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NON-DESTRUCTIVE IN-SITU TESTING USING DYNAMIC TECHNIQUES

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SUMMARY

The use of measured dynamic parameters for the monitoring of the performance of tall buildings is discussed, and recommendations about the use and measurement of each parameter is made.

INTRODUCTION

The use of dynamics techniques has been established by a number of series of full-scale tests from several investigators around the world, on several different types of structure. The tests actually have a wider application than the measurement of dynamic response, since it is possible to look on "static" or "quasi-static" tests as dynamic tests conducted at very low frequency. It is, then, possible to use the parameters measured in dynamic testing to give information about a structure that is often obtained by more conventional means. In fact the potential for dynamic testing is large, because potentially, it is possible to obtain information that is not obtainable in any other way. However, the precision of measurement is vitally important if significant behavioural changes are to be identified, and this is further discussed in this paper.

RATIONALE FOR DYNAMIC TESTING

If an assumption of linear visco-elastic behaviour is made for the dynamic response of a structure, then the equations describing that response are relatively simple in form, and relate the response to a frequency domain product of the forcing function and the complex frequency response of the structure (1). The solution of these equations at resonance leads to the ability to draw some interesting inferences about the building's performance. Identification, by measurement, of the dynamic parameters of natural frequency, damping ratio, and displacement in response to a known force, allows inferences about the mass and the stiffness of the structure to be drawn (this stiffness is approximately the same that would be measured in a conventional static load test). Additionally it is possible to use the measured response of the structure, together with the measured dynamic properties, to infer what the impinging forces must be. This approach effectively uses the building itself as a transducer.

In fact the linear visco-elastic equations do not accurately reflect the response when the amplitude of a mode of vibration increases. The full-scale tests conducted by the Building Research Establishment have sought to investigate the changes that occur with changing amplitude, this is considered below, and the resulting lessons for interpretation of dynamic parameters in terms of building behaviour are discussed.

RESULTS FROM FULL-SCALE TESTS

As a result of the experience of inducing controlled vibrations in structures at various amplitudes (2), it has become apparent that dynamics tests that do not reference the measurements to amplitude leave a great deal of useable information untapped. However, there are some parameters that do not change greatly with changes in amplitude, and these can, therefore, be used only to show whether gross changes in the structure have taken place. A case in point is the natural frequency. Figure 1 shows the relationship between fundamental natural frequency and height for a population of 163 buildings throughout the world. The simple formula that ensues is a function of the small variability of frequency with amplitude, and the probability that given a required height for a building, the design will be constrained to be within certain "norms", which conspire to produce a "normal" frequency. A building which has a fundamental natural frequency which lies a long way from this line may have some unusual aspects to it's behaviour.

The values of stiffness and mass that are possible to obtain from these tests are a guide to the design and behaviour of the structure. It has been suggested (3)

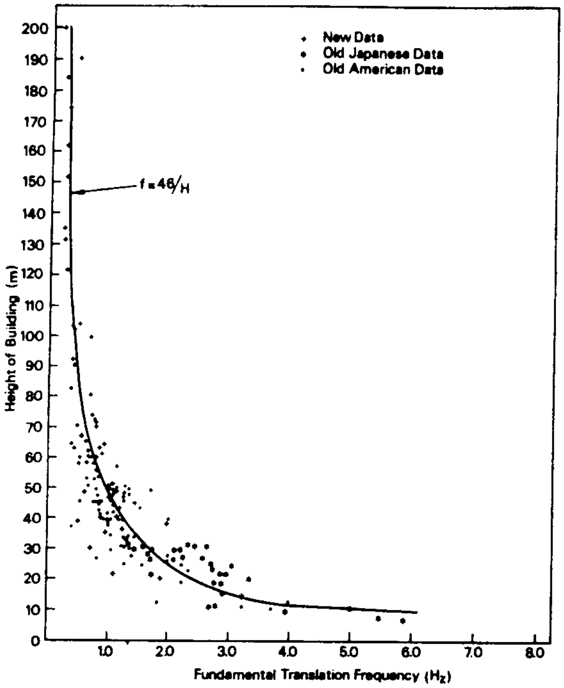


Fig. 1 Frequency vs. height for 163 rectangular plan buildings.

that low amplitude values of damping may also be correlated with natural frequency (and thereby height). In the same way that normal frequency values can indicate abnormal behaviour these normal values for other dynamic parameters can be used as a guide to the normal behaviour of the structure.

The table below is given as an example of the data which result from a induced vibration test on one mode of vibration.It is chosen to be representative.

TABLE 1 SUMMARY FOR DUNSTAN FLOUR MILL

MODE	AMP (m.m.)	FREQUENCY (Hz.)	DAMPING (% crit)	MODAL MASS (x10*6 kg)
NS1	2.75	1.45	2.60	0.875
	2.09	1.46	2.43	0.924
	1.42	1.47	2.42	0.914
	0.75	1.48	2.29	0.916
	0.47	1.48	2.18	0.938
	0.33	1.49	2.11	0.942
	0.18	1.49	2.02	1.000

As can be seen, for quite large changes of amplitude the frequency changes little, whilst the damping value shows relatively large changes. This point is emphasised by considering a unique test conducted in the laboratories of the BRE in 1978. In these tests a quarter scale model of an 18 storey apartment block was constructed and the opportunity was taken to perform vibration tests on it at various stages of it's gradual destruction (6). These tests served to show the gross effects on the natural frequency of removing parts of the structure, but perhaps more importantly, demonstrated that modes of vibration moved apart in frequency when damage to a localised area in the structure occurred. The behaviour of torsional modes of vibration was particularly important here.

ENERGY DISSIPATION IN STRUCTURES

Before considering the measurement of dynamic parameters, and their usefulness, it is instructive to consider the mechanism of energy dissipation, or damping in structures. The equations that are used to describe dynamic behaviour use one of three forms to describe energy dissipation. These are known as the viscous model, the hysteretic model and the friction model of damping. All models have deficiencies in their prediction of response under changing amplitude. In the case of the hysteresis model, it predicts that with increasing damping the natural frequency will increase. In fact the opposite is observed in practice. In the case of the viscous model the prediction is that the amount of energy dissipation remains constant right down to zero frequency. In practice the amount gradually decreases (as is observed in the narrowing of hysteresis loops in model tests). In the case of the friction (or coulomb) model no dynamic solution to the equations is possible at all, as the response merely follows the input.

A combination of the first two models can be assembled in which these two anomalies are avoided (4), and the behaviour observed in practice is predicted. The practical result is that a model for energy dissipation can be formulated in which physically realiseable friction is the mechanism for the energy dissipation.

The mechanism of energy dissipation is then supposed to be the following: For practical purposes, all energy dissipation is caused by rubbing surfaces. Since some of these interacting surfaces are locked together at small amplitudes the amount of energy dissipation will increase with increasing amplitude as more and more of these surfaces unlock at higher stress levels. Eventually, all possible interacting surfaces are unlocked and a plateau level of damping is encountered.

The question of the mechanism at extremely low amplitudes is unresolved, in that it is not yet proven whether, at decreasing amplitudes damping continues to decrease to a zero value at which all surfaces would be effectively locked together, or whether a low amplitude plateau region also exists. If the former is the case then equations from soil mechanics can be used to describe the damping behaviour in this region (5), and if the latter is the case simplified formulae for prediction of damping values (3) are easier to justify theoretically.

Luckily, the middle region, which is most important for the practical case, is the one where most practical data have been obtained. In this region there is a link between stiffness and energy dissipation. As more surfaces mobilise, the stiffness of the structure will decrease, and correspondingly, the damping of the structure will increase. It is this factor which presents possibilities for the long-term monitoring of buildings for integrity purposes. An increase in damping value for similar excitation conditions can be taken to indicate a deterioration in the structure of the building, in that it can be interpreted as indicating the mobilisation of more parts of the building. However, the effects are relatively small (as can be seen from the table), and so the chances of using this effect are greatly enhanced if the excitation conditions are kept constant.

DYNAMIC PARAMETERS AND THE INFLUENCE OF STRUCTURAL CHANGES ON THEM

Each of the measurable dynamic parameters is more or less useful in the long-term monitoring of structures, depending on the obtainable precision of measurement, and on the inferences that can be drawn from the particular parameter. These factors are considered here:

1)Mass

Changes in mass can be used only to indicate gross changes to the structure. A test by BRE in which a building was tested with a water tank at the top of the building first full, and later empty, suggests that forced vibration tests are incapable of resolving differences of 10% of the modal mass. Changes of mass at lower levels in a building have progressively less effect on the dynamic behaviour of the entire structure.

2)Frequency

Natural frequencies show little change for quite large changes to the structure (2). Of more potential benefit is the observation of the inter-relationship of modes of vibration. Analysis of the frequency response to a random excitation tends to show a fragmentation of response, and therefore does not offer much scope for integrity monitoring. (Individual spectral spikes within a resonance region have very large variance errors associated with them.)

3)Damping

The change in damping, in the light of the mechanism discussed above, seems to suggest that this parameter is a useful indicator of structural changes within a building. Measurement techniques, however, are still often quite imprecise. The mechanistic link between damping and stiffness suggests that damping changes may indirectly indicate small localised areas of changing stiffness.

4)Stiffness

The measurement of stiffness gives modal values for an entire structure, and can be calculated from the product of the circular natural frequency squared and the modal mass (ideally summed for all modes in each direction, but for tall buildings the use of only the first translational modes gives a good approximation). The observations for these two parameters are therefore applicable here, and it is concluded that stiffness measurements can be used only to demonstrate gross changes to the structure. This observation applies to more traditional load testing as well.

5)Mode shapes

Mode shapes can be measured most accurately only when conducting induced vibration tests. Their observation can be used to show localised changes in the structure, or the onset of increased soil-structure interaction. A typical set of mode shapes for a tall building is shown in Figure 2.

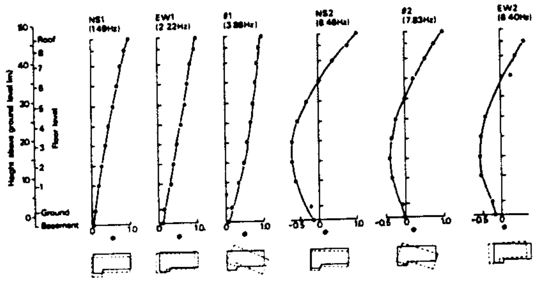


Fig. 2 Mode shapes measured for a 37 metre tall building.

THE PRACTICAL PROBLEMS INVOLVED IN THE USE OF THESE TECHNIQUES

Induced vibration testing seeks to define dynamic parameters under well controlled conditions, for any of several different purposes. The precision to which these parameters can be estimated is fundamentally important to the successful use of the techniques which may be attempted. The temptation to use ambient sources of excitation on the grounds of cost or expediency, is great, but the downgrading of the precision of estimating parameters is significant. This is principally caused by the non-stationary nature of many naturally occurring phenomena (e.g. wind storms). Spectral techniques require stationarity of data, and so the investigator may be forced to use ensemble averaging techniques (7). In this case the quantity of data necessary and the cost of the analysis systems required may outweigh the seeming benefits. Additionally, where several factors may influence the forcing function (e.g. in ocean engineering the variables may be wind speed,wind direction, wave height, current velocity and current direction), then the required data base for accurate assessment of the change in parameters may be prohibitively large. This is not to rule out the possibility that lesser precision may give some pragmatic guidance.

In induced vibration testing a high precision vibrator system is necessary. The stability of force and frequency (1% and 0.1% respectively) are of fundamental importance. The BRE identified a need for such a vibrator system after some initial experience with vibration testing in the early 70's. Accordingly, in 1976, the BRE let a contract to Bristol University to design and build a system which would meet a stringent specification. The prototype system was completed in December 1977 and the full system was operational by August 1978. This system has been used in tests on 11 tall buildings and ten dams. It comprises four exciters, each of which has its' own 'slave' control unit, driven by a master unit which controls the whole system. The frequency required is clocked from a crystal oscillator which is precise to one part in a million. The use of servo control techniques allows the frequency of the vibrators to be controlled to a 0.001 Hz. precision. Operation is possible up to a maximum of 20 Hz.

The exciters each consist essentially of two sets of contra rotating weights to which may be added further weights, thereby allowing the force to be varied. The force produced in this way has been calibrated using a load cell and is well within the 3 per cent of the original specification. With the maximum number of weights attached a force of nearly one tonne peak to peak is achieved at one Hertz. The servo control system allows each unit to be run either in phase or anti-phase to the master control demand, and is accurate to 1 degree. The exciters are mounted on rings of steel designed so that each unit may be rotated to any desired orientation in the horizontal plane. The induced vibration testing conducted by BRE then uses several different force levels to define the dynamic characteristics in the following terms.

1)Displacement or rotation as a function of frequency and position

2)Natural frequencies as a function of amplitude

3)Damping as a function of frequency and amplitude

The equation for response at resonance can then be used to calculate modal mass. Subsequently stiffness can be calculated from a knowledge of natural frequency and modal mass.

The measurement of displacement is normally achieved in tall buildings by the use of accelerometers. These devices facilitate on-site calibration and the acceleration response can easily be converted to displacement if a sinusoidal response is used (induced vibration) or can be assumed.

The measurement of frequency is relatively simple using standardised, modern electronic techniques.

At present, the measurement of damping is achieved in one of the following ways:

i)Half power bandwidth: This method involves assessing the form of the resonance peak. In it's simplest form, measurements of the width of a resonance peak at the $1/\sqrt{2}$ amplitude level, together with a knowledge of the natural frequency can be used to assess the relevant damping value. In fact this approach is an assessment of the frequency domain equations at only two points. It is possible to assess them at all measured points, and this approach leads to an improvement in measurement accuracy (8). Modal interference need not be a problem if curve fitting techniques involving phase and amplitude of response are used.

ii)Run down method: This technique involves exciting the structure to a required amplitude and then suddenly stopping the source of excitation. The ensuing decay of oscillation can be used to assess the damping value, and if this is plotted over a large amplitude range, it can be used to assses the change of damping with amplitude as well (2). Figure 3 shows a record of the decay of oscillation ensuing when the excitation of a building is suddenly ceased. The change of damping with amplitude is easily seen.

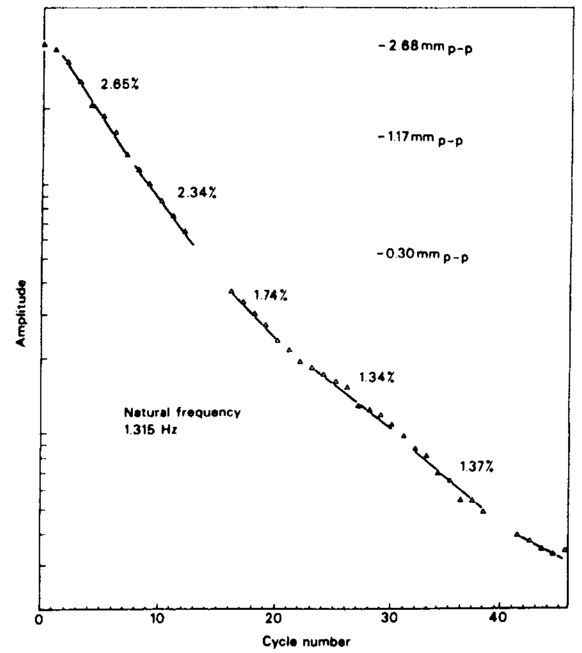
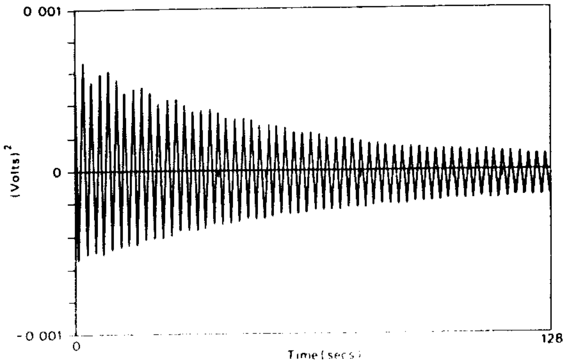


Fig. 3 Decay of oscillation in a fundamental mode of a 16 storey building.

The close proximity (in frequency) of another mode of vibration can cause sufficient interference to make this technique unuseable.

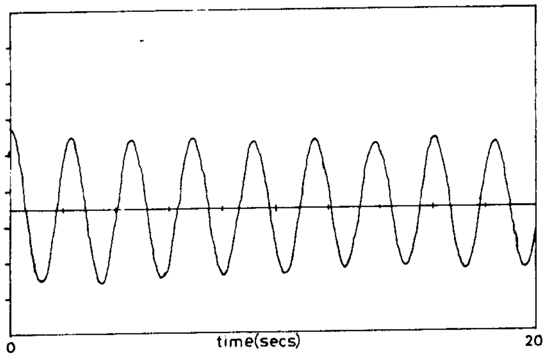
iii)Autocorrelation method: This technique involves spectral analysis of random data. It requires a linear system, a single degree of freedom, and stationary data. If these conditions are met the ensuing estimates of damping are well-correlated with those measured using other methods (9). The method is not useable for investigating changes of damping with increasing amplitude. Figure 4 shows a typical autocorrelation function.



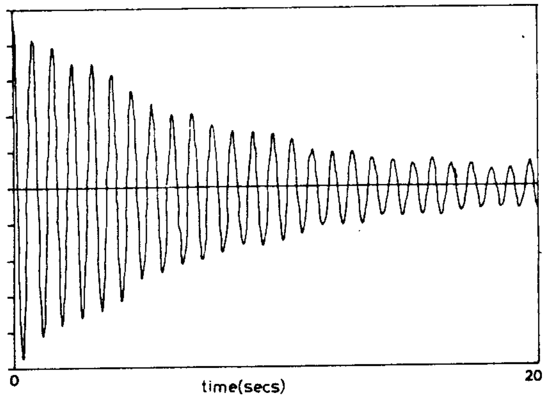
$$\zeta_{N \cdot S_t} = \frac{100}{2\pi} \cdot \frac{1}{40} \ln \frac{19\ 5}{70} = 0\ 51\%$$

Fig 4 Autocorrelation function of the response of the National Westminster Bank building, London,U.K.

iv)Random Decrement: This method was first proposed as an integrity monitoriting exercise for space craft (10). It has been shown to be applicable for structures (8), but also, and more significantly, it can be used with random data, to investigate changes of damping with changing amplitude. However, the constraints on the data source (stationarity, well seperated modes) make it difficult to use effectively to obtain absolute values of damping (8). The decrement signature, however, is sensitive to small structural changes in space craft and may act in the same way for buildings. Figure 5 shows typical random decrement signatures.



National Westminster random decrement signature



Leicester University random decrement signature

Fig 5 Random decrement signatures from two buildings.

DISCUSSION

Monitoring, in many positions on a structure, for strain,acceleration or displacement changes, may be a useable technique for the long term monitoring of the behaviour of a structure. However, dynamics techniques are potentially powerful in being indicators of changes at a fundamental level in a structure. Techniques of monitoring changes of frequency, particularly for higher modes of vibration, have been claimed to be useful in this respect. The reasoning in this paper suggests that the most sensitive measure of changes in a structure may well be that of damping. The two methods which present themselves as being most applicable are the use of induced vibration tests under similar conditions of forcing (because of the precision of measurement), and the use of random decrement signatures under random loading (because of the potential for ascertaining amplitude dependant characteristics and of obtaining structural "signatures"). In the latter case further research is necessary in the use of the method, as only one study has so far been conducted. This did, however, give promising results.

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