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TRANSIENT TESTING OF STRUCTURES FOR VIBRATION CONTROL

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1. Introduction

If experimental measurements are to be made on a complicated structure, the experimenter is confronted with several problems. A technique which has a known degree of accuracy must be chosen, the data must be analysed and presented in a form which facilitates characterisation of the system dynamics and finally, for both technical and financial reasons, it is usually desirable that as little time as possible be spent at the measurement site. It can thus be seen that transient methods for measuring structural frequency response are attractive and the rapid frequency sweep technique has therefore been developed. A description of the method is given here.

There are some general, practical difficulties associated with the measurement of point and transfer functions. For example, it is difficult to obtain representative measurements of point characteristics at high frequencies and signal to noise ratios are often low in transfer measurements. These two problems are discussed here with reference to transient testing. However, even if a limited set of point and transfer characteristics are measured accurately, these quantities do not completely characterise the structure and do not yield information concerning the effects of application of possible vibration control procedures. For these reasons, work has been carried out on structural modelling from experimental data derived from practical measurements on structures and a development in this area is also reviewed.

2 Structural testing

Structures, because they are continuous systems, possess an infinite number of degrees of freedom. The assumption of a finite number of degrees of freedom simplifies theoretical analyses but the problem of analysis by dynamic testing still appears complicated. The problem which confronts the experimenter is to excite the system, measure the response and present the derived information which should be readily understood. The assumption of even a limited number of degrees of freedom is not helpful in this direction. The analysis of multi degree of freedom systems is however generally simplified by applying single degree of freedom system theory to each resonance, the complete response being represented by superposition. This representation is applicable of course only to linear systems and the assumption of linearity is made here, as is almost always the case in resonance testing, the dynamic analysis of non-linear systems being complicated both theoretically and experimentally. However, as structures behave linearly for small deflections, if care is taken in resonance testing to generate only low response levels then nonlinear effects may be ignored |1|. Using the single degree of freedom system analogy for response in each mode of vibration, measurements of natural frequency and damping may be made by using simple analysis procedures. Mode shape measurement obviously involves spatial analysis but this is generally achieved by repeating frequency domain analysis at various points on a structure.

The preceding discussion is concerned with the measurement of the characteristics of each resonance of a structure. It is often required to measure frequency response characteristics over a wide frequency range, perhaps as part of a study of proposed isolation system design. Thus scaled complex frequency response funtions, that is the relationships between excitation and a particular physical response, must be measured. For three-dimensional systems, displacement and its derivatives may be measured in the three coordinate directions, also rotational responses to a given force may be measured; this is of particular importance for example in the investigation of machinery seatings. Most of the dynamic testing currently carried out is however generally concerned with the measurement of response to an applied force in the same coordinate direction.

3 The rapid frequency sweep test method for structural frequency response measurement

It is highly desirable when practical dynamic testing is being carried out in field trials of any type that test times should be as short as possible. Steady state testing is not often used now in this type of work, although steady state methods have been refined recently by the introduction of computer control |2|. Slow sweep testing does offer a reduction in test time but the method is still somewhat time consuming, and measuring systems need a very high dynamic range. Interest in transient test methods as a structural test arose due to the development of digital computer-based analysis systems with fast Fourier transform routines. Consideration of pulse-type forcing functions for transient testing |3| showed that pulses of simple shape are not completely suitable for structural testing because of zeros in modulus spectra which give regions of zero response and uncertainty in measured data derived by division of Fourier transforms. The rapid frequency sweep has been found to be suitable for this purpose.

The rapid frequency sweep, in which perhaps typically two decades in frequency are swept linearly in one second, has an essentially flat modulus spectrum and high cut off rates at the starting and stopping frequencies. The usefulness of this function |4| is obvious and it is applied to the test structure through a conventional, power amplifier-electrodynamic exciter-force transducer combination. The setting up time for this equipment is the same as for the other type of tests mentioned above, although hand-held exciters have been used to advantage |5|, but the test time is very short, being typically about 5 seconds. Frequency response data may then be derived by division of Fourier transforms, this usually being carried out "off-line" from tape recorded data in field trials and "on-line" in laboratory experiments. The reduction in test time is obvious and instrumentation systems with 60 dB dynamic range are adequate |6|; it should be noted that data dynamic ranges in the frequency and time domains are not the same in the transient test, as is the case in steady and quasi-steady state testing. The rapid frequency sweep test method has now been used quite widely, both with direct Fourier transform analysis and the use of correlation techniques, |7-12|. As is most often the case, linear structural behaviour was assumed in those works, and is assumed here, although some attention has been given to the effects of nonlinear behaviour |13|.

The mobility (velocity/force) approach is often used in structural analysis because the data may be used to estimate coupled system performance in a manner analogous to that used in circuit analysis by Electrical Engineers. For example, if vibration isolation systems are to be designed for maximum effectiveness, the point mobilities at the attachments to the mounting structure must be known, the peak mobility levels being very important and it being very useful to gain information on typical levels for various types of structure. Transfer mobilities give an indication of levels produced at stations remote from the source. As noted in section 2, for complete characterisation, the complete set of mobilitites involving all translational and rotational components should be measured. Discussion of measurement problems is however restricted here to the translational case.

Point measurements

It is often required that measurements be made at high frequencies and although upper frequency limits of the instrumentation systems used may be understood, mechanical limitations may not be so clear. At high frequencies a contact resonance may occur between the force transducer or "impedance head" and the structure under test; this is caused by material deformation between the transducer and the test structure. The contact stiffness may be estimated |14| and the contact resonance frequency calculated.

The problem may be illustrated by carrying out measurements on a suspended mass, the mobility of which should theoretically follow a simple characteristic. Measured data are shown in |15|, derived via transient testing with a conventional electrodynamic excitation system, which illustrate the effect. Contact effects were apparent in the point characteristic but the transfer characteristic followed the mass line law to a frequency at which internal resonances of the mass occurred. Such characteristics are to be expected |16| but the theoretical point mobility curve showed that the effects of contact resonance can be predicted and noted in the examination of measured data. At frequencies above the contact resonance frequency, the point mobility followed a stiffness line. Generally, point characteristics will only be useful for estimating coupled system performance if experimental data are obtained with the appropriate area of of contact. Point measurements on built-up structures often exhibit stiffness-like behaviour at high frequencies and this could be due to contact effects.

Transfer measurements

Quite small exciters may be used to obtain point characteristics, assuming linear behaviour to occur. For transfer measurements it could obviously be useful to employ as large a vibrator as possible in order to produce clearly defined response signals with a good signal to noise ratio at the remote station. However, there are usually problems associated with transporting and installing large vibrators in field work. Hence, with only moderate forces being generated, signal to noise ratios may not be very high in transfer measurements. The rapid frequency sweep involves the use of excitation which produces a deterministic response signal which may be contaminated by extraneous noise components. The transient test may however by repeated many times and hence the method lends itself readily to time domain averaging. Exact repetition of the excitation is highly desirable and this may be achieved by use of a very stable oscillator or by repeatedly replaying a single, pre-recorded, rapid frequency sweep. However, phase shift between records will be inevitable because of time-base instability or triggering errors in the acquisition and digitisation of the analogue data.

This effect has been studied for the linear swept sinewave |15|. It is usual in rapid frequency sweep testing to sweep from low to high frequency; the reason for doing this is to minimise record lengths by exciting low frequency resonances first. If a time domain average is to be formed of many sweeps from low to high frequency, it can be seen that small phase errors in data acquisition will cause errors in both the averaged time signal and derived spectrum and these will be particularly evident in the high frequency region. The effects of phase errors have been quantified and typical results are presented in |15|.

The transmission characteristics of structures may also be studied by cross correlation methods; however as flexural wave motion is predominantly of interest, dispersion is a problem. Conventional cross correlation is generally only successful when the transmission paths are nondispersive. Special transient excitation functions have been developed to overcome this problem |12| which enable attenuation measurements to be made at a single frequency. However, if the dispersion law is known, as is the case for beams and plates, a cross correlation function between signals at two points on a structure can be generated which will yield attenuation factors directly |17|. Broad band, transient excitation is applied to the structure and the Fourier transform of the response signal from the first point evaluated. From knowledge of the dispersion law, the first Fourier transform can be multiplied by a transfer function to yield a product which can be inverse Fourier transformed. This generated signal is then cross correlated with the signal from the second point to yield a meaningful cross correlogram. The average attenuation factor can be derived from the peak value of the correlogram.

4 Structural modelling

It will now be apparent from the above discussion that it is possible to obtain a considerable amount of experimental data in a relatively short time using transient excitation and computer analysis. This can lead to the situation where many graphs of required quantities, mobility for example, have been produced and it is difficult to understand the complete dynamic behaviour of the test structure. Conversely, if test programmes are very limited or have to be curtailed, only a limited amount of experimental data may be acquired. In either case, it may be required to predict the response of the structure to some specified excitation, perhaps from a machine mounting, at points which have not been examined experimentally. Also, frequency response functions alone are of no immediate practical benefit for investigating the effects of possible modifications or vibration control procedures which could be carried out. For these reasons, a structural modelling technique has been developed, based on experimental data.

The approach adopted |18| has been to create a mathematical model of a structure employing only measured data and making no assumptions concerning the form of possible governing differential equations. The advantage of this approach is that large amounts of measured data can be reduced to simple numerical parameters which give insight into the vibration mechanisms. In addition, once the model has been created, further analyses concerning the effects of modifications or addition of extra systems are facilitated. The modelling procedure is carried out by using a digital computer to curve fit general algebraic equations to the measured frequency response data of a structure. Generally, sufficient data for the model may be obtained by employing one excitation point and several response measurement stations for transfer function measurement. From the model, transfer functions between any forcing and response stations can be estimated and the problem of physically difficult testing, e.g., the response to moments, is obviated because these functions can be estimated. The parameters obtained after curve fitting are complex mode shapes and resonance frequencies, which are meaningful if vibration control measures are to be attempted.

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