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SENSOR LOCATIONS AND ACTIVE VIBRATION CONTROL IN HELICOPTERS

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Abstract: Vibration control has always been a challenging problem to the helicopter designer. This paper addresses the problem on the formulation and solution of an active vibration control scheme in helicopters, based on the concept of Active Control of Structural Response (ACSR). First, using a mathematical procedure employing Fisher Information Matrix, optimum sensor locations have been identified in a three dimensional model of a flexible fuselage structure. It is observed that irrespective of the excitation frequency, these optimally selected sensor locations experience relatively high levels of vibration. Then, using the measurement from these optimal sensor locations, a Multi-Input-Multi-Output (MIMO) control problem has been formulated and solved to obtain the active control forces required for vibration minimisation in the helicopter fuselage.

Nomenclature

[A], [B], [C]	System matrix, control matrix and output matrix respectively
C_i, C^i	Damping of the i-th gearbox mounting
$[C]_s$	Output matrix defined for preselected sensor locations
E	Idempotent matrix
$\{F_{Hx}, F_{Hy}, F_{Hz}\}$	Hub shears in the nonrotating hub fixed coordinate system
$\{F\}, \{f\}$	Forcing function vector
F^i	Force at the i-th gearbox mounting
${F_s}^i, {F_D}^i, {F_c}^i$	Spring, damper and control force at i-th gearbox mounting
$\{I_{xx}, I_{yy}, I_{zz},\}_{GB}$	Mass moment of inertia of gearbox
$\{I_{xx}, I_{yy}, I_{zz},\}_F$	Mass moment of inertia of fuselage
K_i, K^i	Stiffness of the i-th gearbox mounting
M_A	Number of available sensors
M_L	Initial number of candidate sensor locations
$\{M_{Hx}, M_{Hy}, M_{Hz}\}$	Hub moments in the hub fixed nonrotating coordinate system
$[M]_F, [C]_F, [K]_F$	Mass, damping and stiffness matrices of fuselage in finite elment domain
$[\bar{M}], [\bar{C}], [\bar{K}]$	Modal mass, damping and stiffness matrices respectively
m_B	Rotor blade mass
m_F	Mass of fuselage
m_{GB}	Mass of gearbox
NB	Number of blades in the rotor system
Nm	Number of flexible modes of the fuselage
$\{Q\}_F$	Generalised force vector
$\{q\}$	State vector consisting of degrees of freedom of gearbox and fuselage modes
R	Rotor radius
$\{R_{Hx}, R_{Hy}, R_{Hz}\}$	Perturbational translation of the hub
$\{x\}$	Vector of nodal degrees of freedom
$\{U\}$	Control force vector
$\{y\}$, $\{Y\}$	Output vector
$\{Y_s\}$	Vibratory response at preselected sensor locations
β_F	Structural damping coefficient
$\{\eta\}$	Modal coordinate vector
$\{\hat{\eta}\}$	Estimate of the states of the system
$[\Phi_s]$	Modal matrix corresponding to initial set of candidate sensor locations
$\{\Theta_{Hx}, \Theta_{Hy}, \Theta_{Hz}\}$	Angular displacement of the hub
Ω	Rotor angular velocity
$\{\ \}_{GB}$, $[\ ]_{GB}$	Quantities corresponding to gearbox
$\{\ \}_F$, $[\ ]_F$	Quantities corresponding to fuselage

1 Introduction

The periodic loads of the rotor systems cause vibration in helicopters. With increasing demand for high speed and high performance helicopters, vibration control has become an important objective in the design of modern helicopters. References 1-3 provide excellent review of helicopter vibration and its control. Over the years, the vibratory levels in the fuselage of the helicopters have been reduced by using passive vibration control devices and/ or by suitable structural design. For present day helicopters, the general requirement is to have a maximum vibratory level of 0.1g in the fuselage. However, in future, with the adoption of stringent vibration control, it will become necessary to reduce the vibratory levels below 0.05g or even 0.02g (Ref.4).

Vibration reuction schemes adopted in helicopters can be classified as passive or active control methodologies. The passive control scheme includes hub or blade mounted pendulum absorbers, anti-resonant vibration isolation devices, like DAVI, ARIS, LIVE, structural modifications and structural optimisation. Active control methodologies include Higher Harmonic Control (HHC) , Individual Blade Control (IBC), Active Flap Control (AFC) and Active Control of Structural Response (ACSR). It is important to note that while HHC, IBC and AFC control schemes are provided in the rotating frame, ACSR is employed in the nonrotating frame.

The concept of ACSR scheme is based on the principle of superposition of two independent responses of a linear system such that the total response is zero. In the case of helicopters, the fuselage is excited by the application of controlled external actuators at selected locations such that the total response of the fuselage due to rotor loads and the external actuator forces is a minimum (Refs.5-10). A schematic of the helicopter system with ACSR scheme is shown in Fig.1. The rotor loads ($F_{HX}, F_{HY}, F_{HZ}, M_{HX}, M_{HY}, M_{HZ}$) are transmitted to the fuselage through the gearbox support structure. The support structure is idealised as a spring, damper mechanism and a control force generator. In passive scheme, the control force generator corresponds to a vibration absorber mass (as in ARIS), whereas in the case of ACSR, the control force generator is an active electro-hydraulic force actuator. Preliminary studies based on extensive ground and flight tests have shown promising results in reducing vibration in helicopters. The major advantages of ACSR scheme are: (i) less power requirements, (ii) minimal airworthiness requirements because this scheme is independent of the primary flight control systems, and (iii) selectively minimise vibratory levels at any set of chosen locations in the fuselage.

A key aspect of vibration control is the measurement of vibration. In general, the vibratory levels are measured at tail boom/tail rotor transmission, cockpit instrument mountings, cabin floor and pilot location (Refs.8-10). Even though, these locations may be sensitive, in the light of recent developments (Refs.11-13) on the optimal placement of sensors for system identification, an interesting question arises:*i.e., whether the measurement of vibration at the above mentioned locations truly represents the vibratory levels in the structure or not. In other words, whether the control of vibration at some selected sensitive points in the structure truly corresponds to a reduction of vibration in the whole structure or not.* A review on the sensor placement in distributed parameter(continuous) systems can be found in Ref.14. It is pointed out in Ref.13 that the measurement locations play a major role on the quality of measurement and in some situation modes may be completely missed. For a simple one dimensional structure, the measurement locations can be selected based on experience, but for complicated three dimensional structures the choice is very difficult. Therefore there is need for systematic approach based on mathematical principles to arrive at the optimal sensor locations. In Ref.11, Kammer has described a suboptimal procedure for identifying the sensor locations in large structures for the measurement of frequencies and mode shapes which can be compared with FEM results for correlation studies. This procedure is based on using Fisher Information Matrix and Effective Independence Distribution Vector (EIDV) to eliminate sequentially the redundant sensor locations from an initial set of many candidate sensor locations. In Ref.12, this approach was slightly modified, by considering the controllability and observability matrices of the system, to identify the actuator/sensor placement in a truss structure for modal parameter (natural frequency and mode shape) identification. A comparative analysis of EIDV method and Guyan reduction approach is presented in Ref.13. The comparative study was based on identifying the sensor locations for modal testing of one-dimensional beams and two-dimensional plates. The application of EIDV approach for active control of vibrations in helicopters will be highly useful from the point of view of practical considerations.

The main objectives of the present study are:

- Identification of optimal sensor locations for measurement of vibration in a 3-D finite element model of a helicopter fuselage for active control studies.
- Analysis of vibratory levels observed at the optimally selected sensor locations.
- Formulation of an open-loop control scheme for vibration minimisation, using ACSR scheme.
- Analyse the effectiveness of vibration control using the measurements from optimally placed sensors, in comparison to the control of vi-

bration using measurements from arbitrarily placed sensor locations.

Note: In this paper, the terminology "optimal sensor locations" essentially implies "a suboptimal set of sensor locations".

2 Mathematical Formulation

The mathematical formulation consists of three parts. They are: (i) description of the method for the selection of sensor locations for vibration measurement, (ii) equations of motion of the rotor-gearbox-fuselage system and (iii) formulation of the control scheme. A brief description of these three items, is provided below. The details of the derivation can be found in Ref. 15.

2.1 Mathematical scheme for the selection of sensor locations

The equations of motion of a flexible structure in finite element domain can be written as

$$[M]_F\{\ddot{x}\} + [C]_F\{\dot{x}\} + [K]_F\{x\} = \{F\} \quad (1)$$

Considering the first Nm undamped modes, the modal transformation relation can be written as

$$\{x\} = [\Phi]\{\eta\} \quad (2)$$

Substituting Eq.(2) in Eq.(1) and premultiplying by $[\Phi]^T$, the equations of motion in modal space can be written as

$$[\bar{M}]\{\ddot{\eta}\} + [\bar{C}]\{\dot{\eta}\} + [\bar{K}]\{\eta\} = \{Q\}_F \quad (3)$$

where $[\bar{M}], [\bar{C}], [\bar{K}]$ have a dimension of $Nm \times Nm$ and $\{\eta\}$, $\{Q\}_F$ are vectors of size $Nm \times 1$.

Assuming harmonic input excitation $\{F\} = \{\bar{F}\}e^{i\omega t}$ where ω is a constant, the steady state displacement at any point on the structure can be expressed as

$$\{y\} = [\Phi_s]\{\eta\} \quad (4)$$

where the dimension of $\{y\}$ is $M_L \times 1$ and M_L represents the initial number of candidate sensor locations. Φ_s represents the modal matrix corresponding to the initial set of candidate sensor locations.

To start with, it is assumed that the initial number of candidate sensor locations is greater than the number of modal co-ordinates (*i.e.*,$M_L > Nm$). In state feed back control, an estimate of the states of the system is required and the best estimate can be obtained from the following equations.

$$\{\hat{\eta}\} = \underbrace{[{\Phi_s}^T\Phi_s]^{-1}{\Phi_s}^T}\{y\} \quad (5)$$

The underbraced term in Eq.(5) is denoted as Moore-Penrose inverse or pseudo-inverse (Ref.16) of Φ_s. Since the dimension of Φ_s is $(M_L \times Nm)$ and $M_L > Nm$, the rank of Φ_s is equal to Nm which is same as the number of modal co-ordinates. Hence, there are (M_L - Nm) rows in Φ_s which are linearly dependent on the remaining Nm rows. Physically, it means that there are (M_L - Nm) additional sensors providing redundant information about the Nm modal coordinates. From the point of view of reachability of certain locations and also due to the cost of sensors, it is not possible to have sensors at all locations. Generally, the number of available sensors (M_A) is less than the number of initial candidate measurement locations and it can be greater than or equal to the number of modes (*i.e.*, $Nm \leq M_A < M_L$). The aim is to eliminate those sensors which provide redundant information about the system response. In Eq.(5), the symmetric matrix $[{\Phi_s}^T\Phi_s]$ is denoted as *Fisher Information Matrix.* Premultiplying Eq.(5) by Φ_s yields

$$\Phi_s\{\hat{\eta}\} = \underbrace{\Phi_s[{\Phi_s}^T\Phi_s]^{-1}{\Phi_s}^T}\{y\} = \{\hat{y}\} \quad (6)$$

If Φ_s is a non-singular square matrix, then the underbraced term in Eq.(6) will be a unit matrix. For a general case, let the underbraced term in Eq.(6) be denoted by the symbol E.

$$E = \Phi_s[{\Phi_s}^T\Phi_s]^{-1}{\Phi_s}^T \quad (7)$$

Matrix E is an *idempotent* matrix *i.e.*, $E = E^2$ and its eigenvalues are either 0 or 1. In addition, the trace of the *idempotent* matrix E is equal to its rank (Ref.16). Hence, the diagonal elements of E represent the fractional contribution to the rank of E and the smallest diagonal element (say, E_{ii}) contributes the least to the rank of E. Since the rank of E is equal to the rank of Φ_s, the i-th row of Φ_s contributes the least to the rank of Φ_s. Therfore, the i-th row of Φ_s can be eliminated without influencing its rank. After eliminating the i-th row, the modified Φ_s having a reduced size is used to compute the new E matrix and the process of elimination is repeated. This procedure is carried out sequentially until the number of rows of Φ_s is equal to the number of available sensors M_A. The vector formed by the diagonal elements of E is denoted as the *Effective Independence Distribution Vector* (EIDV).

Since the inverse of *Fisher Information Matrix* is required to estimate the modal vector, (Eq.5), it is important to monitor its Condition Number at every iteration. If there is a drastic increase in the condition number, then the elimination process has to be terminated. It may be noted that the condition number of a square matrix represents the sensitivity of its inverse to very small changes in the elements of the matrix (Ref.17).

In every iteration, one can eliminate either one row (one sensor) or a group of rows (group of sensors) whose corresponding diagonal elements (E_{ii}) are very small in comparison to other diagonal elements. In identifying the optimal sensor locations, the advantage of group elimination is that it requires less number of iterations as compared to single elimination. However, the disadvantage will be that there is a likelihood of increasing the condition number of the Fisher Information Matrix. This important conclusion has been brought out in Ref.18, while addressing the problem of the effectiveness of the selection procedure for optimal sensor locations, i.e., single elimination *vs* group elimination. In addition, Ref.18 also addresses the problems on the sensitivity of sensor locations to structural modifications and the effects of sensor failure on the quality of measurement.

2.2 Equations of motion

For the purpose of application of optimal sensor locations to vibration reduction problems, the coupled rotor-gearbox- fuselage dynamic model was simplified. The simplified model, shown in Fig. 2, consists of a gearbox supported on the top of the fuselage at four locations. The rotor blade dynamics is not included. However, the vibratory hub loads are assumed to be acting at the top of the gearbox, simulating a ground test condition. The gearbox support is idealised as a spring, a viscous damper and an active control force generator for vibration minimisation. Several simplifying assumption have been made in formulating the equations.

2.2.1 Assumptions

1. The gearbox is assumed to be rigid and undergoes vertical translation, pitch and roll motions.

2. The fuselage is assumed to be undergoing rigid body vertical translation , pitch and roll motions, as well as flexible deformation due to elastic modes.

3. The gearbox supports are assumed to be uniaxial members providing forces, only in the z-direction.

4. The centre of mass of the gearbox is assumed to be above the centre of mass of fuselage on same vertical axis.

5. The rigid body rotational motions of the gearbox and fuselage are assumed to be small. Hence, the nonlinear terms involving products of rotational degrees of freedom have been neglected.

6. The products of inertia of the gearbox and the fuselage are assumed to be zero.

2.2.2 Equations of motion of coupled gearbox-fuselage system

The equations of motion of the coupled gearbox-fuselage system can be written in three sets. Set I describes the rigid body equations of motion of the gearbox; Set II presents the rigid body equations of motion of the fuselage and Set III represents the equations of motion of the elastic modes of the fuselage. The details of the equations are given in Ref. 15.

3 Vibration Control

During forward flight, the predominant frequency of the periodic hub loads is NB/rev, where NB is the number of blades in the rotor system. These vibratory loads excite the fuselage structure. The vibratory levels in the fuselage are measured by a set of sensors placed at selective locations. Using the measurements from the sensors, an open-loop (Multi-Input-Multi-Output) control scheme is formulated to minimise the vibration in the fuselage.

3.1 Open-loop control formulation for vibration reduction

The equations of motion of the gearbox-fuselage model are coupled ordinary differential equations, having an harmonic input representing NB/rev hub loads. These equations can be written in state space form as

$$\{\ \dot{q}\ \} = [\,A\,]\{q\} + [\,B\,]\{U\} + \{f\} \tag{8}$$

The details of system matrices [A] and [B] are given in Ref. 15. The output vector representing the response of the structure can be represented by

$$\{Y\} = [C]\{q\} \tag{9}$$

For harmonic input $\{f\} = \{\bar{f}\}e^{i\omega t}$, the steady state response can be written as,

$$\{q\} = [A - i\omega I]^{-1}[B]\{U\} + [A - i\omega I]^{-1}\{f\} \tag{10}$$

Using Eq.(9), the vibratory response measured at pre-selected sensor locations can be written as

$$\{Y_s\} \ = \ [C]_s\{q\}$$

$$
\begin{aligned}
&= [C]_s[A - i\omega I]^{-1}[[B]\{U\} + \{f\}] \\
&= [T]\{U\} + \{b\} \qquad (11)
\end{aligned}
$$

where,

$$
\begin{aligned}
[T] &= [C]_s[A - i\omega I]^{-1}[B] \\
\{b\} &= [C]_s[A - i\omega I]^{-1}\{f\}
\end{aligned}
$$

Formulating a minimization problem as

$$min\ J = \{Y\}^T{}_s\,\{Y\}_s \qquad \text{w.r.t } \{U\} \qquad (12)$$

The best estimate of the control vector minimizing the performance index J can be written as

$$\hat{U} = -[T^T T]^{-1} T^T b \qquad (13)$$

Substituting $\{\hat{U}\}$ from Eq.(13), in Eq.(10) and using Eq.(9), the controlled vibratory response at any location in the coupled gearbox-fuselage system can be obtained. It is important to note that the control force vector $\{\hat{U}\}$ is estimated using the vibratory response at only certain preselected locations in the system. For example, these preselected locations could be the optimally identified locations or they could represent any set of arbitrary locations.

4 Results and Discussion

Using the dynamic model of the coupled gearbox-flexible fuselage system, several studies were pèrformed. The results of these studies are presented in three sections. First section describes the results pertaining to the choice of sensor locations for vibration measurement. A study on the validity of these optimal sensor locations is presented in the second section. The results on vibration control are presented in the third section.

4.1 Choice of sensor locations for vibration measurement

Figure 3 shows a finite element model of a helicopter fuselage. The length of the helicopter model is 8.25m, the height is 2m, and the width is 3m. The fuselage is 4m long, having a width of 2.5m and a height of 1.5m. The tail boom is 4.25m in length, with a horizontal stabilizer having a span of 3m attached near the end. In addition, lumped masses representing two engines, tail gearbox and two end plates are also attached to the structure at appropriate nodes. Total number of nodes and the degrees of freedom of the finite element model are 64 and 384 respectively. The details of the structural properties, node locations and other data are given in Ref.19. It was shown in Ref.19 that the undamped natural frequencies and mode shapes of this model are similar to those of a realistic helicopter.

Assuming that the main rotor system consists of four blades, the vibratory hub loads will have a nondimensional excitation frequency of 4/rev. For the fuselage model, the nondimensional natural frequency of the 20-th flexible mode is 6.41 (Ref.19) which is 50% more than the excitation frequency (4/rev) of the hub loads. Therefore, the first 20 modes of the helicopter fuselage are considered in the vibration analysis.

Considering three rigid body modes (heave, pitch and roll) and the first 20 modes of the fuselage (Nm=20), the modal matrix Φ_s is formulated. Since the vibratory level in the vertical (z) direction is more predominant, without loss of generality, it is assumed that the sensors measure only the z-component of the fuselage vibration. Therefore, in the formulation of Φ_s, the modal displacement in the z-direction only is considered. Initially it is assumed that all the 64 nodes are the candidate sensor locations (i.e., M_L= 64). Employing the procedure described in Sec. 2.1, the redundant sensor locations were eliminated one at each iteration. The final set of 23 optimal sensor locations is indicated by node numbers in Fig. 4.

4.2 Validation of optimal sensor locations

A vibration analysis was performed using the coupled gearbox-fuselage equations, by applying a vibratory force at the top of the gearbox. Total number of degrees of freedom considered in this analysis are 26. These include 3 rigid body modes of the gearbox (heave, pitch and roll) , 3 rigid body modes and 20 flexible modes of the fuselage. The gearbox is assumed to be supported on the roof of the fuselage at the four nodes (39,48,46 and 37). The data used for the vibrational analysis are given Table 1.

The vibratory levels in the fuselage were calculated for different excitation frequency, namely, 1/rev, 2/rev, 3/rev, 4/rev and 5/rev. For the sake of conciseness, only those results pertaining to 1/rev and 4/rev excitation frequencies are presented (Figs.5 and 6). In these figures, the vibratory levels (g-levels) at different nodes are indicated by impulses. The arrows (other than the one indicating the gearbox C.G) indicate the optimal locations for the sensors. For 1/rev excitation, the sensor at node 64 measures the highest level of vibration of 0.48g (Fig.5). For 4/rev excitation (Fig.6), the peak response occurs at node 33. But there are two sensors at node locations 32 and 34 measuring the second highest level of response. These results indicate that the optimally selected sensors measure high levels of vibration.

4.3 Open-loop vibration control

For the vibration control studies, the total number of degrees of freedom of the dynamic model is 26. These consist of 3 rigid body degrees of freedom of the gearbox, 3 rigid body degrees of freedom and 20 flexible modes of the fuselage. Since, there are 23 degrees of freedom for the fuselage, 23 sensor locations were identified by EIDV approach employing single elimination process. These optimally selected 23 sensor locations are indicated by node numbers in Fig.4.

Incorporating an open-loop control scheme, described in Sec. 2.3, an attempt is made to minimise the vibratory response of the fuselage. The control forces, required for vibration minimisation, are evaluated using measurements from several sets of sensor locations. These different sets of sensor locations correspond to (i) optimally placed 23 sensors, (ii) arbitrarily placed 5 sensors(node locations 12, 13, 20, 21 and 64), (iii) arbitrarily placed 10 sensors (node locations 1, 2, 20, 21, 31, 35, 50, 56, 62 and 64) and (iv) arbitrarily placed 23 sensors (node locations 1 through 22 and 64). The nondimensional frequency of the excitation force is assumed to be 4/rev (a 4-bladed rotor system is considered). The relevant data are given in Table 1.

Using the vibratory levels measured at the optimally selected 23 locations, the control forces required for minimisation of vibration in fuselage were calculated. Figure 7 shows a comparison of the baseline vibratory levels along with the controlled response. The fuselage vibratory level has been reduced substantially from the baseline peak acceleration of 0.284g to a level of 0.5E-04g at node location 33. In addition, the vibratory levels at all nodes in the fuselage are reduced to very low levels. But the gearbox C.G experiences an increase in the g-level, i.e., the gearbox g-level increased from a value of 0.0477g to 0.0625g. Figures 8(a) and 8(b) show the magnitudes and the phase angles of the four control forces required for vibration minimisation.The control forces are almost 180 degrees of out-of-phase to the applied external force.

To analyse the effectiveness of vibration reduction using optimally placed 23 sensors, a vibration reduction analysis using different sets of sensors located at arbitrary nodes in the fuselage, was performed. The controlled response for these cases of arbitrary sensor locations are compared with the controlled response for the case of 23 optimally placed sensors. These results are shown in Figs.9-12.

Figure 9 shows the results of the controlled vibratory response, obtained using 5 arbitrary sensors and 23 optimally placed sensors. It is observed that the peak acceleration of the controlled response with 5 arbitrary sensors is 0.31E-02g at node location 43. The peak acceleration of the controlled response for optimally placed 23 sensors is 0.138E-03g at node location 5. Figure 10 shows a comparison of the controlled vibration with 10 arbitrary sensors and 23 optimally placed sensors. For the case of 10 arbitrary sensors, the peak acceleration of the controlled response is 0.211E-03g at node location 33, which is about 53% more than that for the case of optimally placed 23 sensors. Figure 11 shows the controlled response for the case of 23 arbitrary sensors along with the controlled response with 23 optimally placed sensors. For the case of 23 arbitrary sensors, the peak acceleration is found to be 0.203E-03g at node location 41, which is 47% more than that for the case of optimally placed 23 sensors. The magnitudes and phase angles of the control forces for all these case are presented in Table 2. It is interesting to note that though there is very small variation in the magnitudes and phase angles of the conrol forces, there seems to be a large variation in the peak acceleration of the controlled vibratory response of the fuselage. These results clearly indicate that the vibration control using measurements from the optimally placed sensors provide the minimium peak acceleration in the fuselage.

It is observed that in all these vibration minimisation studies, even though there is vibration reduction in the fuselage, the gearbox C.G experiences an increase in the acceleration level (Figs.9-11). So an attempt was made to reduce simultaneously the vibratory levels at the gearbox C.G as well as at the fuselage. In this case, the control forces required for vibration minimisation were obtained using measurements from 24 sensors (23 optimal sensor locations in the fuselage + 1 sensor at gearbox C.G). Figure 12 shows the comparison of controlled vibratory levels obtained by using measurements from 23 optimal locations and those for the case of 24 sensors. It is interesting to observe that with 24 sensors there is no improvement in vibratory levels at the gearbox C.G, but there is deterioration in the fuselage vibratory levels. The magnitudes and phase of the control forces are given in Table 2.

5 Concluding Remarks

The problem of vibration reduction in helicopter fuselage, using the concept of Active Control of Structural Response (ACSR), has been formulated. The equations of motion representing the dynamics of a coupled gearbox-fuselage model have been derived. Using these equations, several studies have been performed. They are (i) identification of optimal sensor locations for vibration measurement and (ii) formulation and solution of a Multi-Input-Multi-Output (MIMO) control scheme for vibration minimisation in a helicopter fuselage. The important conclusions of this study are summarised below.

1. A detailed description of the Effective Independence Distribution Vector (EIDV) approach for

the identification of sensor locations for vibration measurement is presented.

2. Irrespective of the input excitation frequency, the optimally identified sensor locations by the single elimination process, experience high levels of vibration.

3. Vibration control using measurements from the optimally selected sensor lcoations provide maximum reduction in the g-levels of the fuselage vibration as compared to the controlled response using measurements from arbitrarily placed sensor locations.

4. When the vibratory levels in the fuselage are minimised, the gearbox experiences a higher level of vibration in comparison to the baseline g-level. While trying to minimise simultaneously the vibratory levels in the fuselage and gearbox, it was observed that there is no reduction in the vibratory levels at gearbox; but there is a deterioration in the control of vibration in the fuselage.

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Table 1 Data used in the computations

Reference quantities for nondimensionalisation

$m_B = 65kg$ $R = 6m$ $\Omega = 32 rad/sec$

Nondimensional quantities

$K_t = 60.01$ $C_t = 0.033$ $m_F = 33.846$ $m_{GB} = 4.615$

$I_{xxF} = 0.6838$ $I_{yyF} = 2.7350$ $I_{xxGB} = I_{yyGB} = 0.0171$

$$\frac{F_z}{m_B \Omega^2 R} = 0.0001$$

Coordinate of fuselage c.g. from origin at the nose of the fuselage

$x = 0.5632$ $y = 0.0$ $z = 0.0833$

Coordinate of gearbox c.g from origin at the nose of the fuselage

$x = 0.5632$ $y = 0.0$ $z = 0.3333$

Structural Damping for fuselage elastic modes

$\beta_F = 0.005$

Table 2 Magnitude and phase angle of control forces

Control force		Number of sensors used for vibration control				
	Node location	5 arbitrary	10 arbitrary	23 optimal	23 arbitrary	24 23 optimal +1 gearbox
magnitude	39	3.756	3.755	3.755	3.755	3.989
	48	3.756	3.756	3.755	3.756	3.561
	46	3.757	3.756	3.755	3.756	3.563
	37	3.756	3.755	3.755	3.755	3.978
phase angle, (deg.)	39	180.2	180.5	180.4	180.6	180.5
	48	182.4	180.3	180.4	180.3	180.2
	46	178.8	180.3	180.4	180.3	180.2
	37	180.5	180.5	180.4	180.6	180.5

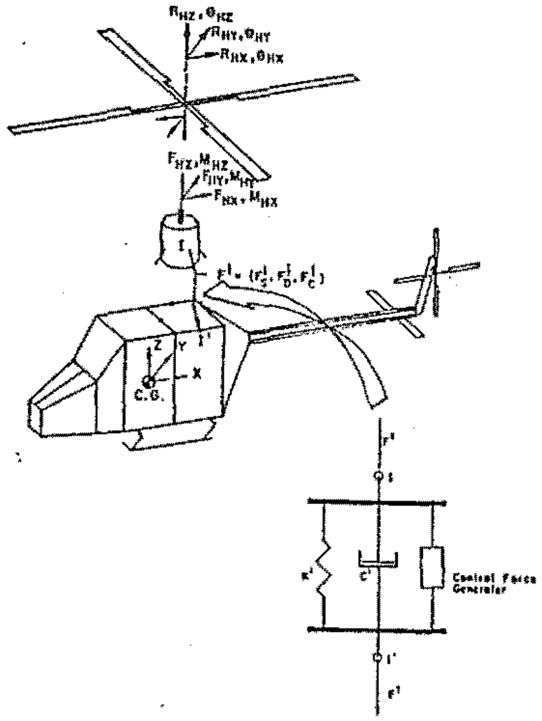

Fig.1 Interaction of subsystems in helicopters

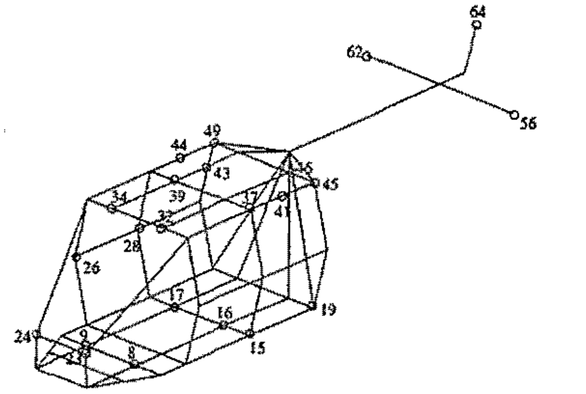

Fig.4 Optimal sensor locations
(Sensor locations indicated by node numbers)

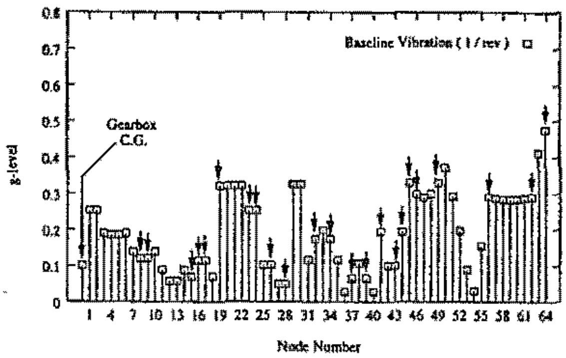

Fig.5 Baseline vibratory levels
(excitation freq. 1/rev)

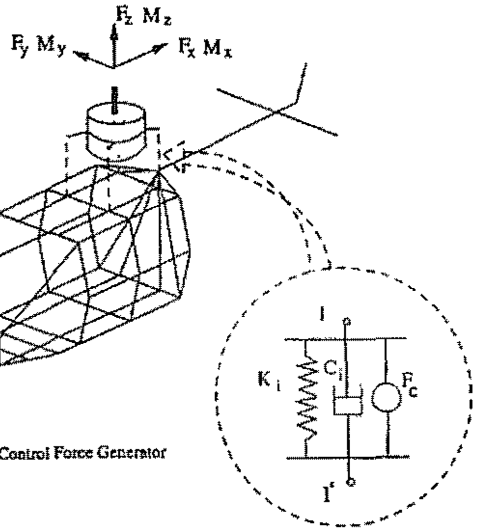

Fig.2 Coupled gearbox-fuselage dynamic model

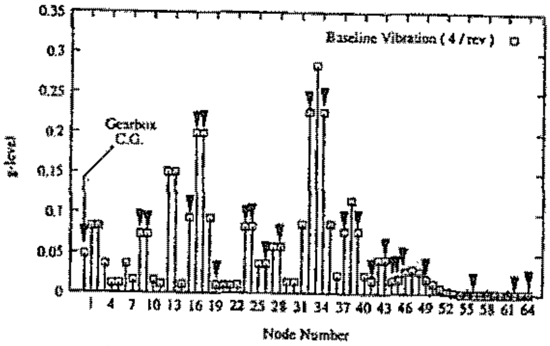

Fig.6 Baseline vibratory levels
(excitation freq. 4/rev)

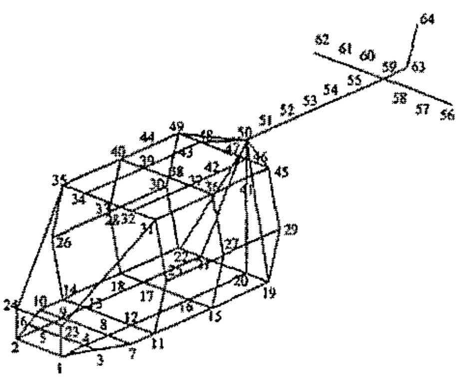

Fig.3 Finite element model of helicopter fuselage

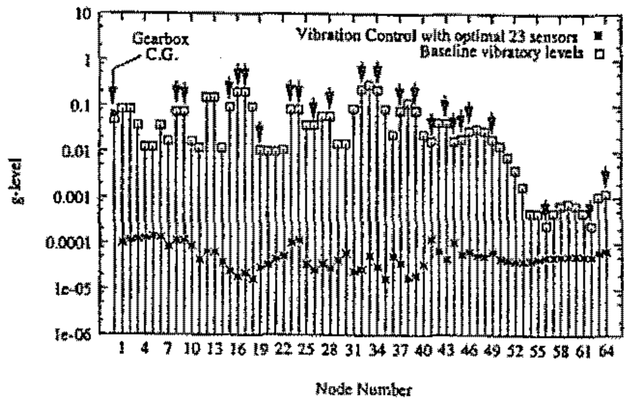

Fig.7 Baseline vibration and controlled response
(23 optimal sensors)

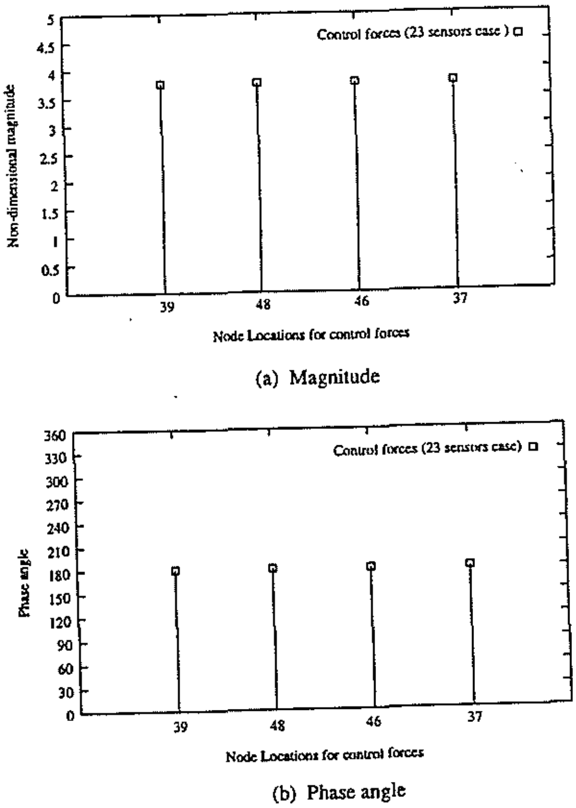

Fig.8 Magnitude and phase angle of control forces

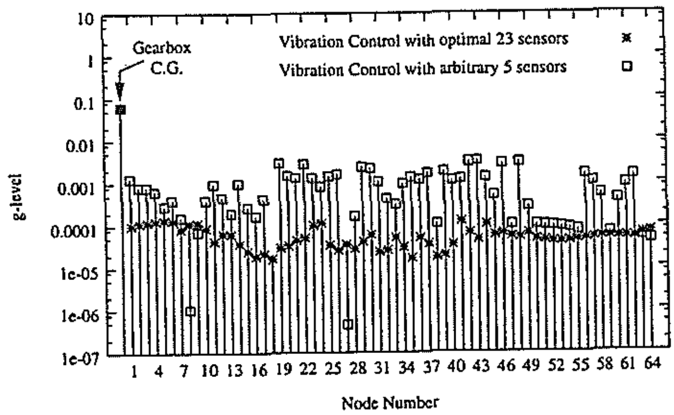

Fig.9 Vibration control with 5 arbitrary sensors *vs* control with 23 optimal sensors

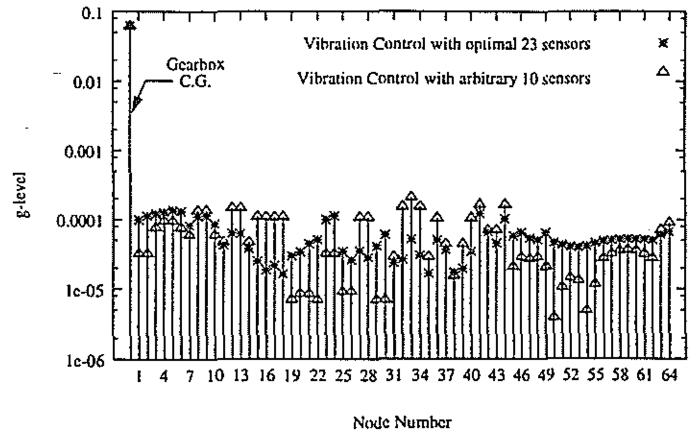

Fig.10 Vibration control with 10 arbitrary sensors *vs* control with 23 optimal sensors

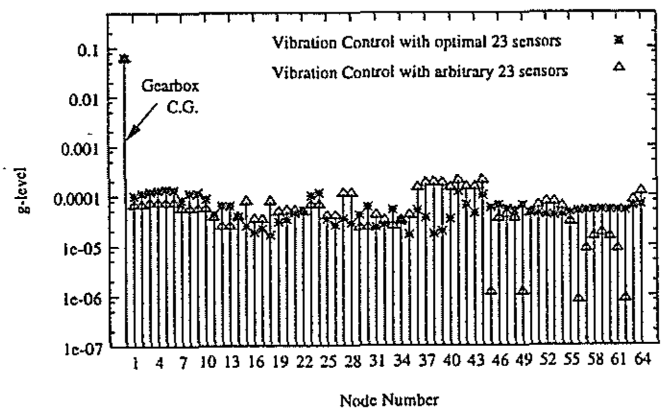

Fig.11 Vibration control with 23 arbitrary sensors *vs* control with 23 optimal sensors

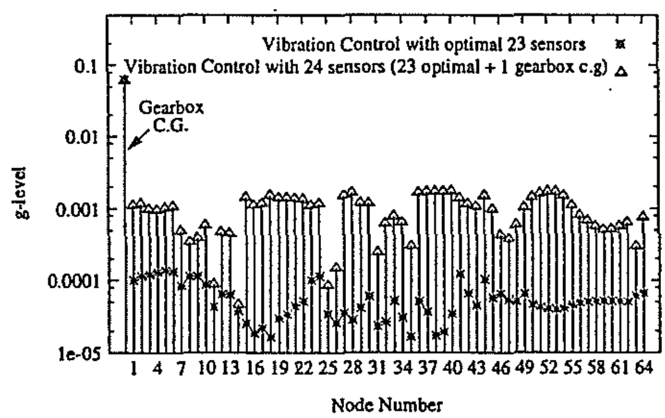

Fig.12 Vibration control with 24 sensors *vs* control with 23 optimal sensors

MISSION PLANNING SYSTEMS FOR HELICOPTERS

J.P. LACROIX SEXTANT Avionique

D. JOLIVOT MATRA SYSTEMES & Information

Planning the mission has always been needed, to a larger or smaller extent, for all military, and even civil, helicopter applications. At least, it is necessary to prepare the navigation and flight plan, to acquire some knowledge of the tactical situation and the mission definition and to plan fuel and ammunition requirements.

Up to the last few years, these planning functions were performed manually by the crew, using very simple tools: paper map, coloured pens and overlays.

The needs have now evolved, as a consequence of:

- improvements in helicopter technology, which provided new sophisticated weapon systems, more effective but complex to manage,
- the evolution in mission requirements: tactical environment, ECM, night and all-weather conditions, but also changes in the type of operations (overseas, humanitary), . new geopolitical context. We can note that this evolution now concerns also civil or paramilitary mission.

Mission planning systems are then compulsory, which have to be both powerful enough and user-friendly as well as easy to access and to operate close to the operation zone, in order to be able to:

- manage complex situations and handle a large number of different parameters,
- exchange big volumes of data with aircraft and C3I Systems or other data servers.

Figure 1 presents a general operational organization, where the helicopter mission planning functions are implemented at the battalion and (Squadron)/combat unit levels. It can be noticed that a common mission planning system, as proposed by MS&I and SEXTANT Avionique, is used at both levels, with physical configurations adapted to the operational needs.

Figure 2 presents more details on the different planning functions which, in the frame of this assumed organization, are activated at these two levels.

Basically, the system is used at the battalion level to prepare tactical situation information and operation orders, and to transfer the corresponding data. At the combat unit level, the systems performs further mission planning functions (terrain analysis, navigation, logistics...) and directly interfaces the helicopter data transfer devices.

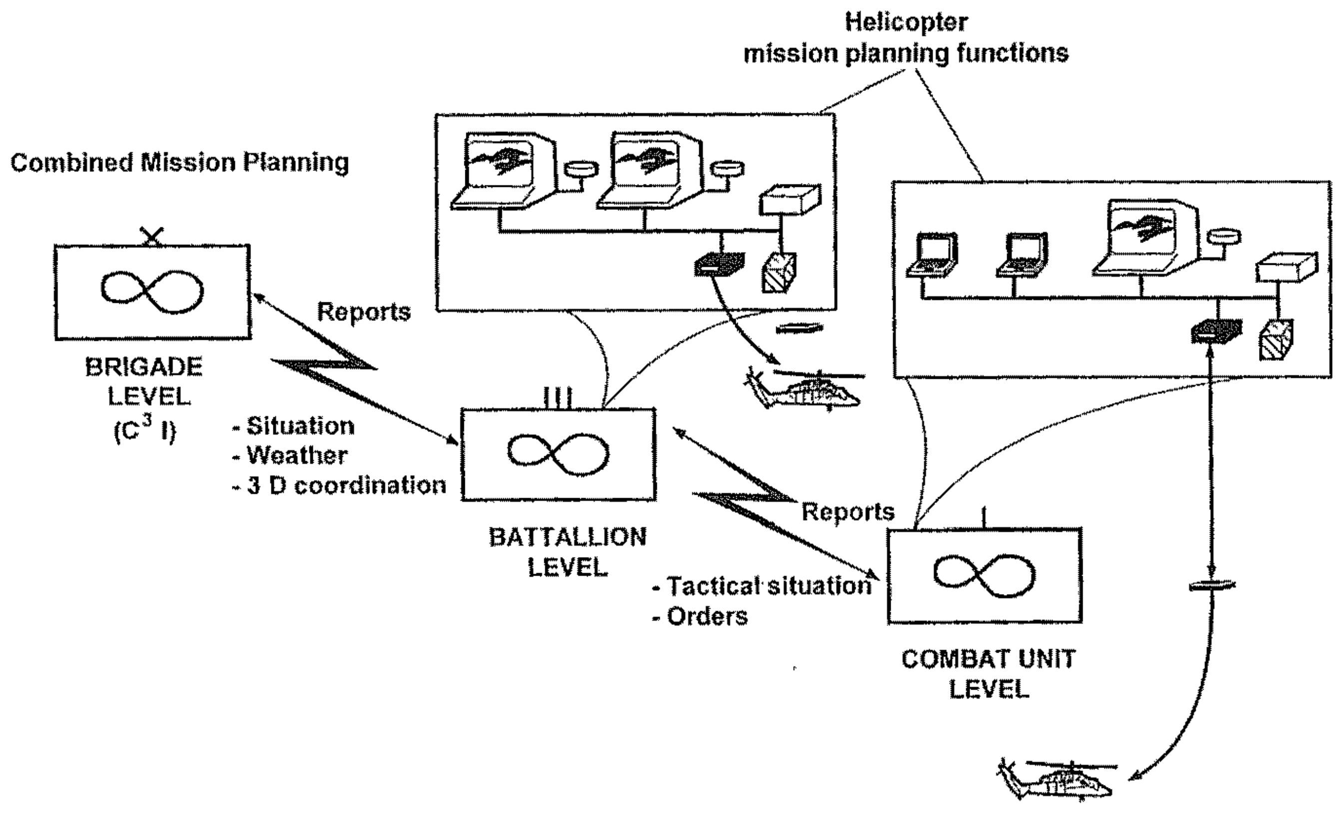

FIGURE 1 - GENERAL ORGANIZATION

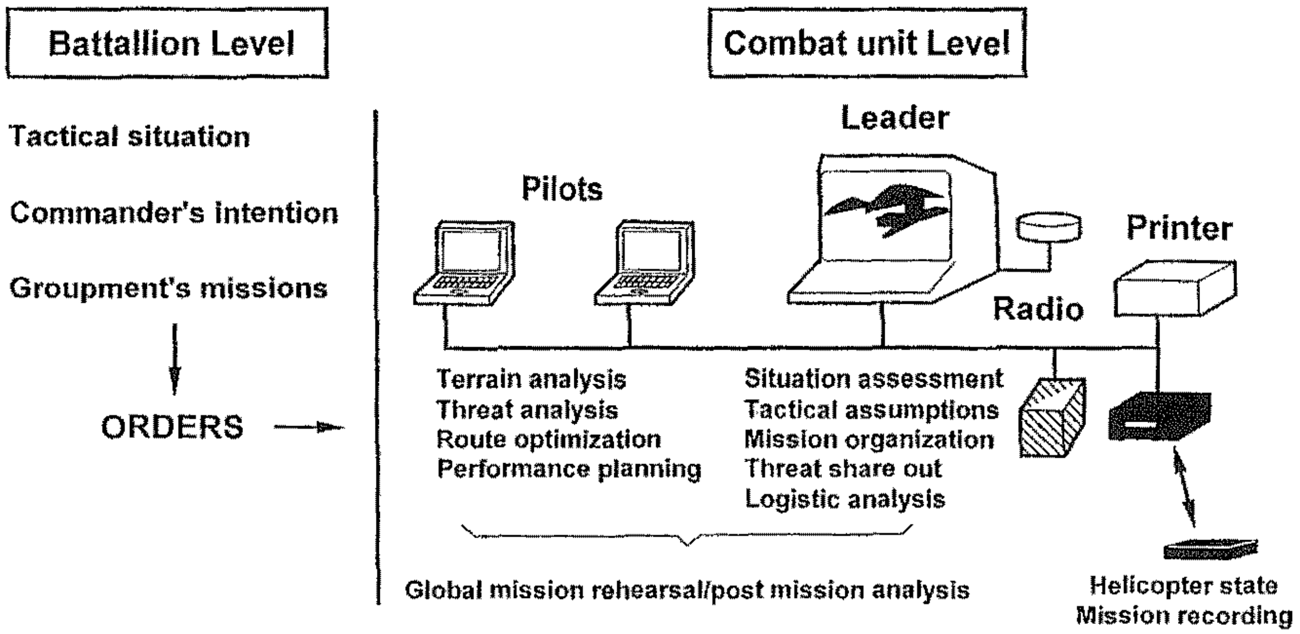

FIGURE 2 - FUNCTIONAL BREAKDOWN