STRUCTURAL DYNAMICS AND VIBRATION CONTROL

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This review of some aspects of structural dynamics research related to vibration control, outlines some developments, over about the last decade and a half at the ISVR, in essentially four areas, namely machinery isolation, vibration transmission through structures, dynamic testing and composite materials.

The use of approximate mobility methods in vibration control is discussed and the development of rapid frequency sweep testing is outlined. The unifying concept of power flow analysis applied to isolation system assessment and vibration transmission studies is demonstrated and it is shown how structural intensity mapping could be a useful method for application in future vibration control work. The impact of composites on structural dynamics research has been considerable but the damping properties of such materials could be improved; this aspect of composites development is discussed together with aircraft acoustic fatigue problems.

1.0 INTRODUCTION

Vibration control concerns the reduction of vibration levels which cause annoyance, possible damage to structures or subsequent undesirable acoustic radiation. It is good vibration control technique to attack the problem at source rather than to initially attempt remedial actions remote from the source. It is inevitable, however, that machines, in particular, generate unwanted vibrations which are transmitted through their mountings into the substructure. The vibration is then transmitted, via various types of waves, through the structural/acoustic paths to areas of interest. Vibration control, within the context of this paper, principally concerns this type of problem. For example, vibration isolation is an obvious common technique for vibration reduction on the substructure near the source and conventional methods often yield good results, although the problem may still persist, perhaps surprisingly, at high frequencies. Frequency response methods analogous to those used by electrical engineers may be used in vibration analysis to predict the coupled performance of the machine-isolator-substructure system. The mobility approach is useful in this context but if it is to be used in a practical way there must be simple rules which permit rapid assessments to be made of proposed designs. The development of such an approach, outlined in this paper, obviously involves considerable theoretical dynamic structural analysis before simplifications can be made. Vibration testing is also often carried out in support of vibration control studies so it is inevitable that vibration control, although sometimes intuitively attempted, is based upon knowledge of dynamic structural behaviour. This certainly can be seen to be true when one considers vibration transmission through built-up structures where a variety of mechanisms influence the propagation of vibrational power. When considering structures it is therefore clear that not only is the structural design, i.e. configuration, important but the material properties, particularly dissipative properties, have a strong role in the transmission process.

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The four sections of this paper concern vibration isolation, vibration transmission through structures, measurement of the dynamic characteristics of structures and the use of "new" materials in high performance aerospace structures. The latter topic could not be included without consideration of the acoustic fatigue problem; although this is not a vibration control problem in the sense outlined above, material properties are important and structural design procedures are necessary for response prediction and fatigue life estimation. Fundamental theoretical and experimental structural dynamics research is obviously a good basis for developing and improving vibration control techniques via knowledge of the mechanisms involved and possible improvements via design. This paper reviews some research carried out at the Institute of Sound and Vibration Research in the structural dynamics field, related to vibration control.

2.0 VIBRATION ISOLATION OF MACHINES

Machinery-induced vibration is often a cause of concern or annoyance in a wide range of situations, such as in buildings, ships etc. In any vibration control problem it is good practice initially to attack the problem at its source to obtain the maximum possible benefit of reduction methods and then to apply other measures to the surrounding structure etc. In the machinery problem the first approach is therefore usually to modify the source in some way to reduce dynamic excitation of the local supporting structure. If reduction of out-of-balance forces etc. cannot be achieved to produce acceptable vibration levels, the next step is to isolate the machine from the supporting structure via resilient vibration isolators. This is perhaps the most often used vibration control technique in machinery installations, as is evident from the engine mountings in every modern motor car. If, however, one considers machinery installations in a building one can see for example via the simple representation given in Figure 1, that the point of concern or interest where the vibration level is to be minimised is often remote from the source or the attachment points of the vibration isolators. The vibration transmission characteristics of structures are therefore of concern. That problem will be considered later in Section 3; this part of the paper concerns only vibration isolation.

It would perhaps appear from study of the extensive published work on vibration isolation that isolation techniques are so well developed and established that no further research would have been carried out in recent years. This is not so because a great proportion of the work, particularly that now included in standard textbooks, concerns representation by mass-spring models of the machine and isolator with a rigid substructure. Such simplifications, which do not allow for deformation of the systems which are coupled by the isolator, have only very restricted validity and limited application to practical cases. In simple terms, if the foundation or substructure below the isolator was rigid, one would hardly need to examine the problem in terms of vibration control. The limitation of use of such simple representations is particularly apparent in the high frequency regime in which resonances of the machine and supporting structure occur which make estimates of vibration transmission based on simple rigid mass - massless spring - rigid foundation models essentially meaningless. This need to consider the dynamic characteristics of the machine (source) and substructure (receiver) has in particular led to the development and application of dynamic structural analysis techniques based on frequency response methods for predicting coupled system performances. If comparison with electrical circuit analysis methods and theorems is helpful, then the analogies may be clearly seen. Procedures for prediction of coupled mechanical system response are developed in [1] using receptances and the methods are well explained. Receptance is the ratio of displacement to force as a function of frequency. Recently, mobility methods have been more widely used, although the procedures are essentially as outlined in [1]. Mobility is the ratio of velocity to force and is probably more commonly used now than receptance because of measurement techniques which enable complex frequency response data of this type to be readily obtained without the often troublesome need for the additonal stage of integration. The reader's attention is drawn to [2] for a very good explanation of measurement problems and the application of frequency response data in mechanical system analysis.

The vibration isolation problem is outlined in Figure 1 and only consider at this stage vibration transmission through an isolator. The coupling of the isolator to the substructure and the system layout may cause forces and moments to act such as to produce deflections along all three coordinate axes and rotations (angular velocities when considering mobilities) about these axes. The motion at the attachment point of the isolator to the substructure, the machinery "seating", is therefore generally complicated and complete description of all the point and cross mobilities is required if the induced structural responses are to be estimated. For simplicity here, however, consider forces which produce pure translational motion only and suppose that in the frequency range of interest inertia forces in the isolator may be neglected. Using mobilities, as is described in [3], the effectiveness of the isolation system may be clearly examined.

E = isolation system effectiveness

$$= \frac{\text{magnitude of receiver velocity when connected directly to source}}{\text{magnitude of receiver velocity when connected through isolator to source}}$$

$$= \frac{M_I}{M_S+M_R}$$

where M_I = the isolator mobility
M_S = the source mobility
M_R = the receiver mobility

Now E should be as high as possible for good isolation and the above expression shows very clearly that for good isolation it is required that M_I be much greater than (M_S + M_R). Similarly, it can be seen that E will become low if source or receiver mobilities become large (resonances in machine or substructure) or if wave effects occur in the isolator and M_I becomes low. This simple discussion serves to illustrate two points. First, coupled system performances may be predicted if mobilities are known and secondly, simple models are, as previously suggested, inadequate at high frequencies. At the present time there is only a little information concerning the point mobilities of sources, such as machines and this will be a topic for continuing study. Although some simplifications may be made concerning the nature of sources by assuming that they are either of the force or velocity type, the perhaps more significant problem concerns mobility characteristics to be ascribed to receivers, i.e. substructures such as floors, bulkheads, machinery seatings etc. It can therefore be seen that if a complete set of measured or predicted data is not available, as is usually the case, assessment methods will be necessarily approximate. Because of these problems, and the need for isolation system assessment procedures which may be rapidly used by structural designers, very simple, approximate formulae have been developed for estimating the point mobilities of common structural elements. The approach is based upon the fact that at high frequencies, typical substructures composed of beam and plate-type elements do not exhibit clearly defined resonances in their point mobility. In such cases the practical structure of finite dimensions may be approximated to by an equivalent infinite structure with a very simple curve for the point mobility characteristic which well represents the average behaviour of the point mobility of the finite structure [4,5]. This approach has been developed considerably recently [6] and the simple formulae may be used to represent seatings and isolation systems in the absence of experimental data and without the use of large computational facilities which might only, if necessary, be subsequently used in a limited way. The results are generally available in [7].

All machines will be mounted on a set of isolators which will be connected between various points on the machine and seatings on the substructure. It is also common to be involved with vibration control problems which involve several machines. It is important to know which transmission paths through the isolators are contributing most significantly to the problem. The fundamental quantity of interest is the vibrational power flow between sources and the receiver. The advantages of examining power transmission are also mentioned later in relation to structural transmission path identification. Returning to isolation systems, it can be seen to be desirable to have a reliable experimental technique for measuring the power transmission through isolators. Any such method sould not be complicated if it is to be used in practical situations as a diagnostic tool. An experimental technique has been developed for measuring the power flow through an isolator [8]. Two accelerometers are used, one mounted at each end of the isolator. Knowledge is also required of the dynamic properties of the isolator. Power transmission through a spring-like isolator can, for example, be measured by using the isolator dynamic stiffness and the cross spectrum of the accleration signals "above" and "below" the isolator. The method has been evaluated in [8]; the underlying theory is presented in that paper together with the results of experiments to validate the method. It has been shown that the two accelerometer method, which involves easily performed cross spectral density analysis, may be used to independently measure the power flowing through each isolator under a machine supported on many isolators. The total power from the source is the sum of the individual contributions from each isolator. An example of measurements taken on a model system is given in Figure 2. The foundation was a beam of finite length with absorbing terminations which behaved as an "infinite" beam. The peak power flow occurred at the mass-spring-"infinite" beam resonance frequency and the level was adequately predicted by simple means. At high frequencies, a considerable amount of power was dissipated in the isolator but the measured power flow agreed quite well with the predicted curve for the system using a force source approximation.

In the earlier part of this section it was pointed out that several types of motion can occur at the point of attachment of the isolator to the seating. Translational and rotational motion may occur via direct and cross relationships. It is important to know which degrees of freedom are significant in an isolation system. It has long been the practice to consider only translational motion normal to the surface of the seating and to ignore other dynamic effects. This is done partly for simplicity of calculation but also because comparison of effects of the source in two of the types of freedom is impossible, i.e. one cannot compare, for example, rotational mobilities with translational mobilities and deduce that one is more important than the other in causing structural response. It is possible, however to predict the vibrational power input to a structure via various mechanisms and establish the relative importance of each mechanism. Again, this stresses the importance of considering a fundamental quantity, power flow, when studying vibration transmission mechanisms. It is often the case that an isolator is attached to a substructure, perhaps a plate, through a "stiffener" which could be a beam with a "T" shaped cross section, for example. If the isolator is attached exactly on the axis of the "T" then force excitation of the plate occurs, but if the attachment is off-axis then moment excitation is also present. Using the simple mobility formulae such as designers might use in order to represent the point frequency response characteristic of the structure, expressions for the power flow into structural elements such as beams, plates and combinations of elements may be derived. Some examples of results of such predictions are given here in Figure 3. It can be seen quite clearly from this diagram that moment excitation should be avoided because this mechanism induces more flexural wave power in beam and plate-type structures at high frequenices than does excitation by a force normal to the surface. The implication is clear; avoid machinery installations which involve moment excitation and high frequency problems will be minimised. This type of power flow study coupled with approximate mobility analyses is most valuable in revealing the practices which are good or poor in machinery installation design. Also do not fail to observe that power flow analysis facilitates comparison of efficiency of excitation mechanisms - this would not be possible by other means.

3.0 VIBRATION TRANSMISSION THROUGH STRUCTURES

The point of interest in a vibrating structure need not always be close to the machine or source of vibration. We may, for example, be concerned with vibration levels in a part of a building which is remote from a machinery installation. It is obviously important that the paths by which vibration is transmitted from the source to the place of interest be identified in built-up structures. In a complicated structure there will be many paths involving transmission by a variety of wave types in various media. The frequency response approach, outlined above, may be used in the definition of transfer functions; for example a transfer mobility defines the velocity at a point produced by a force applied at another point, as a function of frequency. The measurement of transfer functions of this type does not alone yield enough information for transmission paths to be identified. It is therefore sometimes necessary to use other techniques. Some approaches to the problem which have been developed in the past are described here together with power flow techniques which are currently under development.

The most simple method for investigating vibration transmission might be thought to work in the time domain, that is to transmit a pulse through the system under test and monitor the response at various points. However, the presence of multiple transmission paths and frequency dependent transmission characteristics generally precludes use of the method because the pulse shape becomes significantly modified during transmission. Cross correlation techniques are the classically proposed method for examining transmission of vibration and this type of analysis may be used with random or transient excitation. It is hoped that the cross correlation function between the force and response will exhibit peaks corresponding to the various time delays in the transmission paths, with magnitudes related to the attenuation factors associated with each path. This method of analysis has been examined in depth for various types of transmission path [9,10]. The cross correlograms were studied for ideal systems and combinations of ideal systems which might represent the more complex behaviour of practical structures. For example, in a building, vibration transmission may occur through both acoustic and structural paths. In a simple model the acoustic paths may be considered as delay elements and the structure as being composed of resonant elements. Although these representations involve considerable simplification, the approach does permit the examination of situations in which frequency response measurements alone are unsatisfactory. It must be said, however, that in the study of combined element systems both frequency and time domain analysis techniques have sometimes to be used together to facilitate system identification. The approach based on use of combinations of simple systems to explain and represent the behaviour of structural systems is of limited use because non-dispersive transmission is assumed to occur. Flexural wave propagation in structures is dispersive, that is the wave propagation velocity is frequency dependent; pulses containing a broad range of frequencies are therefore dispersed with distance and the use of pulses with broadband spectra is therefore precluded as measurement of delays from conventional cross correlograms is impossible. Further work was therefore carried out to develop test and analysis techniques which are suitable for use with dispersive systems. Two approaches have been examined which involve the use of more advanced signal processing techniques compared with simple cross correlation. The first method, which followed work by Aoshima [11], was developed by Holmes at the ISVR [10] and involves the generation of a special test signal. A transient excitation function consisting of a sequence of bursts produced by intermitting a pure tone was developed and it has been shown that this essentially single frequency excitation function exhibits little dispersion with distance in the flexural vibration of structures. The analysis technique involves cross correlation of the intermitting sequence with the squared response signal and yields correlation functions with clear triangular peaks from which group velocities and attenuation factors can be measured. The second method involves simple transient excitation together with use of an inverse Fourier Transform technique to obtain a function with which to modify the cross correlogram obtained in the conventional way, in order to produce cross correlgrams from dispersive systems which may be understood [12]. It should be clear from the above discussion that the use of well established procedures such as frequency response testing, which still has a very useful role in vibration analysis, and correlation techniques in signal processing which have been subjected to modification, do not lead to complete understanding of the vibrational power transmission which occurs in structures and structural/acoustic systems. If vibration control is to be attempted on a distributed structure, it is important that the mechanisms governing power transmission be identified. All too often, some local change is made to a structure, perhaps the addition of a damping treatment or stiffening in a chosen local area, only to find afterwards that the local vibration level may have changed but the level at the point of interest elsewhere was substantially unchanged. The power flow approach is fundamental in vibration transmission studies; if one refers back to the discussion of machinery isolation in Section 2.0 above, the power flow approach can be seen to be justified in several ways. The power flow approach in vibration isolation shows clearly which isolator or which machine is injecting most vibrational power into the substructure. The power flow approach also permits the line of attack in vibration control to attempt to minimise the problem at or close to the source by minimising the power input to the substructure and thus obviously, if intuitively at this stage, globally minimising the subsequent structural vibration problems. It is also clear from Figure 1 that in only considering the transmission paths through the isolators in a machinery installation one is taking a somewhat naive approach to the problem. Even the simple representation in Figure 1 shows that transmission between source and receiver takes place not only through the isolator but also through other parallel paths which "short circuit" the isolator; the parallel paths are through the air, or surrounding medium, pipework, shafts etc. and other essential connections to the machine. In conventional vibration analyses the transmission characteristics through all of these paths between the source and receiver can only be described in different terms which do not permit comparison in order to establish which paths dominate in the transmission of vibration from source to receiver. Power flow analysis facilitates this comparison! One should be able to study power transmission through isolators, pipes, shafts, acoustic paths etc. When vibration has been input via these various routes to the substructure it is transmitted through the various structural/acoustic paths to the area of interest. Again, study of power flows is vital in as much that the dominant vibration transmission paths should be determined and sensible vibration control procedures applied. This then is the case which supports the need for development of techniques for structural power flow measurement. To summarise, power flow is fundamental quantity of interest in vibration control and the power flow concept unifies the various transmission problems encountered to enable reasonable vibration reduction measures to be attempted. Both theoretical and experimental approaches have therefore been made at the ISVR in the study of strucutural power flow. Acoustic intensity measurement methods are now well developed after the pioneering work of Fahy [13] which enable acoustic transmission paths to be characterised and sources to be ordered in relative importance. Acoustic intensity measurement is not discussed further here; attention is given to the development of structural power flow measurement methods at the ISVR. It is perhaps worth noting at this stage that the term "intensity" in structural measurement means "power flow per unit width".

Theoretical studies carried out so far have been on necessarily simple models. Power flows in grillage-type structures have not yet been examined. The wave propagation and power flows due to force and moment excitation applied to the beam have been studied at the driving point in the far field of an infinite plate with a simple line stiffener [14]. It has been found that the motion at the driving point is largely controlled by the beam. If the beam is excited by a force or moment so that flexural wave motion is induced, then the power transmitted by these waves will initially be associated with the beam. As the waves travel away from the source they radiate into the plate so that in the far field more power is transmitted by the plate than the beam. Power transmission caused by moment excitation producing torsional motion of the beam tends to be predominantly due to the beam at high frequencies, with the plate being more significant at low frequencies. This type of analysis leads to some insight into the physical behaviour of structures and the important mechanisms in vibration transmission. The stiffened plate is representative of a machinery seating and the relative importance of force and moment excitation has already been stressed in this context in Section 2.0 above. Formulae are given in [14] for power flows into various types of structure. It is undoubted, however, that in addition to theoretical anlayses, experimental techniques for measuring structural intensity could be of considerable help in practical vibration control.

Experimental techniques for measuring the power flow in structures have been developed. A considerable amount of theoretical work has been carried out in order to establish the basis of each proposed experimental method. A very significant amount of effort has also been devoted to investigation of sources of error and practical limitations. Initial studies concerned one dimensional power flow due to flexural wave motion. Flexural waves have been examined as this type of wave is easily excited in structures, forms one of the predominant transmission mechanisms and often constitutes an efficient mechanism for sound radiation. Consider the case of a one dimensional bending wave propagating in a beam along the x direction, the power flow is given by:-

$$p(x,t) = B\left[\left(\frac{\partial^3 y}{\partial x^3}\right)\ \frac{\partial y}{\partial t} - \left(\frac{\partial^2 y}{\partial x^2}\right)\ \frac{\partial^2 y}{\partial x \partial t}\right]$$

where B = the flexural rigidity = EI
E = Modulus of Elasticity
I = Second Moment of area of cross-section
and y = displacement.

The first term is the shear force component of power P_s which is the product of the shear force and the transverse velocity and the seond term is the bending moment component P_m, which is the product of the bending moment and the rotational velocity. Pavic [15] began his study of power flow measurement from the above equation which shows that one could determine the time and spatial derivatives of the motion in order to evaluate the terms within the large square bracket in the above equation. The time derivative may be obtained via the signals from transducers mounted on the structure, and the spatial derivatives may be approximated to via a finite difference method. For these purposes a line array of four transducers may be used centred around a point $x=x_0$ with separation Δ between them. If the transducers are denoted by numbers 1 to 4 consecutively, the time averaged intensity may be estimated by use of an expression derived from the above equation using finite difference approximations giving:-

$$\langle P \rangle_T \approx \frac{B}{\Delta^3} \left[\dot{y}_2(4y_3 - y_4) - \dot{y}_1 y_3 \right]$$

It is noteworthy that for the above case, either velocity or displacement is required from each point, thus enabling velocity transducers to be used at points 1 and 2 and displacement transducers at points 3 and 4. Pavic also proposed an arrangement of ten transducers to enable simultaneous measurements to be made of the intensities in two perpendicular directions in plates. The necessary signal processing techniques have been described [15] and it has also been shown that the presence of other types of wave motion, e.g. longitudinal, during flexural measurements should not significantly affect measured intensities [16]. The method proposed by Pavic not only permits directional intensity measurements to be made but yields estimates of the separate components due to shear, bending and twisting. The method has been used to estimate the power flow in a plate; a digital computer was used to perform the necessary signal processing.

Work has continued further recently to develop practical instrumentation for carrying out power flow measurements on built-up structures. Returning to the case of power transmission in beams, far from discontinuities in the beam and the influence of decaying near field waves, the time averaged values of power flow due to shear forces and bending moments are equal. That is, from the above equation, in the stated condition,

$$\langle P \rangle_T = 2\langle P_S \rangle = 2\langle P_m \rangle$$

This simplification, albeit with a qualifying assumption, leads to the possibility of considerable simplification in experimental technique. This type of simplification, leading hopefully to the development of practical apparatus, together with appraisal of errors and limitations has been the topic for continuing study at the ISVR in latter years [17]. A "two accelerometer method" for measuring one dimensional power flows has been developed by Redman-White. It does rely on the fact that, as already stated, measurements are made in the far field and the shear force component is measured and multiplied by two. Analytical work carried out to examine errors in the much simplified method shows that if an error of ± 20% can be tolerated, as is probably reasonably tolerable in this type of work, measurements may be made as close as one tenth of a wavelength from discontinuities. Errors due to basic assumptions and sources of experimental error are well discussed and quantified in [17] and the reader's attention is drawn to that paper for further information. The two transducer method appears very useful for taking measurements on beam-type structures, which of course, include pipework which is often a path in parallel with vibration isolators. In the case of plates, the theory is necessarily more complicated and there are three components of power flow, shear, bending and twisting. Expressions for the three components may, of course, be written from plate bending theory. Following the above approach of simplification, rather than measuring all three components, it may be shown that the intensity J in a given direction in a plate in the far field is given by

$$\langle J_x \rangle = 2\langle J_{sx} \rangle = 2[\langle J_{mx} \rangle + \langle J_{tx} \rangle]$$

where J_x = intensity in the x direction
J_{sx} = shear force component
J_{mx} = bending moment component
and J_{tx} = twisting moment component.

Again, it appears attractive to measure the shear force component rather than to use the more cumbersome ten accelerometer method. To obtain simultaneous intensity measurements in two perpendicular directions, four accelerometers may be used, spaced symmetrically at a distance $\Delta/2$ from the nominal measurement point. This method has been implemented [17] and the four accelerometer method tested by measuring the intensity at points on a circular contour on a plate in a wavefield due to radial power flow from a central source. The measured intensities were used to estimate the total power crossing this contour. Good agreement was obtained between the measured and input total input power.

An electronic structural intensity meter has been built which implements the two and four transducer methods for one and two dimensional intensity measurements [18]. This development represents a very significant advance in the structural dynamics and vibration control field. It is hoped that the portable instrument will find application in future tests on built-up structures. An example of intensities mapped in a plate are given in Figure 4(b) taken from [18]. A series of experiments were carried out in [18] on a large steel plate of dimensions 2.5m x 1.3m and 5.8mm thickness. Dry sand above and below the periphery of the plate in a wedge shape provided "anechoic" boundaries. For the test conditions of Figure 4, two identical lengths of rectangular sectioned steel bar were attached to the plate to provide partially reflecting boundaries near each end. The bar at the left hand end was well fixed to the plate by a layer of cyanoacrylate adhesive but that at the right hand end was only attached via spots of adhesive. Narrow band excitation was used in the form of a frequency modulated signal. The four accelerometer method was used for intensity measurement at 0.05m spacing (corresponding to 0.158 wavelength at the centre frequency). An additional accelerometer was placed at the centre of the array to indicate the RMS acceleration at the measurement point, over the whole excitation bandwidth. The difference in boundary conditions is clear in Figure 4(b). On the left hand side, little power crossed the bar and the intensity pattern is confused due to some circulation of power. On the right hand side there was much less reflection and more power flowed to this side of the plate to cross the boundary into the absorbing termination. These differences can be ascribed to the two different methods of attachment of the bars; the intensity patterns are quite clearly mapped. The RMS accelerations plotted in Figure 4(a) do not lead to any indication of greater power flow to the right hand side, hence merely plotting accelerations does not give useful information, as expected. The intensity map clearly shows how two apparently identical boundaries or discontinuities on a structure may be shown to be different by the application of power flow methods. Power flow mapping shows great promise as a useful technique for the future in vibration control studies.

4.0 MEASUREMENT OF STRUCTURAL FREQUENCY RESPONSE

Vibration testing, in the area of structural frequency response measurement, is generally concerned with measurement of resonance frequencies, damping, mode shapes and scaled frequency response relationships, such as mobility, through a wide range. Often, testing is carried out to obtain estimates of resonance frequencies for comparison with predicted natural frequenices derived from some theoretical analysis. Damping is difficult to predict and experimental work will always be required in this area, not only to measure dissipative characteristics so that damping ratios and loss factors may be inserted into forced vibration claculations but, as will be discussed later, extremely accurate measurements of damping are required in aircraft flutter testing. Frequency response data are required nowadays for modal analysis or structural modelling exercises and also to complement the kind of point coupling studies already discussed in Section 2.0 above. The range of structures to be tested is obviously wide, ranging from ships, aircraft, buildings, motor vehicles etc. to smaller items such as printed circuit boards, for example. The experimental procedure is in each case the same; that is to subject the structure to a prescribed excitation and to interpret the complex, excitation - response relationships. The problem which confronts the experimenter is to excite the system, measure the force and response, and present the derived information which should be readily understood. The analysis of the resonances excited is simplified by applying single degree of freedom system theory to each resonance, the complete response being represented by superposition. This representation is, of course, only applicable to linear systems and the assumption of linearity is most often made in experimental testing; the analysis of nonlinear systems and system identification from experimental data is currently being studied and is certainly a topic which will receive considerable attention in the future [19]. However, as structures generally behave linearly at small deflections, if care is taken to generate only low response levels then nonlinear effects may often be ignored. Using the single degree of freedom analogy for response in each mode of vibration, measurements of natural frequency and damping may be made by simple analysis procedures. For general discussion of techniques for deriving modal characteristics and frequency response data from vibration tests, the attention of the reader is drawn to [20] and [2].

Although the Engineer still often appraises graphical data and derives estimates of frequency response characteristics, computer-based routines are increasingly used. "Modal analysis" routines and systems are commercially available and are used to curve fit to sets of measured data in order to provide estimates of dynamic characteristics. One of the benefits of using such analysis procedures is that displays, most often animated displays, of mode shapes may be produced. Although the use of such displays may sometimes appear to be very limited, it is often very informative to examine mode shapes when vibration testing is carried on components and structural modification for vibration control purposes is attempted. The development of computer-based modal analysis systems is logical and necessary; as will be discussed later in relation to transient testing, it is possible to acquire large sets of structural frequency response data very rapidly via use of digital data analysis systems and it is logical that the power of the computer be used to alleviate data presentation and interpretation problems for the Engineer who, although generally capable and extremely resourceful, is for the foreseeable future only available essentially in "Mark I" form (although some anthropologists might disagree). However, it perhaps suffices to say that the availability of modal analysis systems is greatly beneficial in vibration testing. There is a considerable amount of literature available on the subject; a critical examination of structural modelling is, for example, given in [21], in relation to the derivation of structural characteristics for prediction of the response of coupled structures. Such modelling procedures must remain considerably interactive between the computer and operator, however. Significant errors in predicted dynamic characteristics can occur if errors are made in frequency response measurement or slightly faulty or corrupted data are included in the basis for the model. When modelling a structure from measured data it would be useful if a degree of accuracy for the model could be determined. This would enable an assessment to be made of the use of the model in further analyses.

Now, although the above discussion has outlined the frequency response measurement and analysis problems and current trends in data presentation, little has been said of practical testing techniques beyond the need "to excite the system and measure the force and response". It is possible to perform frequency response tests in a variety of ways, depending on the type of excitation used. Traditionally, "frequency response" is almost always thought of as the steady state response of a system to sinewaves. This approach is that first used in dynamic testing. It is tedious and time consuming, although computer-based incremental sinewave testing systems have been developed which automate the test procedure through a chosen frequency range [22]. There is often insufficient time for steady state testing and for this reason the quasi-steady state or slow sweep test is used. In this method the excitation frequency is slowly varied through the range of interest and it is assumed that the test structure attains steady state response levels in all of the resonances excited. This is sometimes a rather bold assumption but with care and good experimental technique a high degree of accuracy can be obtained. Some sources of error and refinements in technique developed through the years are reviewed in [20]. Commercially available systems combining a beat frequency oscillator which can be slowly swept through a chosen frequency range and a recorder for plotting response magnitudes are used for structural/acoustical testing and servo control systems are incorporated for excitation amplitude control.

Random testing using broadband excitation signals increased greatly in popularity with the advent of digital data analysis systems. The ease with which spectral density and cross spectral density analyses can be carried out on digitised time signals made this type of testing much simpler than in previous years when laborious, and limited, analogue methods of analysis were used. This change in signal processing philosophy also ensured that transient analysis was readily facilitated; in particular Fourier Transform analyses could be quickly and accurately performed on recorded data or on-line from experiments. This development may have been precipitated somewhat, or perhaps the timing was fortuitous, by the "sonic boom" problem due to supersonic commercial flight occurring at about that time. Interest in transient testing as a quantified structural test technique, however, arose primarily due to the development of digital computer-based signal processing systems with Fast Fourier Transform (FFT) routines. Work at the ISVR began in the late 1960s on the development of a transient metod for measuring structural frequency response, principally to carry out rapid measurements on ship's hulls in relation to the machinery seating problem already discussed in Section 2.0 above. The method is generally applicable in structural testing and has been applied very widely to a variety of systems. The technique is based on the use of very rapid frequency sweep excitation in which perhaps typically two decades in frequency are swept in about one second. The rapid frequency sweep technique is the result of a considerable amount of research into the development of a transient method for the rapid measurement of structural frequency response, digital data analysis procedures being used to derive the required dynamic characteristics, either directly or via modelling. The method is described in [23] and the large amount of theoretical and experimental work carried out in the development and validation of the technique is reviewed in that paper together with description of the necessary instrumentation and practical, experimental technique. It is recommended that anyone involved, or about to become involved, in this type of testing should read reference [23]. The impatience of experimenters is well known to the author and if the prospect of reading a fairly lengthy paper appears formidable when one wishes to proceed quickly with the experiment, then attention is drawn to the fact that the paper contains a short section "a simple guide to practical testing" which might be of assistance and does not take long to read. It should perhaps be noted here to obviate some confusion that the rapid frequency sweep technique is often referred to, for brevity, by those other than the author, as "chirp testing".

An example of a critical type of vibration test which requires extremely accurate measurement of damping and is relevant to the lives of a large part of the population is the aircraft flutter test. Flutter is a dynamic instability of an aircraft structure which could damage or destroy it suddenly. It occurs at speeds above the so called flutter speed which varies with the Mach number at which the aircraft is flying. It is necessary to carry out experimental tests, usually called "flutter tests", because of the difficulty of reliably predicting aircraft flutter speeds from calculations and from wind tunnel tests. It is also impossible to predict structural damping levels and this further reinforces the need for practical testing. The problem and approaches to testing and signal processing are very well described in [24]. The method of testing is to excite the structure and measure the response, usually employing accelerometers. The responses are then analysed to give resonance frequencies and damping associated with a large number of resonances in the frequency range of interest. Such measurements are taken on a prototype aircraft at a range of speeds and altitudes; the test and analysis times are necessarily short. A variety of excitation techniques have been used such as, using naturally occurring turbulence, vibration exciters, "stick shakes" pyrotechnic devices referred to as "bonkers"! etc. The procedure followed is to fly the aircraft at progressively higher speeds and Mach Numbers checking for incipient flutter by extrapolating the measured damping values of the critical resonances to the next speed and Mach number[24]. Because of the limited test time and the need to rapidly process results, the transient technique is attractive in this type of work. The rapid frequency sweep technique has been used recently for flutter testing by applying this type of forcing function to the structure, in flight, via hydraulic exciters operating inertially. A pair of exciters, with control of their relative orientation has been used to excite an aircraft in flexural and torsional modes. The excitation and response signals from transducers were processed to yield damping information. The aircraft which was investigated by the method is the British Aerospace 146 passenger aircraft as shown in Figure 5. This use of the rapid frequency sweep technique in a critical area of study is rewarding and is indicative of the confidence which may be placed upon results obtained in this way. The method may be developed further in the years to come. One recently proposed advance in technique concerns the use of a digital signal generator to produce the rapid frequency sweep test waveform rather than analogue methods as have been used in the past [25]. This method has the advantage that the excitation spectrum may be shaped, via inverse filtering techniques, to compensate for exciter characteristics and interaction effects and very high "cut-off" rates may be produced at the spectrum limits. The rapid frequency sweep technique also shows promise as an oscillatory shock waveform for the environmental testing of equipment [26]. It is clear, however, in shock problems generally, that although test techniques may be improved, damage potential in practical structures and systems needs considerable study in the years to come if quanitified assessments are to be made for predictions of likelihood of structural damage or system malfunction. The basis for such general assessment is not yet clear, although the author believes that an energy-based method might be useful [27].

5.0 THE USE OF NEW MATERIALS IN HIGH PERFORMANCE AEROSPACE STRUCTURES

It is now well known that materials with high stiffness to weight ratio may be made in the form of fibre reinforced plastics to build high performance structures which are required for aerospace applications. Carbon fibre reinforced plastics (CFRP) are one type of composite which has been used to advantage in that field. The researches carried out through the past few decades on CFRP have necessarily concerned such topics as investigation and control of material properties, development of analytical techniques for structural analysis, fatigue testing and use of non-destructive testing techniques for locating flaws and monitoring damage propagation in practical structures. The range of work carried out on composites in the structural dynamics field is therefore very broad and it is clear that CFRP will be used much more widely in the years to come. Already, there has been a considerable increase in the use of composites in aircraft construction with considerable weight-saving being achieved [28,29]. The use of composite materials in structures has increased the possibility of selecting materials and configurations in structural design so that structures can now be much better designed to withstand in-service loading. The parameters which the designer may influence are, choice of constituent materials, that is fibres and matrix, the fibre volume fraction and the "lay-up" of the fibres in the resin. Now although the elastic properties and hence stiffness to weight ratio characteristics of CFRP have been studied in depth and exploited in practice, a much lower scale of effort has been devoted to investigating damping properties. Work is now underway on the study of damping properties of CFRP and the development of composites with high internal damping. In brief, we would like to have a stiff, light, heavily damped structural configuration using a fibre reinforced material. This part of the paper outlines some work which has been carried out or is currently underway at the ISVR on the damping of composites and the response of structures to in-service loading. The latter problem has also necessitated re-appraisal of design procedures which have been applied to conventional metallic structures in the past, in order to examine their relevance to composite structures. This aspect of the subject is also mentioned in relation to the acoustic fatigue of aircraft structures.

The criteria which are important in selecting constituent materials for vibrating structures are well explained in [30]. The very useful approach developed by Adams and Mead in that work was to examine the influence of modal parameters on structural response and then, using a simple but justifiable relationship between modal and material constants, the role of material properties was implied. A type of parameter study was developed to use a "figure of merit" for indication of the relative performance of structures composed of a given material under the action of various types of loading. For example, in the case of a structural mode excited by a random force, the material with the highest value of $[E^{-1/2} \rho^{1/2} \eta]^{1/2}$ yields the lowest root mean square stress. E is the modulus of elasticity, ρ is the material density and η is the modal loss factor (damping). Although such analyses may appear to be simplied, the importance of damping is clear in this case and the argument is, of course, even clearer in the case of resonant response under sinusoidal loading! In the case of shock excitation, the influence of material properties on the response of structures is not so clear; this is essentially because, as already noted above, criteria which firmly indicate damage potential have not yet been fully established. The proposal made in [27] that shock damage may be related to the energy input to a structural system indicates that it is again important to increase structural damping. Two methods of improving the dynamic properties of CFRP are being investigated:-

- the use of aligned discontinuous fibre reinforcement, perhaps in conjunction with continuous fibres, thus offering greater variability and control of resultant modulus of elasticity, damping and mouldability.

- the selection and use of a highly damped matrix material.

These studies have necessitated the development of both accurate experimental methods for measurement of material properties and novel moulding techniques for manufacturing specimens. Measurement of material properties in flexure and shear are carried out using fairly well established techniques [31,32] although some effort has to be devoted to deriving material damping properties from modal properties via knowledge of the stress distribution in the test specimen; for the shear case see [33,34]. Details of techniques for reliably moulding specimens with short, aligned fibre reinforcement are also given in [34].

The use of discontinuous carbon fibre reinforcement in plastics can yield a material with moderately increased damping as well as high modulus of elasticity compared with continuously reinforced composites. At short fibre lengths more shear strain is imparted to the matrix material and energy dissipation is increased. It can be seen that the CFRP composite offers the possibility of both high stiffness (from the fibres) and high damping (from the matrix-fibre interaction), a combination which may well prove valuable for structural purposes. The properties of these materials may be determined experimentally by testing composite specimens or by analytically predicting material properties as a function of the properties of the constituents and their geometrical relationship. The compromise which might be achieved in flexure is indicated in Figures 6(a) and 6(b) [35] which show modulus of elasticity and damping curves as a function of fibre aspect ratio (fibre length/fibre diameter). The data were derived theoretically but were confirmed via complementary experimental studies. The results of this study show that damping may be controlled to some extent via selection of fibre aspect ratio. The experimental studies involved commonly used fibres of 7μm diameter (hence the l/d scales in Figure 6) which had been chopped into short lengths and aligned in the test beams. It can be seen that at fibre lengths of about 0.25 to 0.75mm an increase of damping was achieved but this was associated with a decrease in stiffness. These trends may be exploited via a compromise construction in the fibre length region indicated. The damping values achieved were, however, not very high; there is therefore a need for matrix materials (resins) with enhanced dissipative properties.

For this reason, studies are underway concerning the use of more highly damped matrix materials in CFRP, using continuous and discontinuous reinforcement, under simple and combined loading. The objective is consistent with the above discussion, i.e. to develop a CFRP material or composite structural configuration achieving intermediate stiffness and damping properties compatible with high performance structural requirements. The results from preliminary studies are given in the latter part of [36] together with theory developed for derivation of loss factor information at high stresses which result in combined loading at the associated large amplitude flexural vibrations. The results are encouraging; a beam specimen was made which had a relatively high modulus of elasticity (115 GN/m^2) and flexural loss factor of 0.01. Whilst this damping value is not as high as would perhaps be wished, it is much greater than the loss factors associated with more conventional constructions (~ 0.001). Unfortunately, the stiffness of a composite in directions other than that of the fibre reinforcement is governed by matrix properties. Consequently, this specimen had low stiffness and strength in torsion and would perform poorly if subjected to shear loads, although undoubtedly the shear loss factor would be higher than the value quoted above. It should not be forgotten, however, that the objective is to ultimately arrive at a structural configuration which yields desirable dynamic characteristics. The studies carried out so far relate to material properties and the desirable trends in behaviour may well be exploitable via combinations of constituents in an advantageous "lay-up" in a composite structure. The results obtained so far are encouraging.

The practical structural design aspect of work on high performance structures has arisen again because of the use of composite constructions. In service, aircraft structures, for example, are subjected to dynamic loading which may cause fatigue damage. This is particularly a problem for panels which may be subjected to very high intensity acoustic excitation in regions close to jet engine effluxes. A considerable amount of research has been carried out in the past concerning the prediction of dynamic strains induced in aluminium alloy structures under the action of random acoustic loading. A major part of that effort was concerned with the development of simple methods for response prediction using the fundamental mode approximation for estimating induced strain levels. The design procedure was established by Clarkson [37] and has been extensively used in aircraft design and well validated for metallic structures. However, the use of new materials, such as CFRP, has necessitated some re-appraisal of the "Engineering" approach to dynamic response prediction. A necessary part of any such work is experimental testing using high intensity noise sources to drive panels and structures composed of arrays of panels. The test methods are well established, see [38] and [39] for example, but the controversy will probably always exist as to whether or not "siren testing" in a travelling wave facility is representative enough of the practical case in the aircraft installation and how results may be correlated between the two cases. However, such experimental work continues and the current stage is that there is renewed interest in acoustic fatigue testing, particularly related to composite structures, and higher levels of excitation are sought in order to be able to test specimens for aerospace applications.

The approach to structural design of composite structures for acoustic fatigue resistance is based on a mixture of theory and experiment to establish the design formulae, see [40,41] for example. Studies have been carried out to specifically examine use of the simple, single mode approximation formula of Clarkson for the prediction of composite panel response. The method may be used for thick, multi-layered plates but thin structures compared of a few layers exhibit grossly nonlinear behaviour which precludes use of such methods [42]. The thickness requirement for applicability of the simple stress estimation procedure is that, for typical aircraft constructions, panels should have six or more layers of fibres. The stress prediction methods are now available in data sheet form

[43] although the procedures are necessarily more complicated than that for metallic structures because of the great range of parameters involved in composite construction and computer programs form part of the data sheets. In other situations where nonlinear behaviour occurs in dynamic structural response, the prediction of fatigue life is difficult although some study has been made of nonlinearity due to large deflections, albeit at this stage in homogeneous beams, which suggest that the resulting induced combined dynamic loading may be reasonably well analytically modelled in order to facilitate fatigue life estimation [44,45].

The combined loading situation which naturally occurs in most structures has been largely overlooked but can be of critical importance in structural performance. Almost all structures are subjected to static (or quasi-static) loading with dynamic loading superimposed. This has been alluded to already in the damping studies discussed above. The skins of aircraft are subjected to compressive or tensile, in-plane loading together with, in some areas, acoustic loading. The in-plane tensile loading case has received much attention over the years because of the loading induced due to cabin pressurisation and this work is well reported upon in the literature. Compressive loading studies have been much rarer but the problem does occur in some aircraft skin panels during flight. The analogy with compressive loading of a strut perhaps immediately comes to mind when making a first appraisal of the problem and this comparison is useful because an effect of static, in-plane compression is to initially reduce the natural frequencies of a panel. The case of isotropic plates, under combined acoustic excitation and static, in-plane compression has been examined both theoretically and experimentally [46]. The work continued with composite (CFRP) panels [47] and damage in the form of an edge crack was included [48]. The effect of such damage is shown in Figure 7, which illustrates the change in the natural frequency of the 1,1 mode of a CFRP plate as a function of crack length and applied compression. Damage in composite structures and damage propagation are topics which will be studied in the years to come, not only because of accidental damage which may occur but because of imperfections which will always be present in these inhomogeneous materials. This aspect of composites research has not only stimulated structural dynamics activities but has brought about significant developments in non-destructive testing techniques. Not only is damage location important but damage propagation monitoring is of paramount importance in relation to structural integrity and life, although no clear rules for fatigue limits or damage tolerance have yet emerged for use by designers involved in aerospace work. Returning briefly to the compressive loading problem, it is accepted that certain parts of CFRP skins on aircraft might buckle and recover during in-flight loading. Post buckle behaviour is therefore now being examined.

It can be seen that not only has the introduction of composites into aerospace construction stimulated dynamics work in the "materials" field but structural dynamics work has received some considerable impetus to enter regimes which previously have not been well explored. Finally, one should not end with having given the impression that composites are only used in advanced aerospace constructions. The fields of application today are numerous [49]. For example, the tennis racquet has undergone some considerable structural changes recently [50].

6.0 CONCLUDING REMARKS

This review of some aspects of structural dynamics research related to vibration control has outlined some developments with which the author has been involved in essentially four areas, namely machinery isolation, vibration transmission through structures, dynamic testing and composite materials. The control of machinery induced vibration via resilient isolation was considered and frequency response methods for predicting coupled system performance are being used, although the need for simple approximate formulae for use in design calculations has been recognised. From this work, however, the need has also been recognised for a new approach to vibration transmission path identification; the fundamental and unifying concept of power flow analysis has therefore been introduced, both in theory and experiment. One of the most significant, recent developments is the structural intensity meter which enables power flows to be "mapped" in built-up structures to facilitate transmission path and mechanism identification. This technique shows great promise as a useful aid for vibration control studies in the future. There will, however, always be the need for more conventional experimental studies to determine resonance characteristics of structures in chosen modes of vibration, either as an activity which is complementary to theoretical work or as a critical test on complicated structures; flutter testing is a good example of the latter type of work. The rapid frequency sweep technique has been developed to fulful this role and its success has been greatly due not only to the availability now of good digital signal processing systems but also to the fact that it has been the subject of a considerable amount of critical theoretical and experimental investigation and validation in order that it should be accepted as an accurate structural vibration testing method. The method may be refined further in the years to come and may also find application in other areas such as shock testing but it is now well established amongst the variety of methods available to the experimenter who is involved in frequency response measurement. Dynamic testing work generally in the years to come will also increasingly involve the study of nonlinear systems and the associated identification problems.

The increasing use of composite materials in the aerospace industry has created a new stimulus for structural dynamics research. This involves study of material properties, structural design, dynamic response prediction, damage propagation, etc. if the full potential of this type of construction is to be realised. Design of structures to withstand in-service loading should be possible using the most suitable materials and structural configuration. Part of that requirement is damping control. It is undoubted that stiff, lightweight materials and structures can be made. Is the stiff, light, heavily damped material or construction a possibility without the use of additive damping treatments? It is believed that such a development is possible.

7.0 REFERENCES

[1] R.E.D. Bishop and D.C. Johnson, "The Mechanics of Vibration", Cambridge University Press, 1960.

[2] D.J. Ewins, "Measurement and application of mechanical impedance data". Part I Introduction and Ground Rules. Journal of the Society of Environmental Engineers", 3-12, 1975.
Part II Measurement Techniques, Journal of the Society of Environmental Engineers, 23-33, 1976.
Part III, Interpretation and application of measured data. Journal of the Society of Environmental Engineers, 7-17, 1976.

[3] E.E. Ungar and C.W. Dietrich, "High frequency vibration isolation" Journal of Sound and Vibration 4(2), 224-221, 1966.

[4] M.C. Junger, "Experimental measurement of impedance or mobility." Journal of Applied Mechanics, 277-278, June 1955.

[5] E. Skudrzyk, "Vibration of systems with a finite or infinite number of resonances". Journal of the Acoustical Society of America 30, 1140-1152, 1958.

[6] H.G.D.Goyder and R.G.White. "Vibrational power flow from machines into built-up structures. I - Introduction and analysis of beam and plate-like foundations. Journal of Sound and Vibration, 68(1), 59-75, 1980.

[7] R.G. White, "Vibration Control II." Chapter 26 in Noise and Vibration edited by R.G. White and J.G. Walker, Ellis Horwood 1982.

[8] R.J. Pinnington and R.G. White. "Power flow through machine isolators to resonant and non-resonant beams". Journal of Sound and Vibration, 75(2), 179-197, 1981.

[9] P.J. Holmes, "The experimental characterisation of wave propagation systems. I, non-dispersive waves in lumped systems". Journal of Sound and Vibration, 35 (2), 253, 1974.

[10] P.J. Holmes, "The experimental characterisation of wave propagation systems. II, Continuous systems and the effects of dispersion". Journal of Sound and Vibration 35(2), 277, 1974.

[11] N. Aoshima and J. Igarashi. "The measurement of flexural wave propagation by correlation techniques". University of Tokyo, ISAS report 436, 1969.

[12] G. Pavic and R.G. White, "On the determination of transmission path importance in dispersive systems". Acustica, 38(1), 76-80, 1977.

[13] F.J. Fahy, "Measurement of acoustic intensity using the cross-spectral density of two microphone signals". Journal of Acoustical Society of America, 62(4), 1057-1059, 1977.

[14] H.G.D. Goyder and R.G. White. "Vibrational power flow from machines into built-up structures. II Wave propatation and power flow in beam stiffened plates." Journal of Sound and Vibration, 68(1),77-96, 1980.

STRUCTURAL DYNAMICS AND VIBRATION CONTROL

[15] G. Pavic. "Measurement of structure borne wave intensity. Formulation of the methods." Journal of Sound and Vibration, 49(2), 221-230,1976.

[16] G. Pavic. "Techniques for the determination of vibration transmission mechanisms in structures". Ph.D. Thesis, University of Southampton, 1976.

[17] W. Redman-White. "The experimental measurement of flexural wave power flow in structures". Proceedings of the Second International Conference on Recent Advances in Structural Dynamics". ISVR, April 1984.

[18] W. Redman-White. "The measurement of structural wave intensity". Ph.D. Thesis, University of Southampton, 1983.

[19] G.R. Tomlinson and N.E. Kirk. "Modal analysis and identification of structural nonlinearity." Proceedings of the Second International Conference on Recent Advances in Structural Dynamics. ISVR, April 1984.

[20] R.G. White. "Vibration Testing". Chapter 27 in Noise and Vibration edited by R.G.White and J.G. Walker. Ellis Horwood, 1982.

[21] H.G. D. Goyder. "Methods and Application of Structural Modelling from measured structural frequency response data". Journal of Sound and Vibration 68(2), 209-230, 1980.

[22] D.J. Ewins and P.T.Gleeson. "Experimental Determination of Multi-directional mobility data for beams. Shock and Vibration Bulletin 45(5). 158-173, 1975.

[23] R.G. White and R.J. Pinnington. "Practical application of the rapid frequency sweep technique for structural frequency response measurement". The Aeronautical Journal of the Royal Aeronautical Society, 179-199, 1982.

[24] M.R. Turner. "Analysis Techniques used in aircraft flutter testing". Symposium on experimental techniques in applied mechanics. Polytechnic Institute Bucharest, Nov. 1972.

[25] J.S. Bolton and M.D.C.Dyne. "An improved technique for the valuation of structural dynamic response." Mecanique, Materiaux Electricite. Revue des techniques au service de l'industrie, Mars-Avril, 1984.

[26] R.G. White. "Shock testig using a controlled, oscillatory waveform". Journal of the Society of Environmental Engineers, 1-11, 1982.

[27] R.G. White. "The material damping of carbon fibre reinforced plastics in shock and vibration control". Mecanique Materiaux Electricite. Revue des techniques au service del'industrie, Mars-Avril, 1984.

[28] D. Velupillai, "British Aerospace goes for composites". Flight International, November 1978.

[29] J.F. Schier and R.J. Juergens. "Design impact of composites on fighter aircraft. Pt I They force a fresh look at the design process". Aeronautics and Astronautics, 21(9), 44-49, 1983.

[30] R.D. Adams and D.J. Mead. "Selection of materials for vibrating structures". Machinery 120, 1972.

[31] G.C. Wright. "The dynamic properties of glass and carbon fibre reinforced plastic beams". Journal of Sound and Vibration 21(2), 1972.

[32] R.G. White. "Some measurements of the dynamic properties of mixed, carbon fibre reinforced plastic beams and plates." The Aeronautical Journal of the Royal Aeronautical Society, 318-325, 1975.

[33] R.J. Hooker. "High Damping Metals". Ph.D. Thesis, University of Southampton, 1975.

[34] E.M.Y. Abdin, "Dynamic Properties of some carbon fibre reinforced plastics". Ph.D. Thesis, University of Southampton, 1982.

[35] E.M.Y. Abdin and R.G. White. "Dynamic properties of aligned short carbon fibre reinforced plastics in flexure and torsion" to be published.

[36] T.A. Palmer and R.G. White. "Development of carbon fibre reinforced plastics for use in high performance structures". Fibre reinforced composites 84. Proceedings of the Conference, University of Liverpool, April 1984.

[37] B.L. Clarkson. "Stresses in skin panels subjected to random acoustic loading". The Aeronautical Journal of the Royal Aeronautical Society, 1968.

[38] B.L. Clarkson. "Acoustic fatigue test facilities". Chapter 19 in Noise and Acoustic Fatigue in Aeronautics, edited by E.J. Richards and D.J. Mead. John Wiley, 1968.

[39] B.L. Clarkson and S.A. Pietrusewicz. "The University of Southampton random siren facility." Report, ASD-TDR-63-91, 1963.

[40] I. Holehouse. "Sonic fatigue design techniques for advanced composite airplane structures". Ph.D. Thesis, University of Southampton, 1984.

[41] J. Soovere. "Dynamic response of acoustically exicted stiffened composite honeycomb panels". Ph.D. Thesis, University of Southampton, 1984.

[42] R.G. White. "A comparison of some statistical properties of the responses of aluminium alloy and CFRP plates to acoustic excitation." Composites, October 1978.

STRUCTURAL DYNAMICS AND VIBRATION CONTROL

[43] Engineering Sciences Data Unit (ESDU), London.
Data sheets on:-
1. Estimation of the stiffnesses and apparent elastic properties of laminated flat plates.
2. Natural frequencies of rectangular, specially orthotropic laminated plates.
3. Estimation of RMS strain in laminated panels subjected to random acoustic loading.

[44] M.M. Bennouna and R.G.White. "The effects of large vibration amplitudes on the fundamental mode shape of a clamped-clamped beam". Journal of Sound and Vibration 95(2), 1984.

[45] M.M. Bennouna and R.G. White, "The effects of large vibration amplitudes on the dynamic strain response of a clamped-clamped beam with consideration of fatigue life". Journal of Sound and Vibration, 95(2), 1984.

[46] R.G. White and C.E. Teh. "Dynamic behaviour of isotropic plates under combined acoustic excitation and static in-plane compression". Journal of Sound and Vibration, 75(4) 527-547, 1981.

[47] C.E.Teh and R.G. White, "Dynamic response of isotropic and anisotropic panels under simulated flight loading conditions" Proceedings of the first international conference on recent advances in structural dynamics". ISVR, 1980.

[48] C.E.Teh, "Dynamic behaviour and acoustic fatigue of isotropic and anisotropic panels under combined acoustic excitation and static in-plae compression." Ph.D. Thesis, University of Southampton, 1981.

[49] Modern materials in manufacturing industry. The Fellowship of Engineering, 1983.

[50] R.C. Haines, M.E. Curtis, F.M. Mullaney and G. Ramsden. "The design, development and manufacture of a new and unique tennis racquet". Proceedings of the Institute of Mechanical Engineers, 197B, 1983.

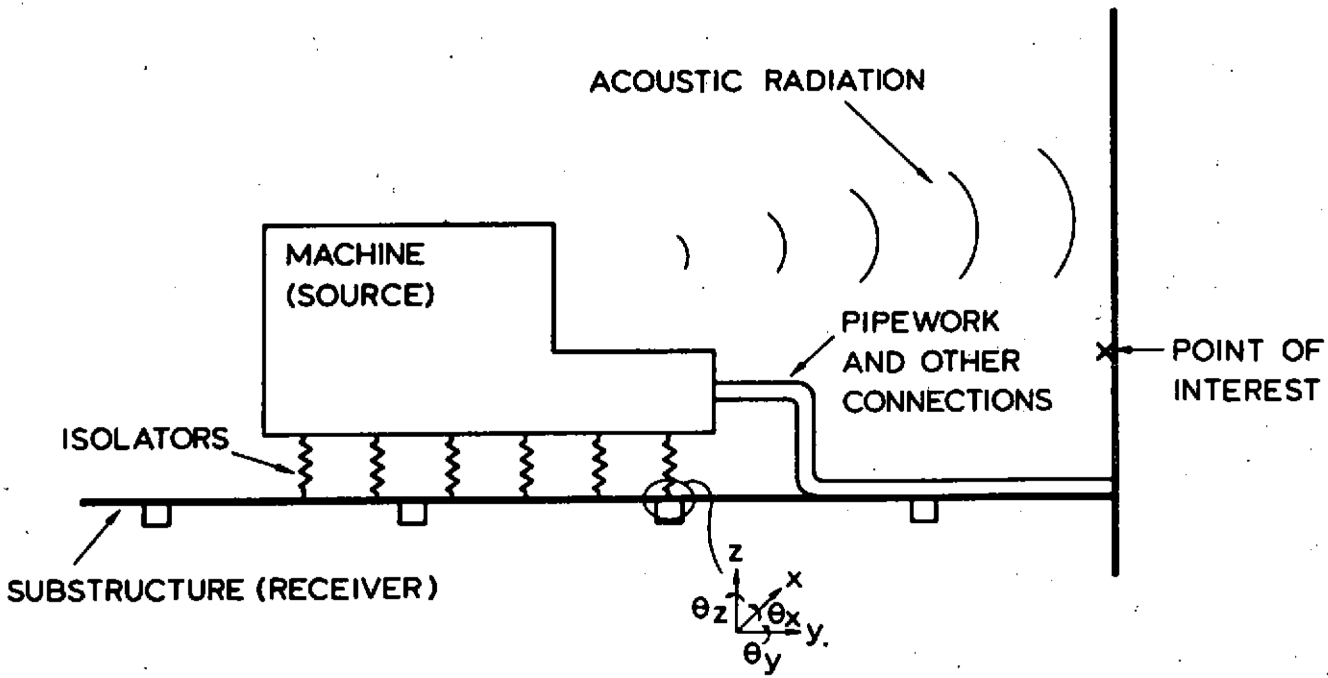


FIG. 1 A MACHINE INSTALLATION

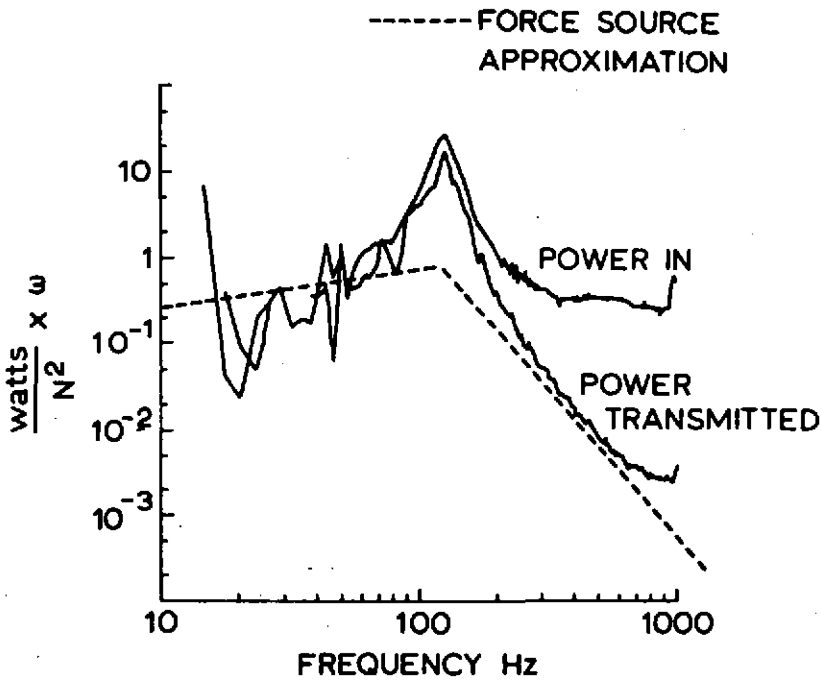


FIG. 2 POWER × ω, INPUT TO ISOLATOR AND TRANSMITTED TO AN "INFINITE" BEAM, FOR UNIT FORCE SPECTRAL DENSITY.

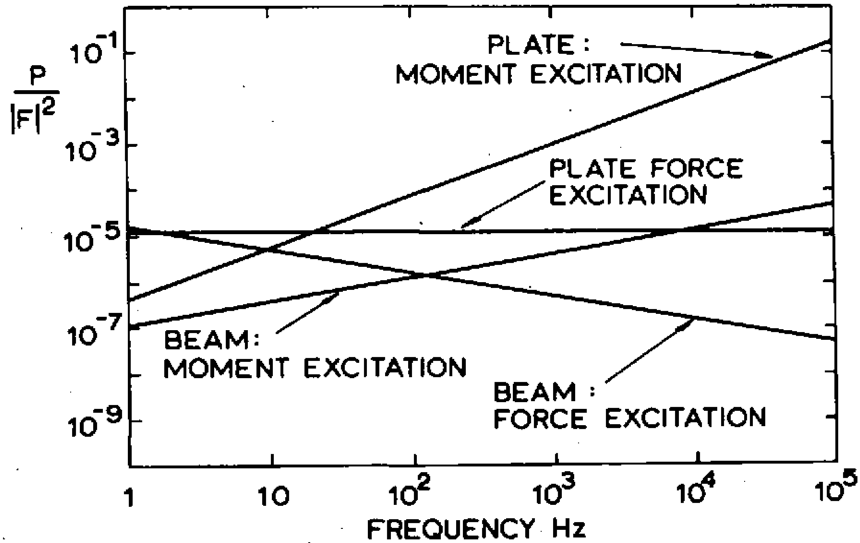
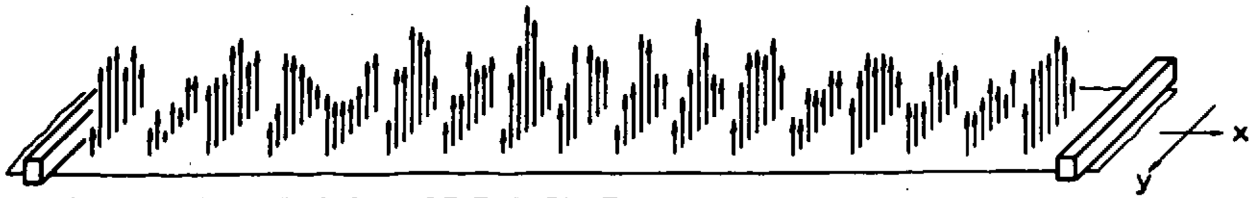
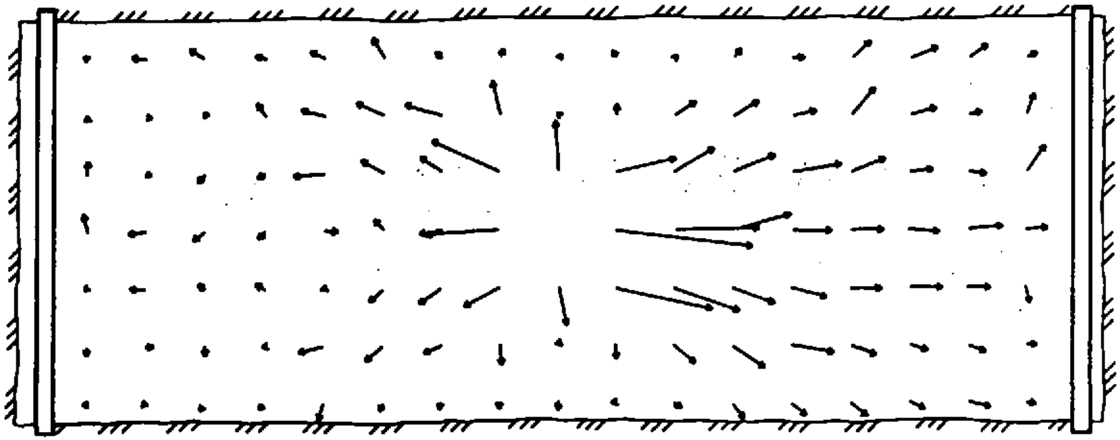


FIG. 3 POWER INPUT TO FLEXURAL WAVE MOTION IN A BEAM OR PLATE DUE TO FORCE OR MOMENT EXCITATION.



(a) ACCELERATIONS OF THE PLATE



(b) POWER FLOW DUE TO FLEXURAL WAVE MOTION IN THE PLATE

FIG. 4 POWER FLOWS AND ACCELERATIONS IN A PLATE WITH REFLECTING DEVICES AT THE ENDS.

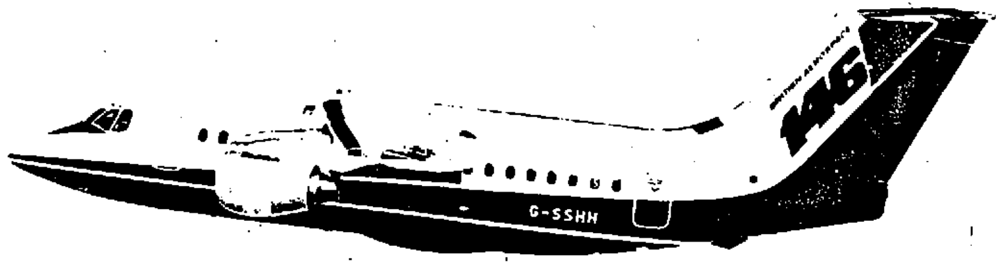


FIG. 5 THE BRITISH AEROSPACE 146-100 AIRCRAFT WHICH RECEIVED FLUTTER CLEARANCE FOR CERTIFICATION BY TESTING USING THE RAPID FREQUENCY SWEEP TECHNIQUE.

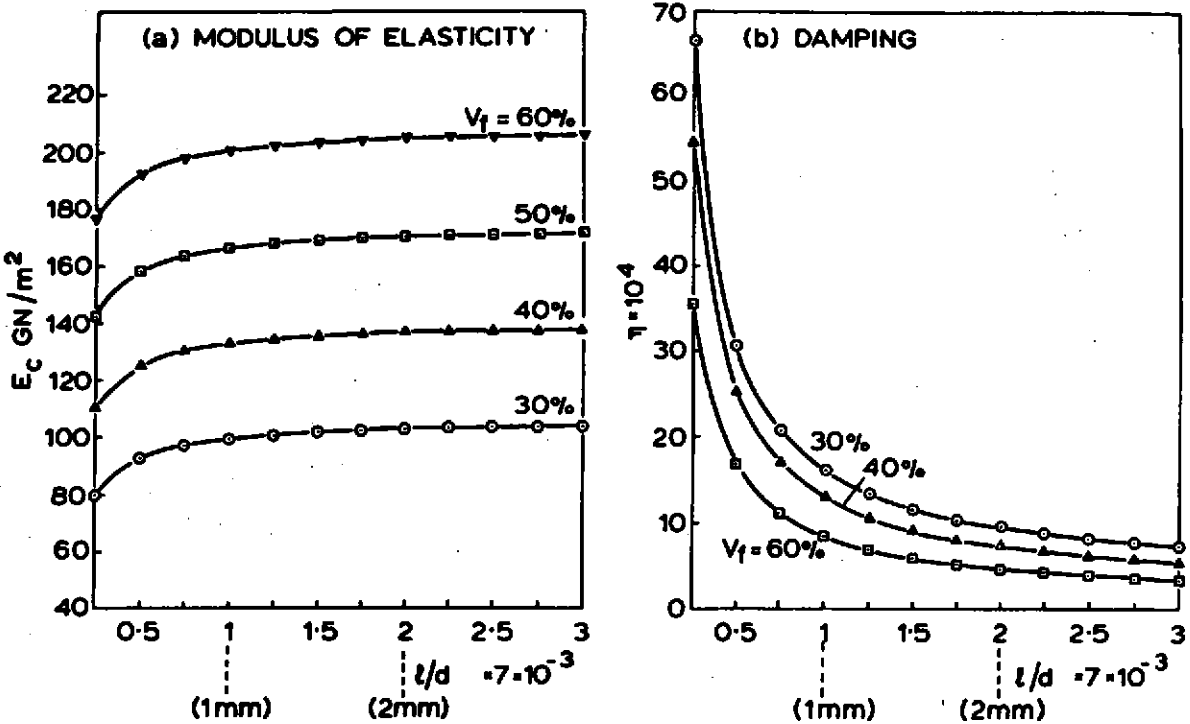


FIG. 6 VARIATION OF MODULUS OF ELASTICITY, Ec, AND LOSS FACTOR η WITH FIBRE ASPECT RATIO, ℓ/d, FOR ALIGNED, SHORT, CFRP COMPOSITES FOR VARIOUS FIBRE VOLUME FRACTIONS, V_f.

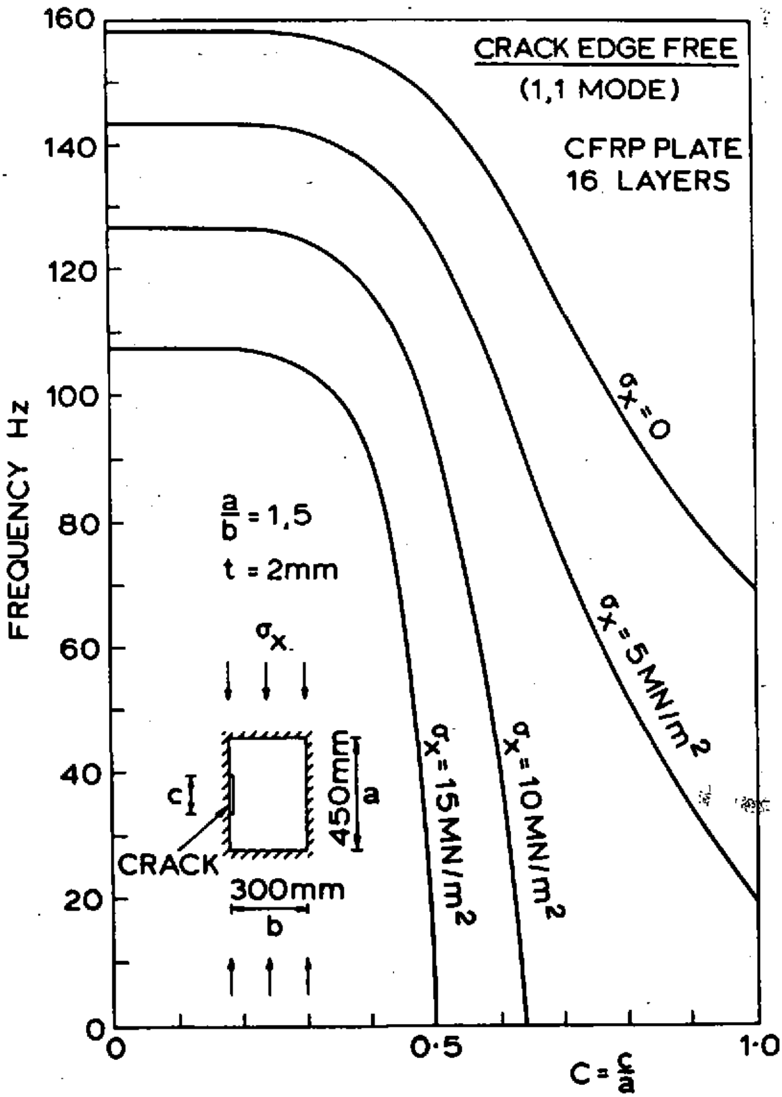


FIG 7 EFFECT OF CRACK LENGTH AND COMPRESSIVE STRESS ON THE NATURAL FREQUENCY OF THE 1,1 MODE OF A CFRP PLATE.