THE UK'S HELICOPTER VIBRATION PREDICTION CAPABILITY

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ABSTRACT

Minimizing helicopter vibration at the design stage and throughout in-service life can contribute greatly to enhancing operational performance and reducing life-cycle costs. This article reviews the current UK capability for predicting the vibratory forces generated by the rotor system and the response of the helicopter structure to these forces. The article illustrates the problems that face the helicopter dynamicist in designing for minimum vibration and outlines some of the solutions available. Despite significant recent improvements, further work is required to improve both the analytical methods for predicting vibration and the experimental techniques for acquiring test data for correlation purposes.

Introduction

Rotor-induced vibration has a significant effect on the reliability of helicopter structures, components and installed equipment. The reduction of vibration levels will enhance reliability and availability and lead to reduction in Life-Cycle Costs (LCC)[1]. In addition, reduced vibration and noise will lead to enhanced operational performance by providing a better environment both for the crew members and for sensor and weapon systems.

The primary concern is with the vibration that results from the main and tail rotor vibratory forces at blade-passing frequencies and multiples thereof. This article reviews the current status and experimental validation of methods for analysing such vibrations. Sources other than the rotor system, such as vibratory forcing associated with the meshing of gears and forcing from vortices shed by the fuselage, are less relevant to overall reliability and are not covered in this review. They are relevant however to internal noise and vibration at acoustic frequencies, which are significant, for instance, to crew comfort. The techniques required to predict them are addressed in the report on the Reduction of Helicopter Interior Noise (RHINO) project[2].

Designing a helicopter with a low level of vibration requires a detailed knowledge of both the aerodynamics and dynamics of the rotor system, to enable the rotor vibratory forces to be predicted, and of the dynamics of the fuselage, to avoid resonances arising from the close proximity of the fuselage modal frequencies to the rotor forcing frequencies. Whilst simplified models can be used to examine trends, a detailed mathematical model of the helicopter is required for the accurate prediction of the levels of vibration.

Although the structure of the rotor blade is much simpler than that of the fuselage, the representation of the interaction of the aerodynamic forces and the rotor dynamics is crucial, and the interaction of a blade with the vortices shed by preceding blades must be properly represented. In addition to the lift force and moments generated by the rotor, there are unwanted vibratory forces at multiples of the rotational speed (R) in the rotating reference frame and at multiples of the rotational speed times the number of blades (n) in the fixed reference frame of the fuselage. Thus, for a four-bladed rotor, n=4, the unwanted vibratory forces will occur at 4R, 8R, 12R etc. The magnitude of the vibratory forces generally decreases for the higher harmonics. The tail rotor will also generate vibratory forces, also at multiples of the number of blades (n) and the rotational speed (T), i.e. nT, although because of its smaller size the forces will be that much smaller.

Thus the dynamics of the rotor system must be tailored to reduce the magnitude of the unwanted vibratory forces by placing the modal frequencies of the main rotor well away from the forcing frequencies of R, 2R, 3R etc. This can be achieved in the design:

Passively

By the suitable choice of structural characteristics and the addition of non-structural mass.

Actively

By the use of Higher Harmonic Control (HHC) and Individual Blade Control (IBC) systems, and smart structures technology.

In the absence of accurate predictions of the rotor vibratory forces, the dynamicist can still take steps to reduce the fuselage response by incorporating passive and/or active vibration reduction systems—for example:

- Rotor-head and fuselage mounted absorbers.
- Isolation systems (Dynamic Anti-resonance Vibration Isolator (DAVI), Nodal Beam).
- Active Control of Structural Response (ACSR) systems.

All of these systems imply a mass penalty:

- A DAVI system requires an interface between the rotor/engine/gearbox assembly and the fuselage.
- Rotor-head and fuselage-mounted absorbers introduce parasitic masses.
- An ACSR system requires hydraulic or electromagnetic actuation.

Thus it is preferable to be able to design the basic structure to have a low response by changing the structural stiffness in a local region. Successful instances of local stiffness changes applied to production aircraft are:

- The Type 8c struts on the LYNX (FIG.1), which stiffened the joint between the tail-boom and fin and reduced the vibration in the cabin.
- The struts on the EH101 bridging the gap between the number 2 engine take-off housing and the gearbox, shown shaded black in (FIG.2), which reduced the overall level of vibration in the fuselage and on the engines.

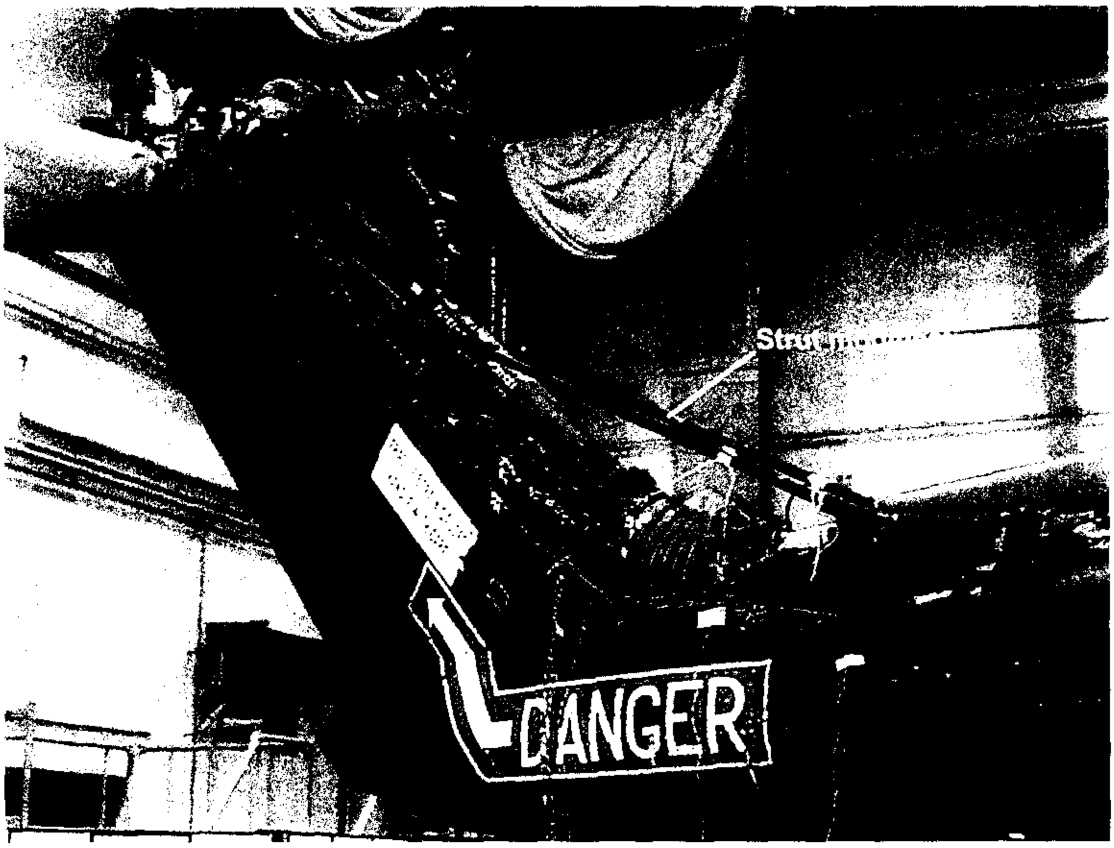


FIG.1 - LYNX TYPE 8C STRUTS

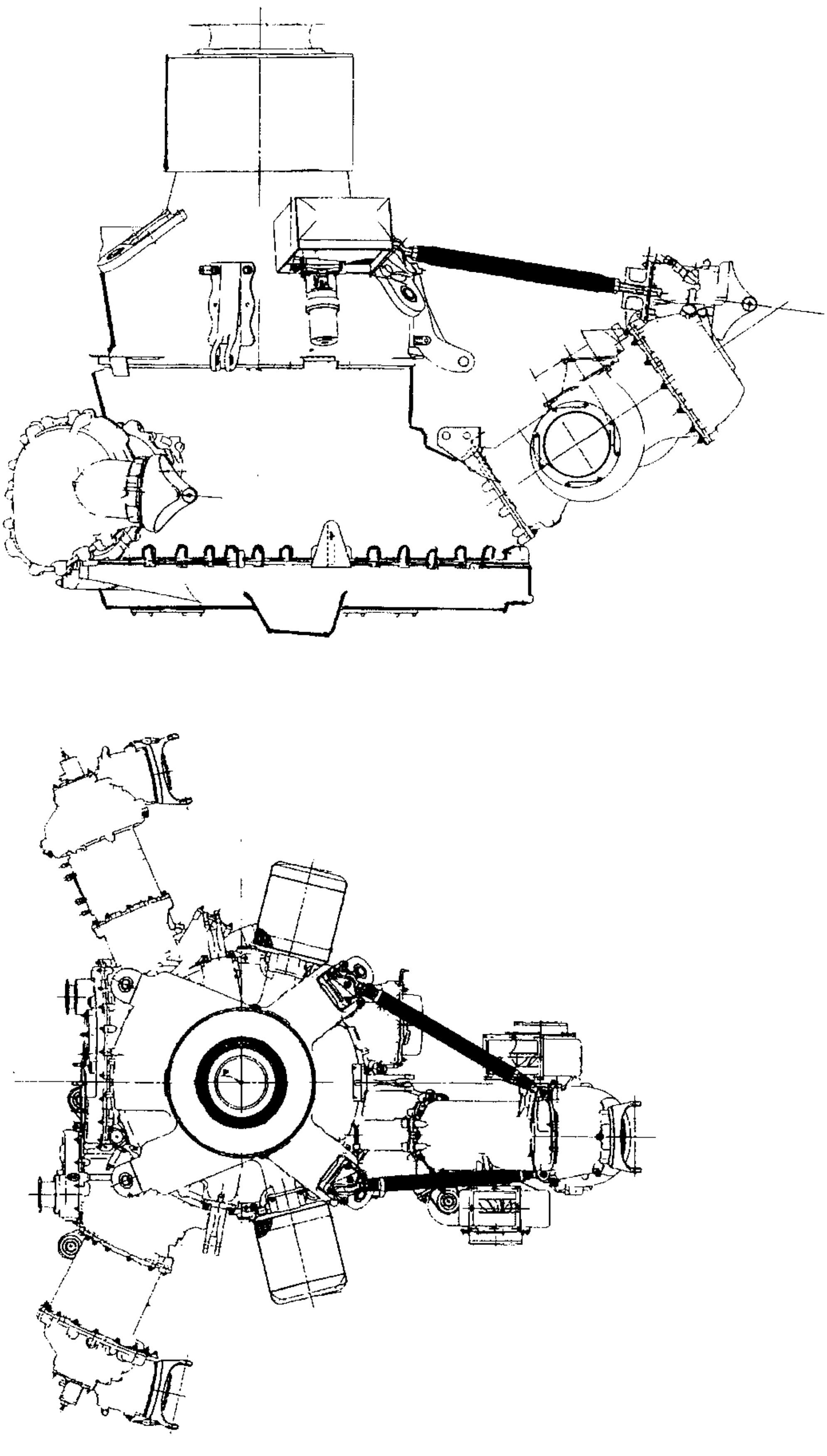


FIG.2 - EH101/MERLIN MODIFICATION - SIDE AND PLAN VIEWS OF GEARBOX

The GKN Westland Helicopters' active vibration reduction system as implemented on MERLIN (FIG.3), uses hydraulic actuators mounted in the four gearbox support struts to input suitably sized and phased forces to reduce the vibration measured at a set of control points located in the fuselage. The system controller adapts to the changing dynamics that will result from different forward speeds or changes to the payload and determines the appropriate actuator forces to reduce the level of the vibration at the control points and hence generally throughout the airframe.

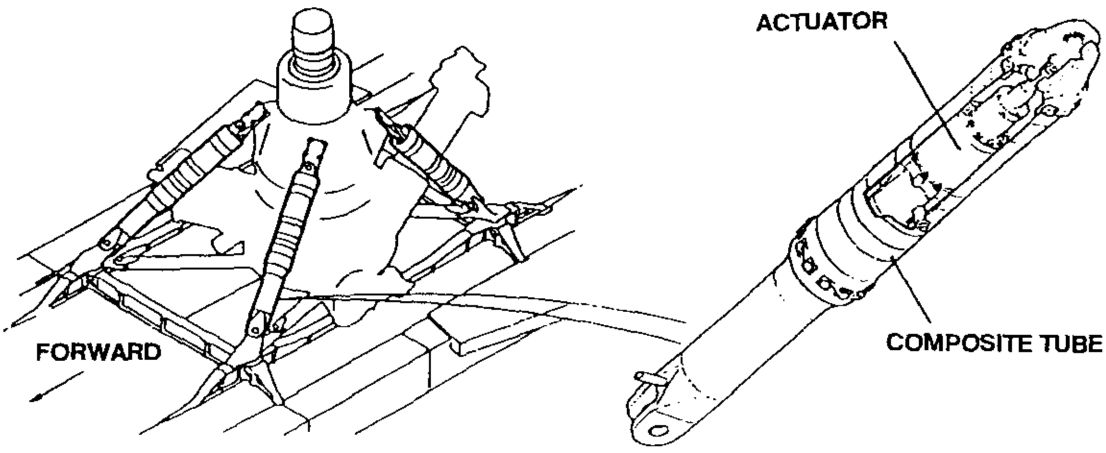


FIG.3 - EH101/MERLIN ACSR CONFIGURATION

Background

Factors affecting vibration

The dynamics of complicated structures, rotor blades and fuselages, can be represented in a very compact form using a modal representation. This approach simplifies the calculation of the vibration levels and aids the understanding of the vibration characteristics. The modal representation takes the form of a set of shapes, the displacements of a set of points distributed throughout the structure, and the mode frequencies, masses and dampings. The modal characteristics of the structure can be calculated using mathematical models or derived from tests.

The forced response of a linear structure can be calculated by summing the responses of the individual modes when excited by the modal forces (i.e., the external forces and moments transformed into modal co-ordinates). Factors that affect the level of the response are the:

(a) Magnitude and phase of the applied forces.

(b) Modal displacement of the point, or points, at which the vibratory forces are applied.

(c) Modal displacements of the points at which the response is being monitored.

(d) Closeness of the mode frequency to the forcing frequency.

One would normally expect there to be a large response from a mode that has a frequency close to the forcing frequency. However, it follows from (b) above that if the shape of the mode is such that the displacement at the point of application of the force is zero, no work is done by the external force and the modal response will be zero. This is irrespective of the frequency separation and the displacements at the monitored points. Also, from (c), if the shape of the mode is such that there is no motion at any of the monitoring points, the response at those points would be zero irrespective of the magnitude of the force and the closeness of a mode frequency to the forcing frequency. However, it must be remembered that in the latter case there will be responses at points other than those being monitored, and that these responses could adversely affect the life of the structure and any attached components.

Usually the dynamicist will not rely on the presence of modes with favourable shapes, and the structure will be designed to have mode frequencies that are well separated from the forcing frequencies.

Rotor vibratory forces

The vibratory forces that result from flying the rotor edgewise are periodic and occur, in the non-rotating system, at discrete frequencies that are multiples of the number of blades (n) and its rotational speed (R). Thus there will be fore-and-aft, lateral and vertical vibratory forces and roll, pitch and yaw vibratory moments at nR, 2nR, 3nR etc. The vibratory forces at the higher harmonics, 2nR etc., are usually at much lower levels than those at blade-passing frequency, typically by some 10-12 dB.

The vibratory forces produced by a rotor system depend on the interaction of the aerodynamic forces resulting from the rotation of the blades, combined with the movement of the aircraft through the air. The resulting periodic forces excite the modes of vibration of the rotor system, the form of which is determined by the rotor blade's:

- Structural geometry
- Stiffness
- Mass
- Damping distributions.

To reduce the magnitude of the rotor vibratory forces, it is important to separate the rotor mode frequencies from multiples of the rotor rotational speed, R; the dynamicist will design the blade to avoid frequency coalescences at the normal operating conditions of the rotor. A spoke, or Campbell, diagram showing typical variations of modal frequencies with rotor rotational speed, and the frequency coalescences that are to be avoided, at the operating speed of 600 RPM, is shown in (FIG.4). Thus, an important stage in the prediction of the rotor vibratory forces is the calculation of the rotor modes, shapes and frequencies. DERA and GKN Westland Helicopters have collaborated on analytical techniques and this has resulted in the development of the Coupled Rotor Fuselage Dynamics (CRFD) program.

Various techniques can be used to reduce the magnitude of the vibratory forces when the rotor is designed. These techniques come under the general heading of aero-elastic tailoring and can involve:

- The aerodynamic design of the rotor, in plan-form and cross-section.
- The dynamic design of the blade, stiffness and mass distributions and the coupling of blade flapping and torsion motion.
- Active systems, higher harmonic control, individual blade control
- Rotor-head mounted vibration absorbers.

Fuselage vibration

At the design stage, the dynamicist needs to be able to calculate the forced response levels that will result from the predicted rotor-head forcing. To be able to calculate the vibration with any degree of confidence, a detailed mathematical model of the fuselage is needed. This is usually derived using the finite element approach in which the mass and stiffness of the structure are represented by discrete elements connected to points that define the geometry of the fuselage. Whilst simplified models can be used to examine

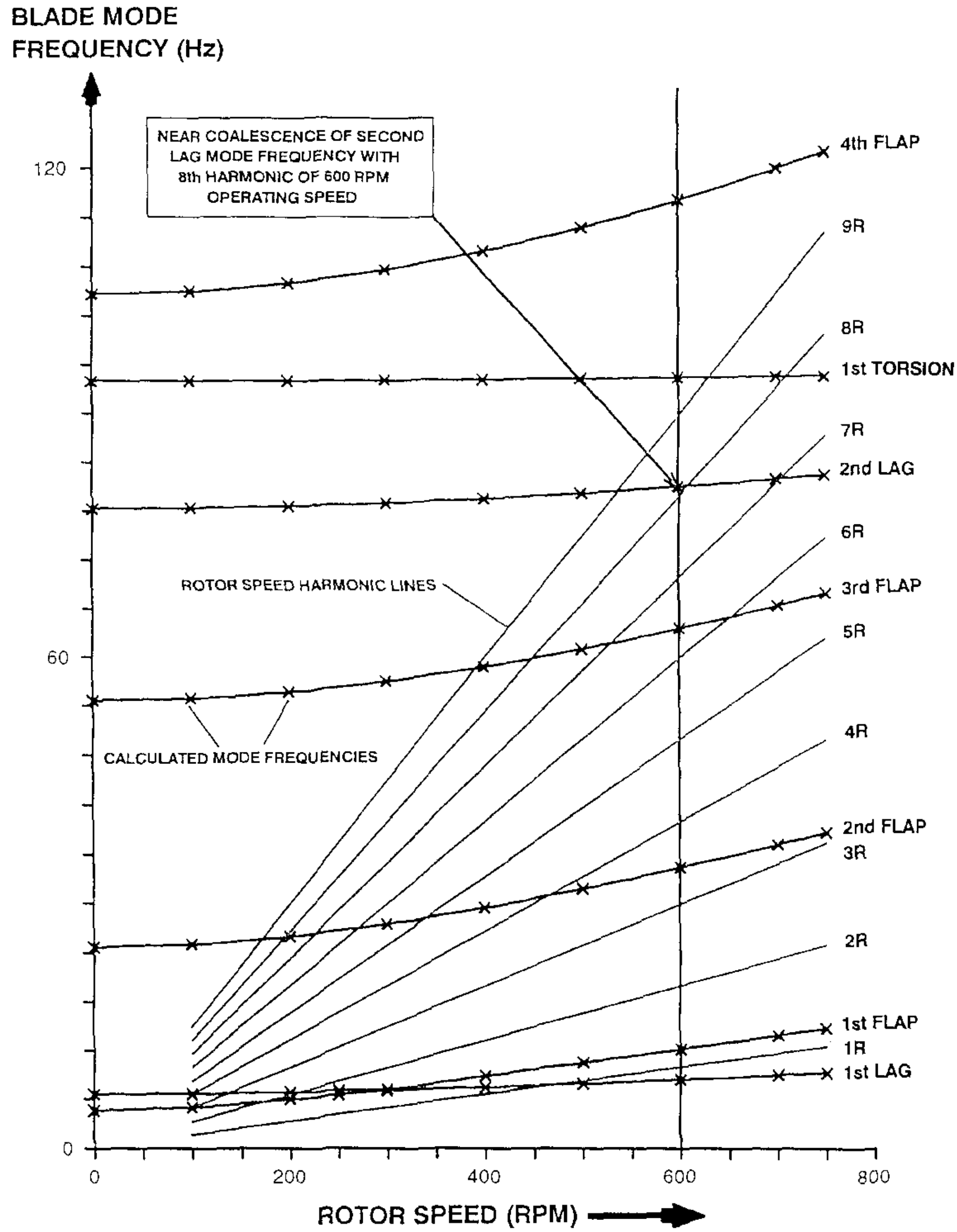


FIG.4 - CAMPBELL DIAGRAM SHOWING PLACEMENT OF ROTOR MODE FREQUENCIES

trends, a detailed model is required for the accurate prediction of the vibration levels. Sufficient detail is not available until a late stage in the design process; thus it is important that efficient techniques are available to assess quickly the vibration response and to identify beneficial changes.

To check the accuracy of the mathematical model, the basic structure is subjected to a shake test in which a representative configuration—fuselage plus gearbox and engines—is suspended by a low frequency support and its modal characteristics measured. These characteristics, modal frequencies, masses and shapes are then correlated with analysis and, ideally, the model is adjusted to match the test. In practice, the identification of modelling errors in the light of test results is extremely difficult and in the past a lot of reliance has been placed on the experience of the dynamicist. Recent developments in the techniques of model updating[4] need to be applied to large-scale models so that the procedure can be automated.

Passive approaches to vibration control fall into the three general categories of isolation systems, absorbers and structural modifications. Isolation systems and absorbers are generally effective over a narrow frequency range about some central tuned frequency, for example the blade passing frequency (nR). As the rotor speed varies from the normal operating value, the effectiveness of the vibration reduction device is reduced. For an isolation system to be fully effective, it must isolate all of the load paths between the rotor/gearbox/engine assembly and the fuselage; inevitably the incorporation of an interface between these assemblies has an associated weight penalty. Fuselage-mounted absorbers are effective in reducing the response in a local area. Passive structural modifications are difficult to identify and are usually effective over a small speed range (since they are designed for specific rotor forcings), but usually they bring a very small weight penalty. Two examples of effective structural modifications, the Type 8c struts on LYNX and the struts between the gearbox and number 2 engine take-off casing on MERLIN.

Active approaches to vibration control fall into the same three general categories as the passive systems; once again, all of the load paths between the rotor system and the fuselage must be isolated if the system is to be generally effective. The GKN Westland Helicopters' Dual Point Actuator (DPA), currently in production for MERLIN, can be considered to be an active structural modification where the Single Point Actuator (SPA) variant is an active absorber. In both the SPA and DPA systems, accelerometers are located at selected control positions in the airframe to measure the vibration. A dedicated computer-controller processes this information, calculating the optimal set of forces to reduce vibration, and provides control of the actuators that are applying the forces. With an adaptive controller, that is one that recalculates the forces as the dynamics of the aircraft change, the active system can be effective over a range of speeds and as the payload changes. The level of vibration reduction obtained does, however, depend on the identification of suitable sites for the actuators and the controlling accelerometers. Finite element models of the aircraft would be used to locate suitable positions for the actuators and control points to maximize the effectiveness of the system under changing conditions. The ACSR installation on EH101 and MERLIN uses four actuators located in the gearbox support struts and ten accelerometers distributed in the fuselage. Redundancy is present in the system, as the controller is able to adapt to failures of the actuators and/or sensors. However, the level of vibration reduction achieved with the degraded system would then be lower.

Predictive capability

Rotor vibratory forces

The current UK predictive capability has recently been assessed in a dynamics workshop on rotor vibratory loads sponsored by the American Helicopter Society Dynamics Committee.[3] The intention of the workshop was to improve the fundamental understanding and predictive capability of rotor dynamics by a comparison between vibratory hub loads predicted by a variety of advanced rotor codes and flight test data. To gain an insight into the potential benefits that could arise from the use of different levels of analytical sophistication, it was proposed to highlight and quantify improvements achieved in progressing from a relatively basic and common level of rotor modelling to 'state of the art' complexity. The work programme was defined in three phases:

(1) The correlation of baseline models.

(2) The use of upgraded analyses to a standard representative of current technology models.

(3) The use of further enhancements for improved technology models.

Eight aero-elastic computer codes were used to predict the vibration levels of a LYNX at forward speeds of 64 and 158 knots. Both DERA and GKN Westland Helicopters participated in the workshop; the names of their analysis codes and those of the other participants are shown in Table 1. Details of the baseline models and the changes made to the baseline analyses to progress to the current technology models are given in reference 3.

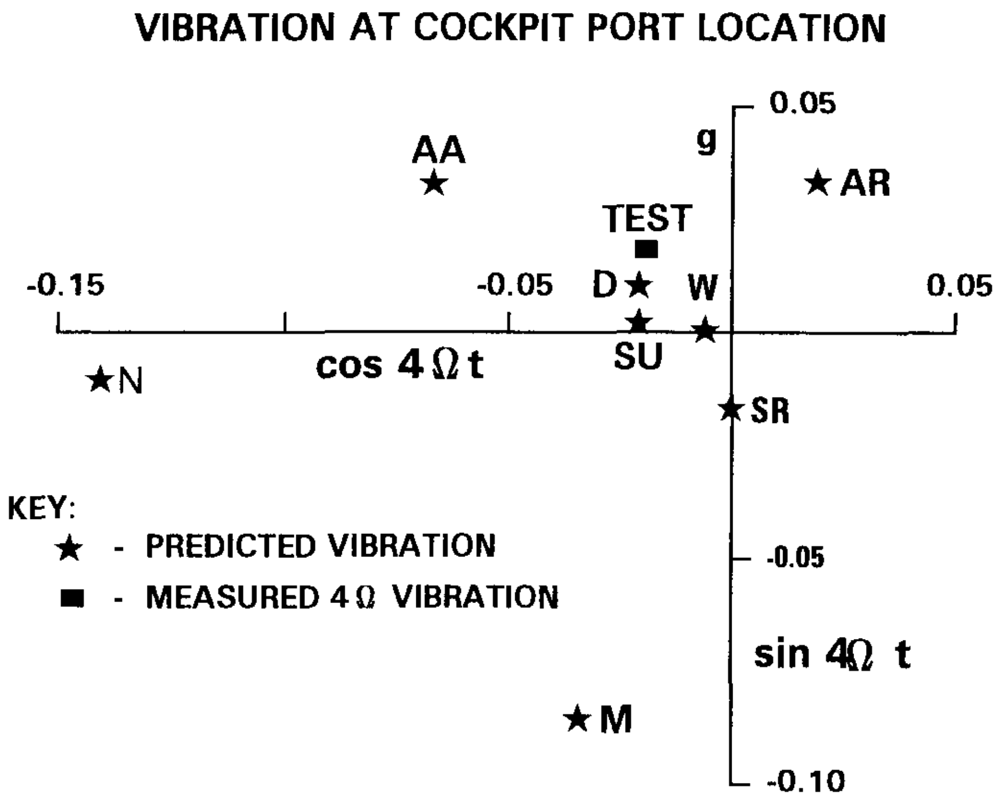
TABLE 1—WORKSHOP PARTICIPANTS AND ANALYSIS CODE USED IN FIGURES 5 AND 6

Organization	Analysis code	Abbreviation
DERA	CRFM	D
GKN Westland Helicopters	R150	W
US Army Aero Flight Dynamics	2GCHAS	AA
Advance Rotorcraft Technology Inc	Flight Lab	AR
University of Maryland	UMARC	M
US Naval Surface Warfare Centre	CAMRAD	N
Sikorsky Aircraft	RDYNE	SR
Sikorsky Aircraft	UMARC/S	SU

LYNX flight test data was used in the workshop. The configuration studied related to an aircraft weight of 4082 kg (9000 lb) with a rotor loading coefficient of Cw/σ of 0.071 and the original metal blades. As hub vibratory loads could not be measured directly on the aircraft, the GKN Westland Strain Modal Synthesis (SMS) method was used to estimate the flight loads using measurements taken on an array of blade and hub strain gauges as detailed in reference 5.

Although the features of the baseline model codes were not identical, they were sufficiently similar for the rotating blade modal frequencies to be correlated. All participants used the same structural and inertial definition of the blade and hub to calculate the *in vacuo* rotating mode frequencies at a nominal rotor speed of 326 rpm for comparison with test data derived from a spectral analysis of strain gauge measurements. The modal frequencies, predicted by the various codes and normalized with respect to the rotational speed, were within 4% of the average and agreed fairly well with test.[3]

The vibratory load predictions from the current technology models were transformed by the rigid fuselage transfer functions into vibration responses at the port and starboard sides of the cockpit for low speed and high speed conditions (64 knots and 158 knots). The acceleration response (g) at blade passing frequency (4R) for the low speed condition is shown in (FIG.5) and the high speed condition in (Fig.6), where the predictions by DERA are marked with a D and those by GKN Westland with a W.



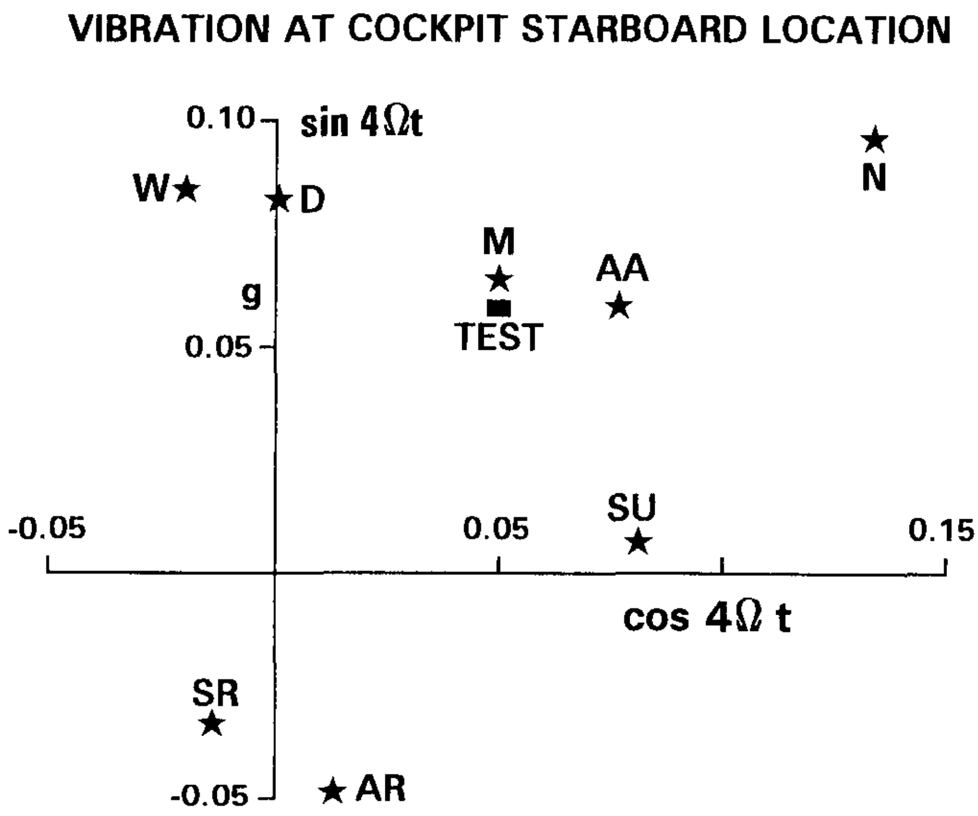


FIG.5 - COCKPIT VIBRATION AT 64 KNOTS, MEASURED AND PREDICTED USING THE CURRENT TECHNOLOGY MODELS

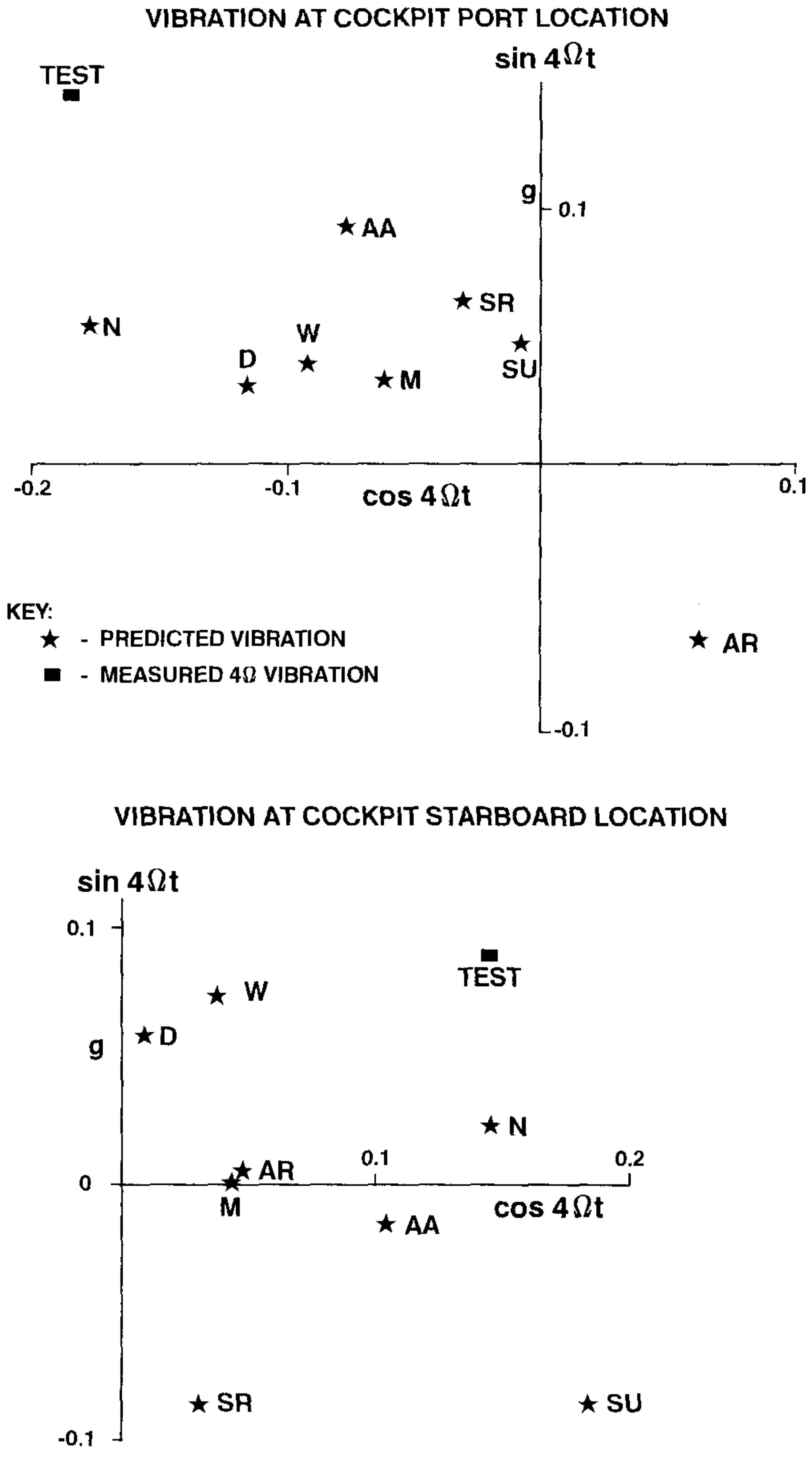


FIG.6 - COCKPIT VIBRATION AT 158 KNOTS, MEASURED AND PREDICTED USING THE CURRENT TECHNOLOGY MODELS

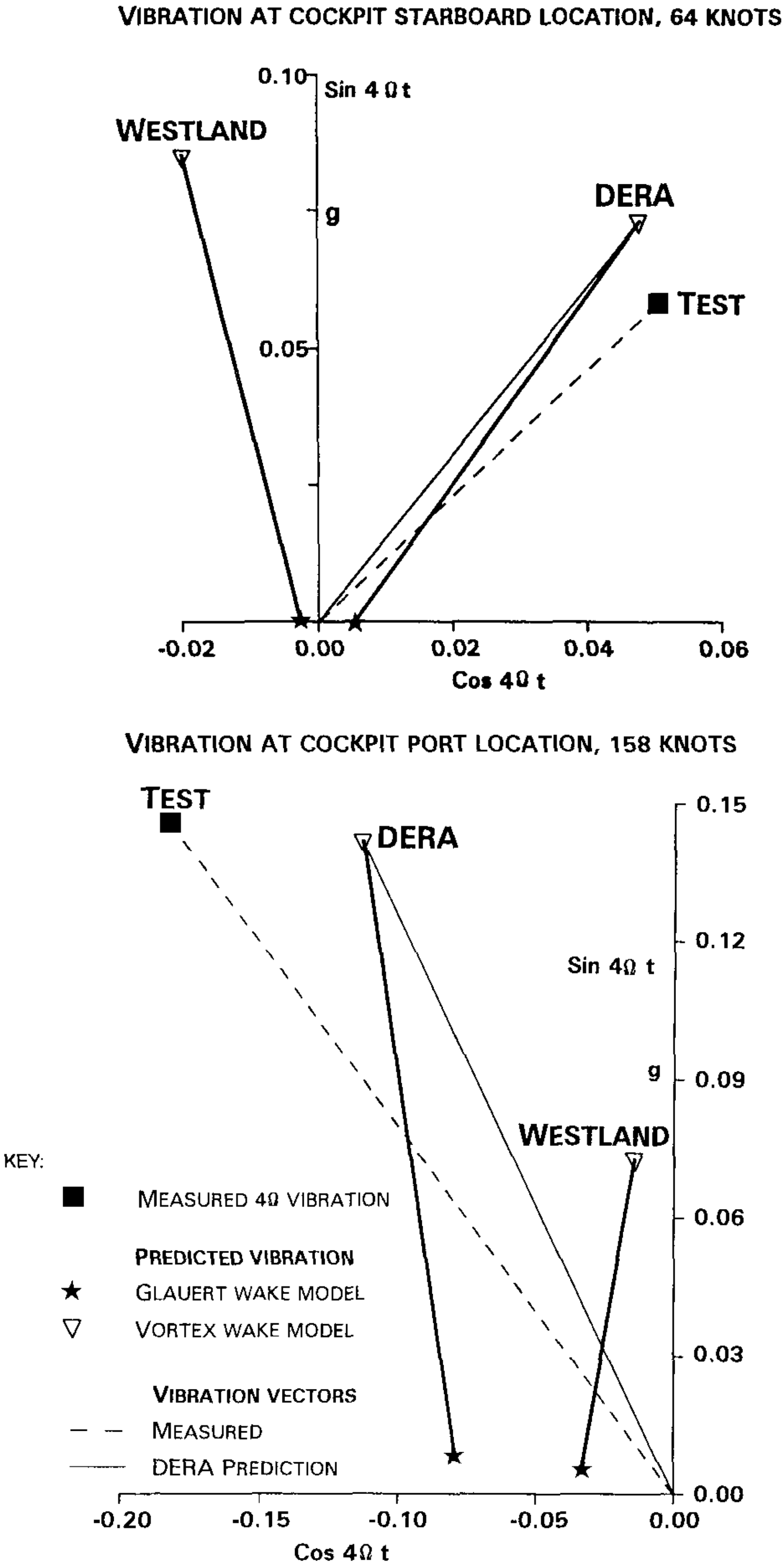


FIG.7 - CHANGES IN PREDICTED VIBRATION RESULTING FROM USE OF IMPROVED WAKE MODELS

Figures 5 and 6 show the scatter of the predictions. The DERA and GKN WHL codes predict the amplitude of the vibration reasonably well at low speed but not at all well at high speed, and the other codes perform no better. For the high-speed condition (158 knots), reference 3 shows that the average predicted vibration amplitudes are some 55% of the average cockpit level obtained from flight measurements.

Reference 3 also examines the effect of specific changes to the analyses. It concludes that the inclusion of a free wake model greatly enhances the vibration correlation and, to a lesser extent, the inclusion of fuselage models and unsteady aerodynamic theories improves the prediction of the phase of the vibratory response. The effect of changing the wake model from a Glauert momentum model to more advanced models is shown in (FIG.7). The vibration levels predicted using a Glauert wake model are shown by asterisks. The level predicted using vortex wake models is shown by a small triangle, and a line links the two values for a particular code. For the DERA (D) current technology model the Quackenbush/Soliman free wake model[6] was used. The GKN Westland code (W) was the only one not to use a free wake model, and it shows poorer correlation with test than the others, in particular in the phase of the response. The magnitude of the vibration predicted by DERA at the cockpit starboard station for 64 knots was 10% greater than test, whilst at the port station at 158 knots the vibration was 22% less than measured.

Fuselage vibration

The introduction to the final report of the GARTEUR Helicopter Action Group (AG08) on helicopter vibration prediction and methodology,[7] states:

> "A major problem area in helicopter structural dynamics is the prediction of the fuselage vibration levels. Generally, the Finite Element (FE) method is used in the design of a new helicopter to calculate the dynamic characteristics of the structure. Although the FE method has proven to be a powerful analytical tool the FE model has to be updated, using data from experimental investigations, due to the complexity of the structure.
>
> Although much progress has been achieved in the application of the FE method the accurate prediction of structural response still proves to be a difficult task. These difficulties arise in part from the fact that helicopter structures, as opposed to fixed-wing aircraft structures, are complex three-dimensional systems. The predictive methods have to cope with the following helicopter features:
>
> - The airframe is a lightweight design carrying large concentrated masses such as the gearbox and engines.
> - The airframe shell has a number of large cut-outs that significantly affect the dynamic characteristics.
> - Vibration reduction systems are often installed between the fuselage and the gearbox.
> - Vibration characteristics that can change significantly with the helicopter configuration, e.g. the carriage of stores, and with different flight conditions.
>
> The complexity of the system, i.e. the combined airframe, engines and gearbox, usually results in modes of vibration which show the participation of the whole airframe with the light-weight structure having motion of large amplitude and, just as importantly, the massive parts which may be showing small amplitude motion. The difficulty is enhanced by the lack of sufficiently detailed mass and stiffness data

early in the design. To avoid costly development delays and major design modifications it is vital that reliable predictions are available in the early stages of the design."

Both DERA and GKN Westland Helicopters participated in this action group. It was clear that our joint predictive capability of fuselage response was equal to, and in some respects better than, those of the other participants.

Currently, DERA and GKN Westland are undertaking research on a time-expired LYNX airframe, XX907, to measure the vibratory strains and accelerations at key locations in the airframe when the structure is subjected to vibratory forces. An existing finite element model of the structure is being updated and refined in those areas where the strains are being measured so that the analytical predictions can be correlated with test. The preliminary results from this study are used as the basis for this assessment of predictive capability since the databases of analytical and experimental results have been updated over the years and represent the state of our current technology.

The successful prediction of fuselage vibration depends on the availability of accurate models of both the rotor system and fuselage. Whilst the lack of accurate predicted rotor vibratory forces limits the scope of our predictive capability, it does not prevent the fuselage being designed to avoid resonances that would arise from structural modes having frequencies close to the rotor forcing.

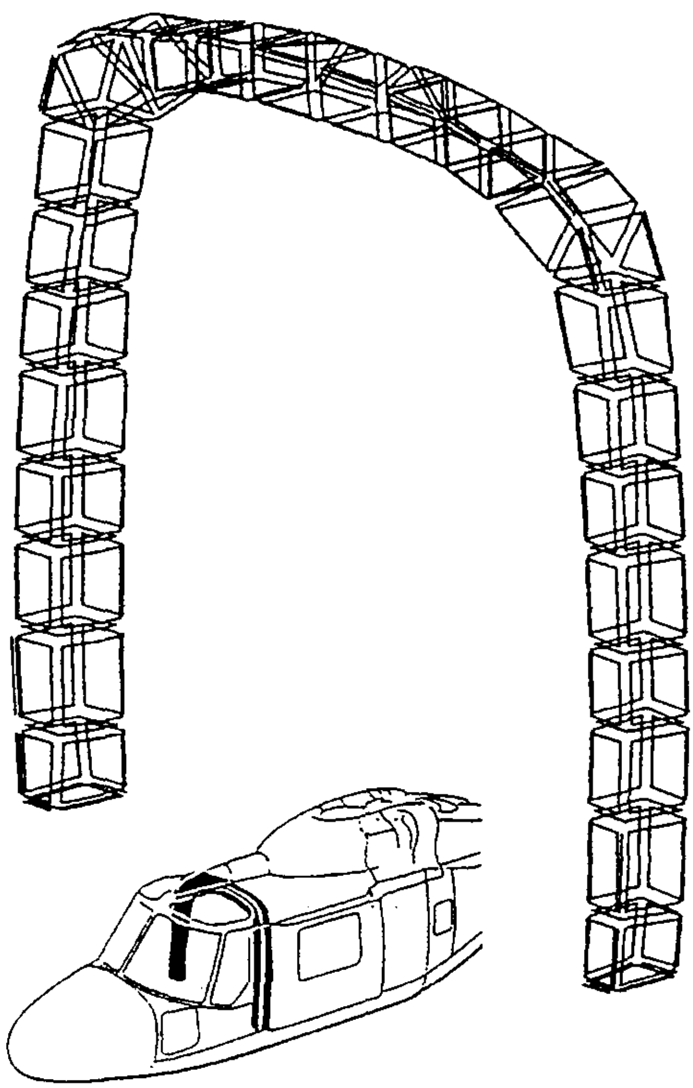


FIG.8 - FINITE ELEMENT IDEALIZATION OF LYNX FUSELAGE FRAME

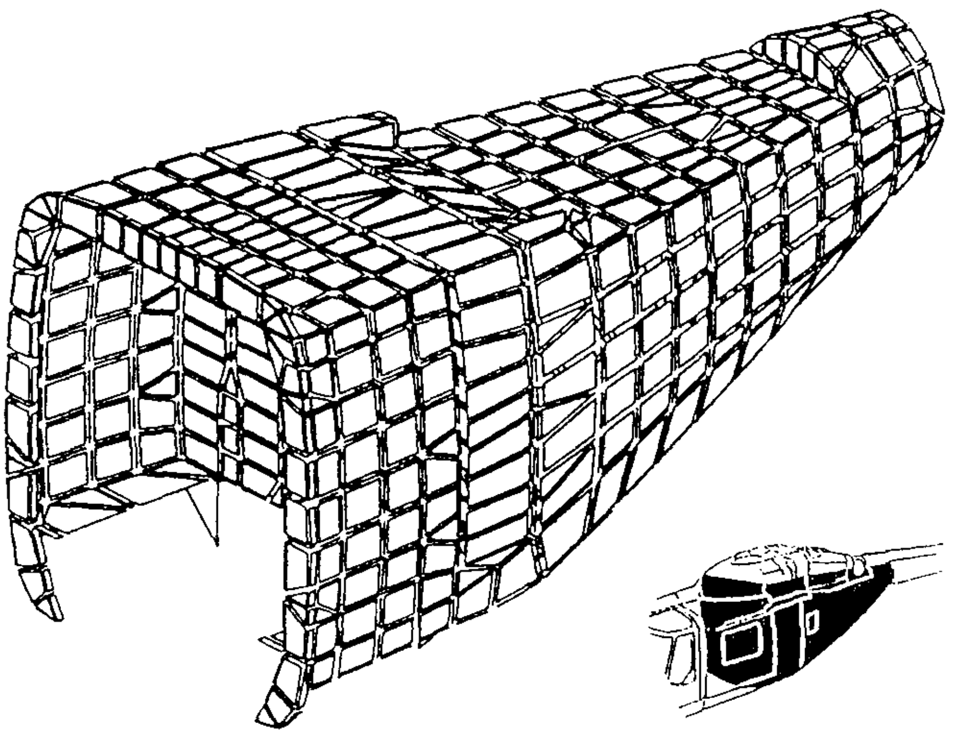


FIG.9 - FINITE ELEMENT IDEALIZATION OF LYNX REAR FUSELAGE

The finite element idealizations of typical LYNX XX907 substructures are shown in (FIGS8 to 10), together with a sketch showing the locations of the substructures in the airframe. The major task is to represent accurately the structural features that are present in the real structure without introducing too much detail in the model. Experience has shown that a model that is to be used to predict the overall modal characteristics of the helicopter can be less detailed than one that is required for the prediction of stresses.

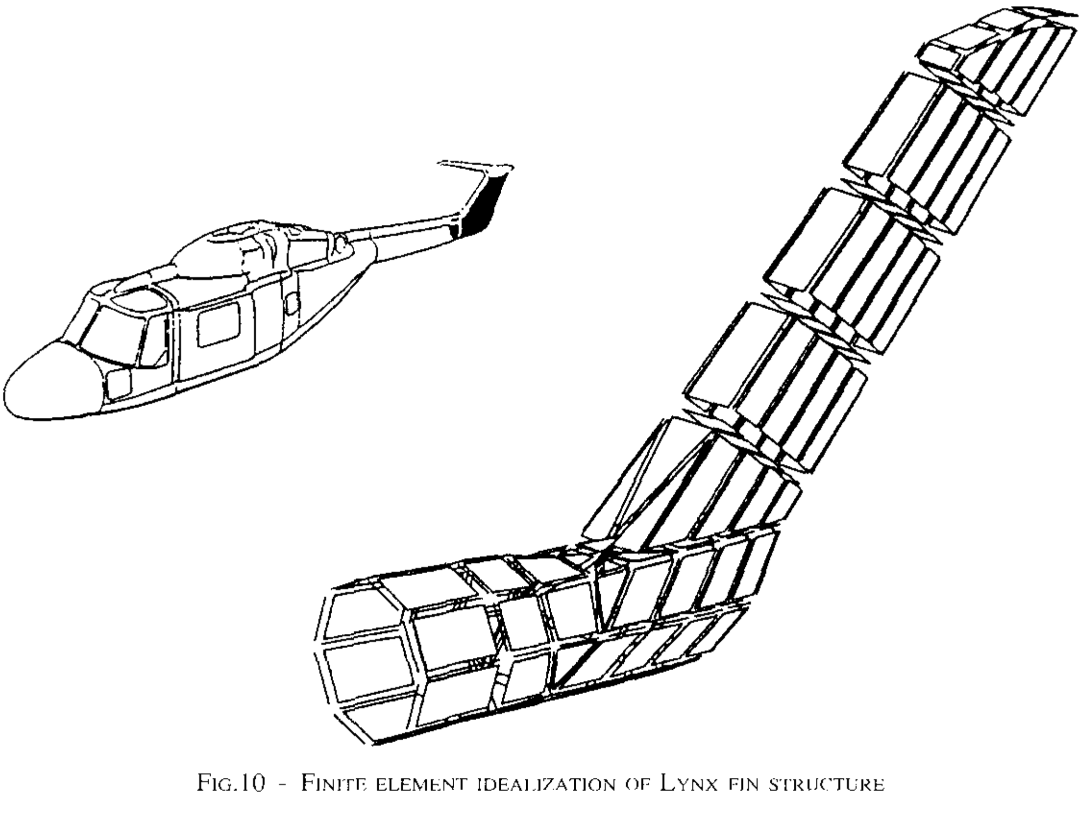


FIG.10 - FINITE ELEMENT IDEALIZATION OF LYNX FIN STRUCTURE

The complete finite element model, with the rotor system replaced by a representative dummy head, is shown in (FIG.11). This model has been analysed to calculate the modes of vibration in the frequency range 0 to 50 Hz (the blade passing frequency for the LYNX is 21.7 Hz) and these have been correlated with the INSET[8] test data from reference 9.

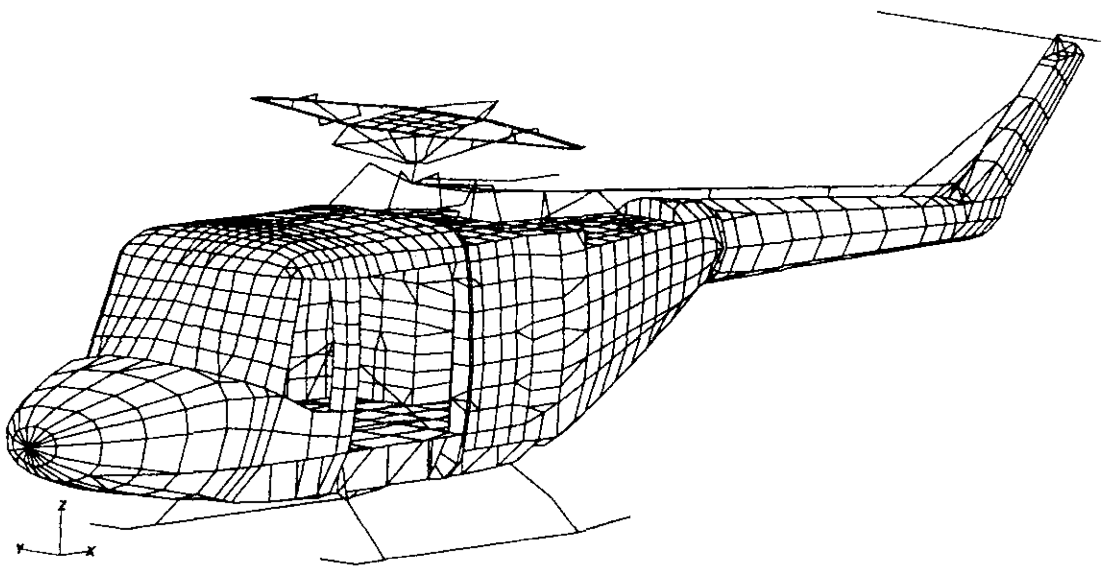


FIG.11 - FINITE ELEMENT IDEALIZATION OF LYNX XX907

The modal frequencies from test[9] and the first 14 modes from analysis are shown in table 2 together with the percentage difference in frequency for those modes whose shapes correspond. A description of the mode shape is also given. The degree of correlation of the mode shapes (test and analysis) is quantified using the Modal Assurance Criteria (MAC), and is also listed in the table. The shapes are perfectly correlated if the MAC value is 1; values greater than 0.9 would indicate a good level of correlation and values in the range 0.8 to 0.9 would require further examination.

TABLE 2—LYNX XX907 modal frequencies

Test results		FE Analysis results				
Mode No	**Mode frequency Hz**	**Mode No**	**Mode frequency Hz**	**% difference in frequency**	**Mode shape correlation coefficient MAC**	**Description of mode shape**
1	6.59	1	6.69	1.52	0.967	Fuselage lateral bending
2	6.82	2	7.33	7.48	0.942	Fuselage vertical bending
3	7.80	3	8.46	8.46	0.939	Rocking of skids on rear ball joint
4	11.98	4	12.03	0.42	0.992	Tailplane vertical bending
5	14.83	5	15.47	6.14	0.774	Fuselage 2nd vertical bending
6	17.05	6	17.21	0.94	0.840	Tailplane fore-and-aft bending
	*	7	20.43			Skids lateral—antiphase
7	21.34		*			Engines lateral—in phase
8	23.83	8	23.69	-0.59	0.890	Fuselage 2nd lateral bending
	*	9	25.26			Engines lateral/vertical—in phase
9	26.15	10	26.76	2.33	0.551 (0.840z)	Fuselage 3rd vertical bending
	*	11	26.96			Engines lateral—in phase, fuselage lateral
10	27.53	12	27.22	-1.12	0.771	Front fuselage torsion, skids vertical antiphase, skids lateral in phase
	*	13	28.94			Engines lateral—antiphase
	*	14	29.80			Engines lateral—antiphase, fuselage vertical.

Note: * indicates that a matching mode shape was not found

It is good practice to plot the modal displacements for the correlated modes on a scatter diagram, preferably separately identifying the different direction of the motion, i.e. fore-and-aft (x), lateral (y) and vertical (z). Typical examples are shown in (FIG.12), in the left hand graph, the MAC value is greater than 0.9 (mode 2), and in the right hand it is less than 0.9 (test mode 9 and analysis mode 10). It can be seen in the latter that the motions in the

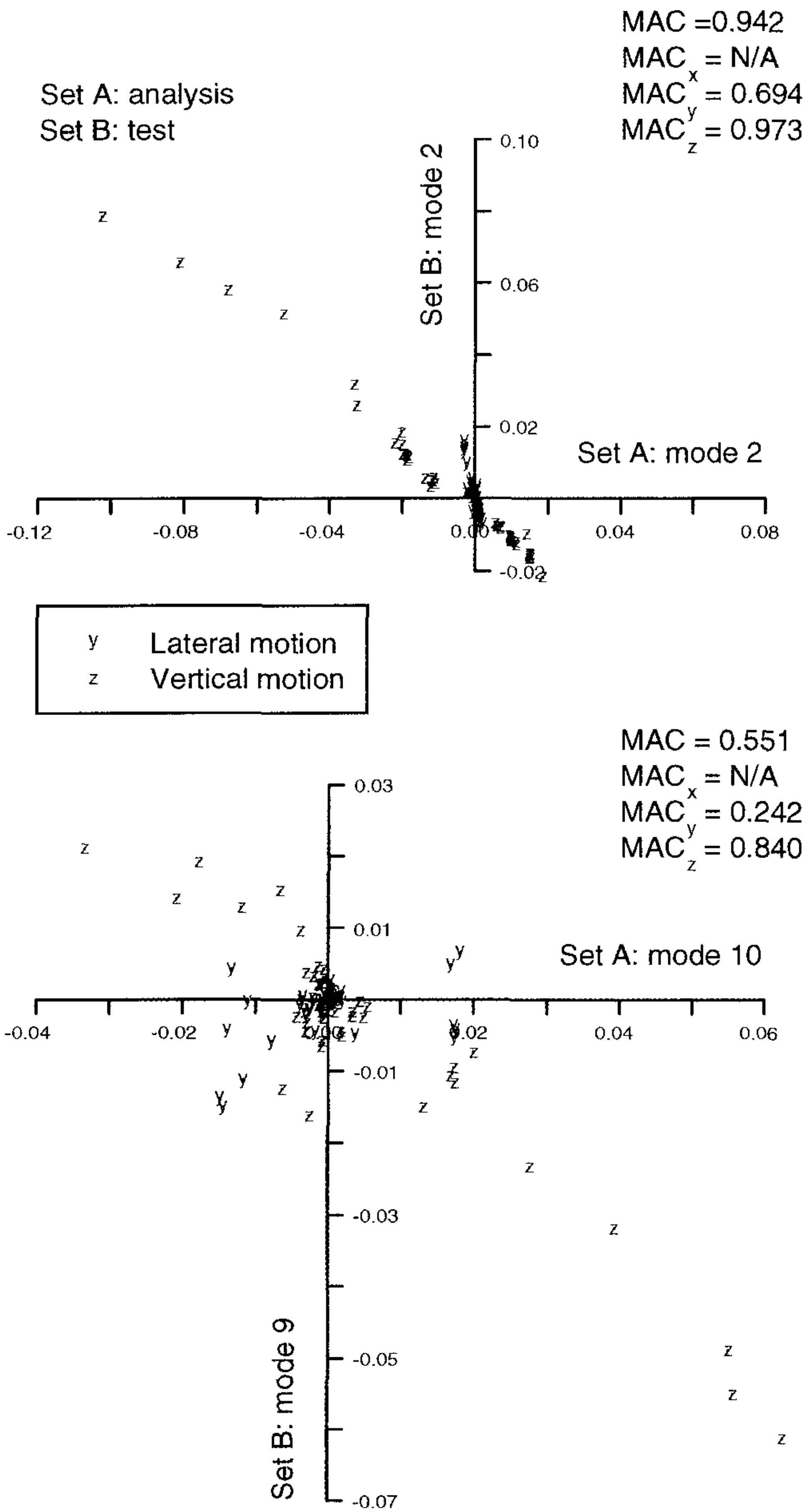


FIG.12 - MODE SHAPE CORRELATION. GRAPHICALLY USING A SCATTER PLOT AND QUANTIFIED USING THE MODAL ASSURANCE CRITERIA (MAC)

vertical direction (z) are fairly well correlated whilst those in the lateral direction (y) are not. Displacements in the fore-and-aft direction have been eliminated from the correlation, as they were not measured. If the test and analytical mode shapes were perfectly correlated, then the points would be on a single straight line. The y displacements for mode 2 are on a straight line but the slope is different from that of the z displacements. The MAC values for the individual components are also shown on the graphs and it can be seen that, for test mode 9, the displacements in the y direction are uncorrelated (MAC=0.242). If these values are ignored (they are all smaller than the z deflections, as they correspond to the third vertical bending mode of the fuselage), the correlation coefficient increases to 0.840.

Apart from mode 5, the shape correlation for the first six modes is very good, although the frequencies of the analytical modes with predominantly vertical motion are some 7% higher than test. The overall correlation in the important region of the blade-passing frequency (21.7 Hz) is poor and there is evidence that the coupling between the lateral and vertical motions is less in the analytical model than that shown in the test. It is in this frequency region that there is significant motion of the engines in the modes.

Discussion

The study conducted by the AHS dynamics workshop members on rotor vibratory loads highlighted the need for an accurate representation of the rotor wake. The study also quantified the improvements that can be obtained when the Glauert momentum model is replaced by a free-wake model. The DERA analysis using the free-wake model of Quackenbush and Soliman improved the correlation with test dramatically. The rotor frequencies predicted by DERA and GKN WHL were generally within 4% of the measured values except for the frequency of the first lag mode, which was 8.5% below that measured. The accuracy of the mode shape predictions was not quantified.

The predicted modal properties of LYNX XX907, in terms of mode frequencies and shapes, have been compared with those measured in the laboratory with the rotor replaced by a dummy head. Whilst the correlation of the shape of the first six modes is good, the frequency correlation for the vertical bending modes is disappointing. The first and second fuselage vertical bending frequencies are predicted to be 7.48% and 6.14% higher than measured. The predictions in the all important region of the blade-passing frequency (21.7 Hz for LYNX) are patchy and there is evidence that the coupling between the vertical and lateral bending motions of the fuselage are not correctly represented in the model. The 8.46% over-prediction of the frequency of the first mode of the skids could be reduced, by measuring the stiffness across the rear ball joint and adjusting the FE model, but this local mode is not important since it would not be excited by the rotor vibratory forces.

The complexity of the helicopter fuselage structure, and the need to represent the important load paths whilst keeping the model as simple as possible, have meant that the dynamicist has had to use a lot of judgement when setting up the finite element model. The increased use of computer aided design and computer aided manufacture techniques is likely to improve significantly the accuracy of the model geometry but at the expense of increasing its size.

Even at this present level of analytical capability, there is still value in producing models for current applications, albeit efforts must be continued to seek improvements in the methodology. The development of MERLIN from the pre-production EH101 aircraft has been hindered by the lack of an accurate finite element model. The dynamicists have been forced to use their engineering judgement and experience to identify modifications that, possibly, would reduce the fuselage vibration; these modifications then need to be engineered and flight tested. Various ideas were assessed by GKN WHL and DERA in the early stages of the development, but the expected reduction in vibration, when checked by flight testing, was either non-existent or much less than predicted. This failure was not all attributable to the deficiencies in the model, as some of the structural modifications were not fully effective in implementing the desired change to the structure. The same model was, however, accurate enough to determine the position and size of the ACSR active vibration reduction system, which has been so successful on the EH101/ MERLIN.

Conclusions

Although significant advances have been made in predicting rotor vibratory loads, the analytical methods have not yet been developed to the stage where they can be used with a model of the fuselage to predict with any confidence the levels of vibration that will be experienced in flight. The collaboration between DERA and GKN WHL in the generation of the coupled rotor fuselage dynamics analysis, and the developments of this code that are in hand following the AHS dynamics workshop, should result in significant improvements. However, further correlations with full-scale and model-scale tests are required to increase confidence in their use and to identify any shortcomings in the analyses. Similarly, the predicted modal properties of the fuselage, whilst showing good agreement with test for the lower order modes, need to be more accurate in the range close to the blade-passing frequency of the rotor.

Despite these shortcomings, the current analyses can still provide a valuable insight during the design and development phases into the overall vibration characteristics of a helicopter. Their application is particularly useful in assessing the sensitivity of existing designs to modifications. Failure to apply such methods will inevitably increase the risk of unsatisfactory design and consequent programme delays to find solutions by 'cut and try' methods, resulting in higher development costs and, if satisfactory solutions are not found, in an increase in vibration-related in-service problems.

Thus, the use of accurate analytical methods will be particularly important, for example in reducing the risk of unacceptable vibration characteristics resulting from changes made during the course of the in-service upgrades for MERLIN and WAH-64. Further, the enhanced methods for the prediction of rotor vibratory loads will also be central to the BERP IV technology demonstrator programme, which in turn will lead to improvements for future projects.

In summary, research into the prediction of helicopter vibration, and the associated transfer of the technology to industry, are essential to the design of aircraft with a low level of vibration and will have direct benefit in reducing life-cycle costs. Without research in this area, in-service problems will continue to occur and lead to reduced operational effectiveness through restrictions on the flight envelope and to unscheduled maintenance. The transfer of the results of the research will also be relevant to prime contract purchases of equipment and to off-the-shelf buys.

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