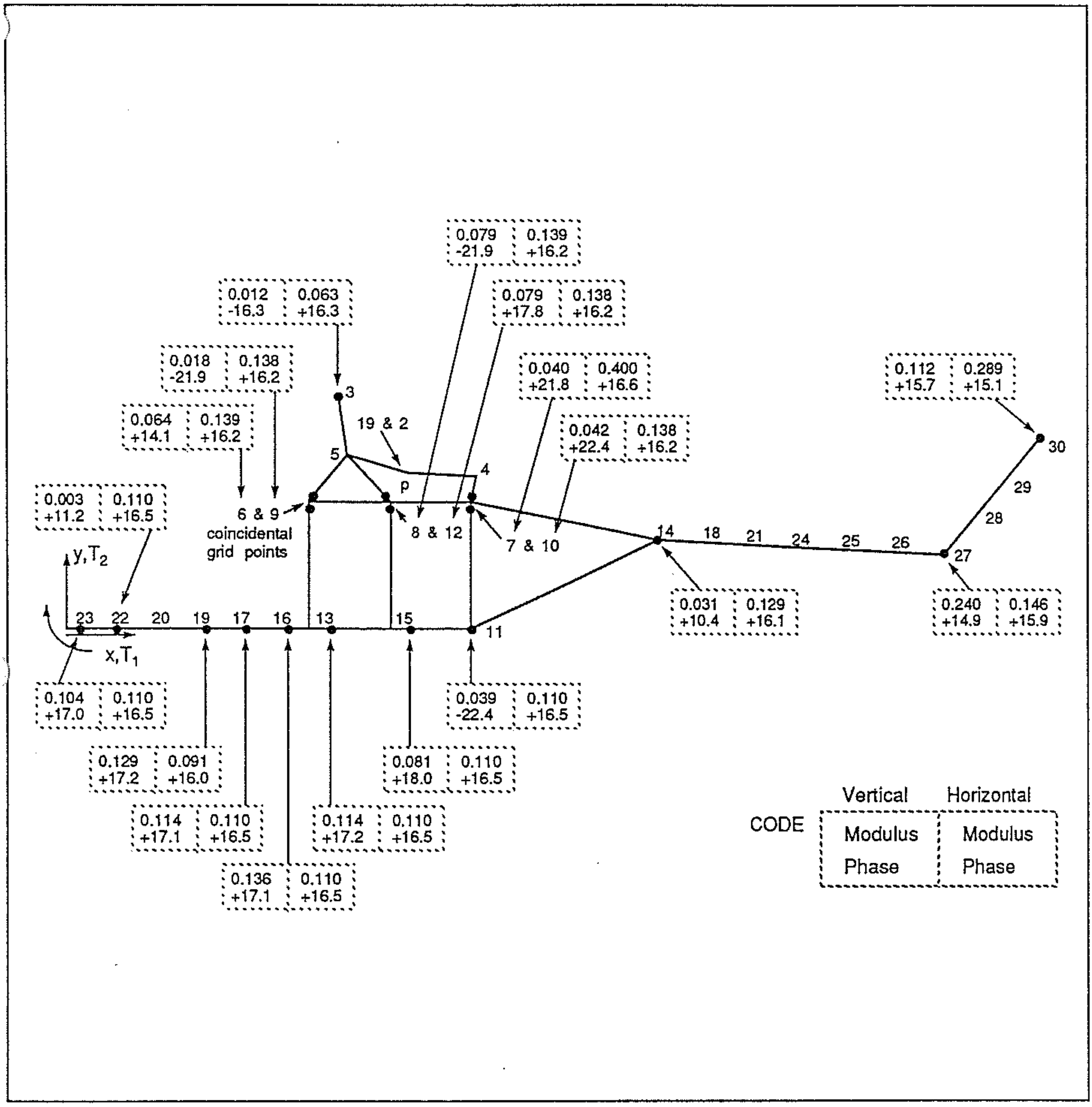

FIGURE 14 : Response of Stick Model at $\mu = 0.4$

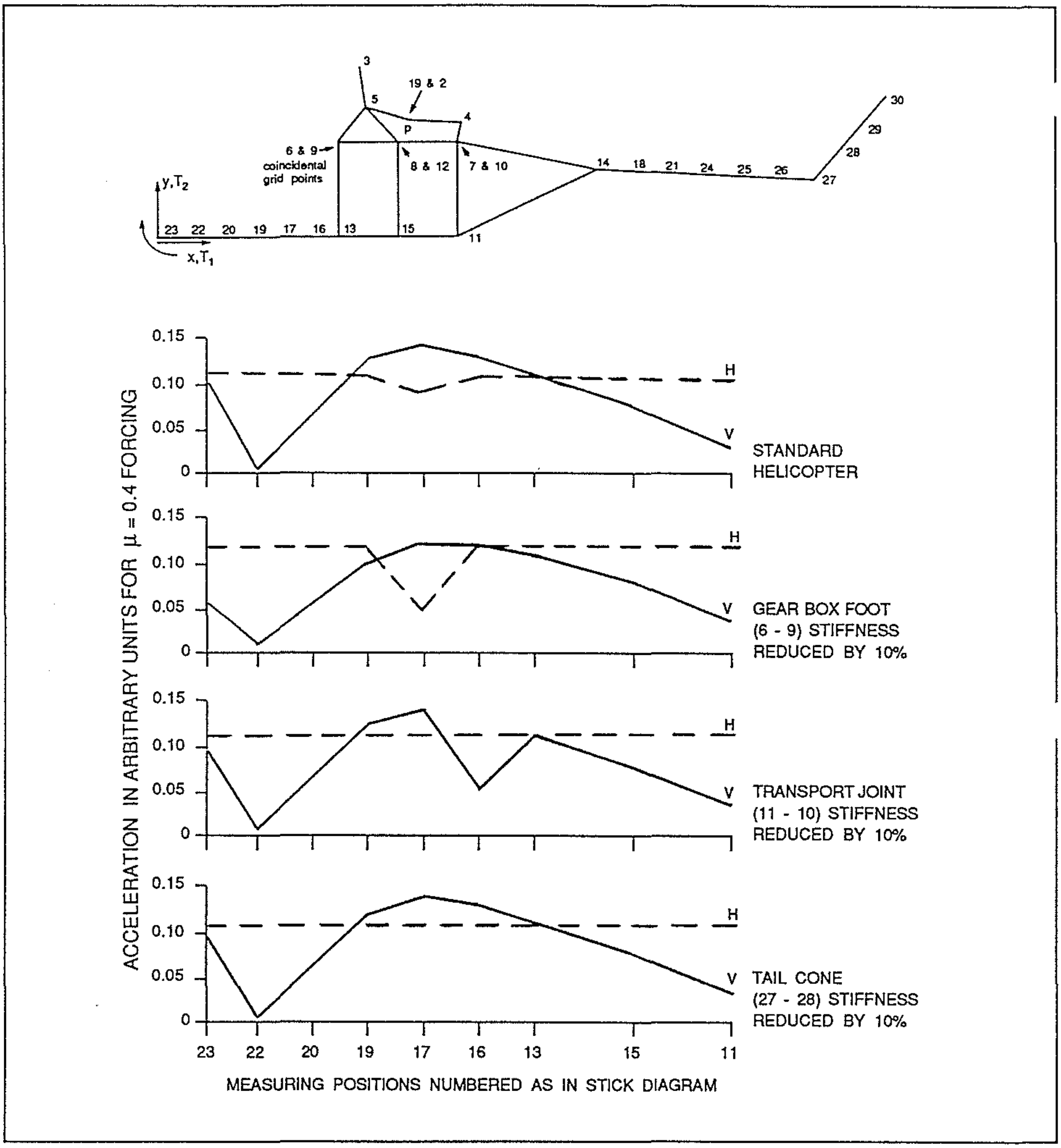

FIGURE 15 : Predicted accelerations along Fuselage Floor for listed defects at $\mu = 0.4$

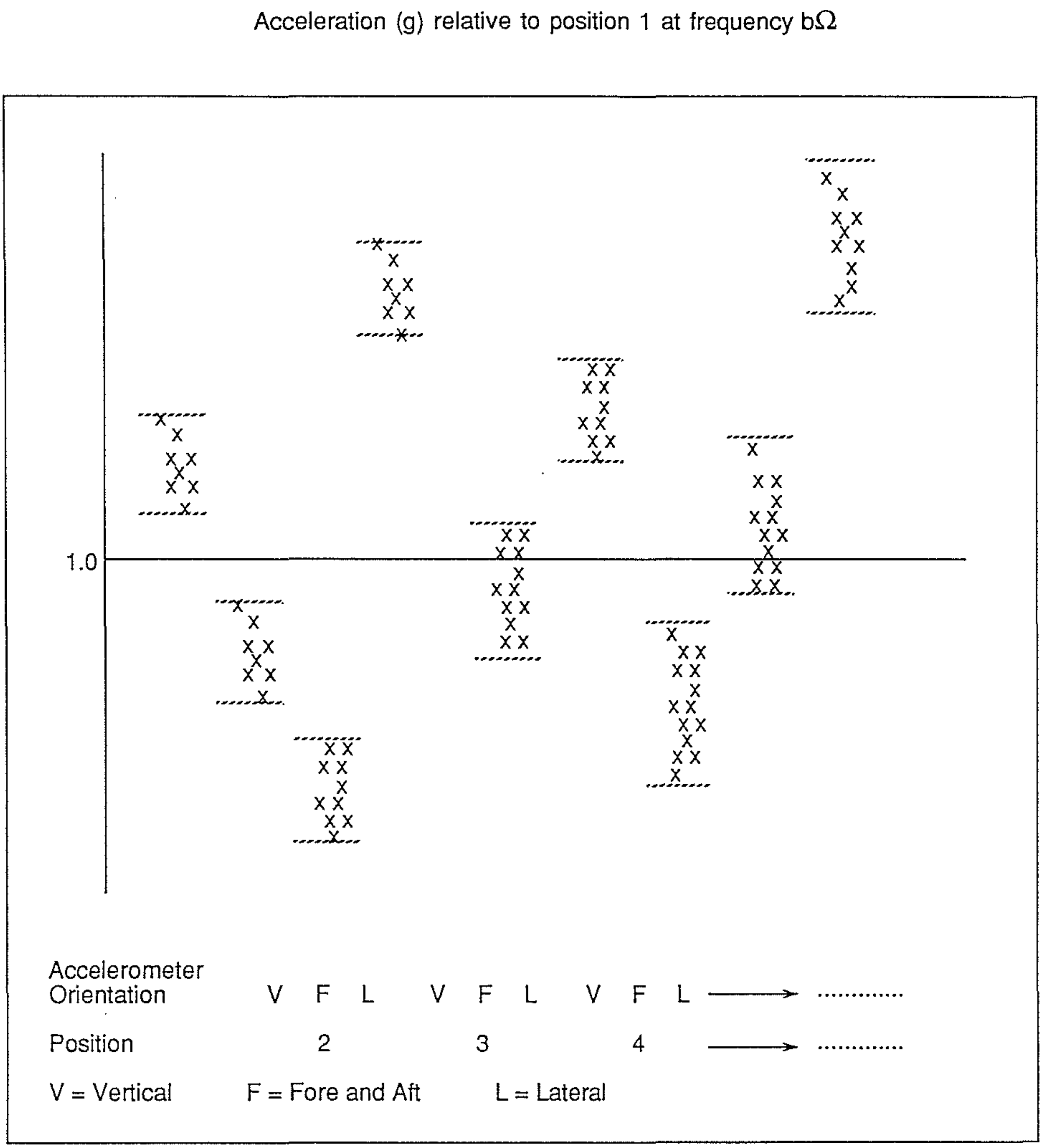

FIGURE 16 : Example of acceptable vibration amplitudes at frequency bΩ