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SOME DEVELOPMENTS IN PROTOTYPE TEST ON DAMS

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SUMMARY

How to use transfer function to identify modal parameters of prototype dams will be discussed in this paper. Some new excitation and analytic methods are adopted to carry out parameter indentification more efficiently. Compared with traditional method, the new methods are lower in cost and more accurate in their findings.

TRADITIONAL METHOD AND SOME RESULTS

The main characteristic of the prototype test for civil and hydraulic structures is its bulkiness and difficulty in excitation. Since the fifties, prototype tests on dams have been carried out by one or some synchronized shakers. In this method, according to certain frequency space, steady excitation is carried out in every frequency. Then a frequency response curve could be obtained in frequency domain. According to peaks on this curve frequency, damping and modal shapes can be identified, assuming that the structure may be treated as a single DOF near the peak.

This method proves to be quite efficient in many cases. Some different kinds of dams, sluices and towers were tested in situ by AWRRI. Here is an example of prototype test on a multiarch dam for lateral vibration modes. The sketch for measurement stations on buttress located on the river bed and the modal shapes for $n=1,3,4$ are shown in Fig.1. the response curve is shown in Fig.2. It is seen from the modal shape that the buttresses can be calculated as a two dimension plate. As $n=2$, the corresponding modal shape is a space shape. The connected condition between buttresses should be considered. Neighboring buttresses possess opposite phase. The nodal line is approximately the central line of the arch cylinder. As $n=1$ and $n=2$, the overlapping is quite serious on the response curves and it is difficult to describe it with one DOF' s frequency response curve.

The advantage of steady excitation with shakers is its concentrated input energy and higher single-noise ratio for measurement data. However, some large scale shakers have to be provided. Such shakers often require high accurate frequency stability and high frequency resolution up to 0.05 Hz or more which is very difficult to attain. These shakers are always heavy and costly. So test with shakers incurs more time and higher cost. Only a limited number of dams can be tested in this way.

With the development of the technique for signal analysis, ambient vibration becomes an accepted practice for dam excitation. It is assumed that ambient vibration is an Ergodic random input and possesses white noise character. Fourier transfer of response output at every point on dam is a frequency response curve. The model parameters may be identified in the same manner as steady excitation.

Some major concrete dams in Anhui province had been tested under ambient vibration by AWRRI. From our analysis, it can be seen that for light dams, for example, the multi-arch dams and thin arch dams, the result is very good. Sometimes two response frequency curves get from shaker and ambient vibration respectively almost show the same pattern and from which not only modal frequency but also the shapes may be identified. See Fig. 2.

The advantage of ambient vibration is economic both in time and instrument. The key problem of identification is the coherence function. For gravity dams, the result of ambient vibration is not very successful even modal frequencies are not identified clearly except fundamental frequency. Recently modal identification for dams based on transfer function and transient excitation has been introduced. Test in such manner shows both advantage of two methods described above. It can be carried out in a wide field.

TRANSFER FUNCTION AND CURVE FITTING

To adopt only frequency response curve to identify modal parameters modal frequency is mainly determined by the peak on the curve. As on many such curves the peaks are not very clear and difficult to determine, it often gives rise to mode missing. Generally modes of complex structures are quite dense and the interval between two modes is only a few 0.1 Hz. In such case to identify often causes some deviation or mistake. Because of the influence of neighboring modes the shapes are often distorted and the nodal line can even be lost or changed. If two modes are very near they may be taken as a mode. As the identification of all parameters rely only on one peak point, it is not so reliable.

When the input force is introduced, the information of phase lag between input and output signal should be included. If the test frequency resolution can be improved to the degree required, then the situation can be remedied and all modes may be identified accurately. For the vibration system with n-DOF through Laplace transfer, its governing equation can be written as :

$$X = H\ F \qquad (1)$$

Here X F stand for Laplace transfer of output displacement and input force respectively, and H stands for matrix of transfer function. This matrix contains all information of every order of modal parameters. It can be found by measuring the input force and output displacement at each required point. Using the theory cueve to fit experimental curve, the modal parameters of the structure may be identified. Generally speaking , the structural vibration can be expressed by complex modes. The matrix of transfer function may be written as:

$$H = \sum_{j=1}^{n} \left[\frac{A_j}{s - s_j} u_j u_j^{T} + \frac{A^{*}_j}{s - s^{*}_j} u_j^{*} u_j^{*T} \right] \qquad (2)$$

Here $s = \sigma + i\omega$ is a complex variable, $s_j = \sigma_j + i\omega_j$ is a complex eigenvalue which consists of jth modal damping and frequency; A_j is a complex constant; u_j is jth modal vector and it is a complex vector with different phases at each point. The upperscript $\times$ stands for the conjugate value. From (2) it can be seen that H may be expanded into superposition of n numbered one dimension matrix. Such spreading characters of modes guarantees that the information is complete as single point excitation.

In a certain frequency range using (2) measured transfer function exceeding some level is to be fixed with undetermined parameters as variable. Then pth-qth order modal parameters can be obtained. When curve fitting is applied, every measured data with certain response level will offer contribution to the identification of modal parameters. Occasional error at individual point is not able to influence the accuracy of the result. Moreover, curve fitting may separate pollution of neighboring modes and reject it. Near modal frequency in addition to the amplitude of transfer function will reach peak of transfer function, the phase will change sharply. Imaginary and real part draw approximately a circle with variable s as a parameter. The identification can be carried out directly by this character. As long as resolution of the frequency is fine enough it can be identified clearly if a peak on response curve is a modal frequency.

The transfer function may be measured by shaker in step by step.(Ref.1) In this way the resolution is not so fine and unchanged. If the resolution is required to raise accuracy in analysis, it can not be carried out. As described above, the performance takes a long time.

MODAL IDENTIFICATION BY TRANSIENT EXCITATION

In order to improve the test in situ and overcome the above shortcoming, a transient impulse excitation and a corresponding identification is developed. According to these methods, the instruments are almost similar to those used in ambient vibration but it is able to obtain transfer function with continuous spectrum. The result of identification can be similar to the result gained from steady excitation by shakers. Sometimes the result can surpass that by shaker. The frequency resolution can be almost as good as required and can be adjusted in identification. The fine resolution will reduce the number of missing mode to a minimum. Because a series of technique of signal analysis are applied, the accuracy of identification can be assured. It takes little time to perform the test in the field.

Impulse excitation on dams is generated by a small self-designed rocket placed on a certain point with a forced sensor. In the time domain, signal of the impulse comes nearly to a triangle. Its peak value depend upon fuel quantity and the width of impulse depends on fuel prescription. Because of the low frequency characters of civil structures, it is all right when the impulse width is under 10ms. The range of frequency can reach as high as 25 Hz. The typical flow graph by transient excitation is shown in Fig.4. Force and displacements are recorded by sensors. The transfer functions can be obtained by signal analysis.

The main probleme facing transient excitation to identify modal parameters of structures are ; how to get high accuracy transfer function and improve the signal-noise ratio, how to guarantee enough frequency resolution in signal process and how to provide enough data of measured transfer function for identification and how to use the curve fitting technique to identify the required parameters.

In order to improve the accuracy if transfer function apart from raising signal noise ratio of instrument measuring system, the multi-average data is generally employed to eliminate noise with good results. Tests show the coherence function reaches nearly 1. A number of techniques can be used to improve the signal noise ratio of transfer function in signal processing. For example various kinds of window technique can be used especially the exponential window for transient excitation which proved to be efficient. In addition, many kinds of filter technique can be used to eliminate noise. For example, a generalized Wiener filtering method can pick out signals from high background noise In a word , for original signal with continuous spectrum, various techniques of signal processing can be applied to get the information we required. Generally, the informaton provided in this manner is richer than discrete excitation.

Owing to transfer function excited by impulse possess continuous spectrum, after signal discretion, the frequency resolution depends on sample number N and sample rate Δt, e.i. $\Delta f=1/n\Delta t$. To avoid frequency alias Δt is also limited by Nyquist frequency, i.e. $\Delta t \leqslant 1/2\ fc$; Here fc is the highest freqnency contained in the signal. Limited by sample rate, the resolution is difficult to exceed 0.1 Hz in DFT. According to super low fre quency and damping character of dams, the width of half-power band are only 0.1-0.3 Hz below 10 Hz. As required for curve fitting, no less than 5-6 points measured are required in half-power band, otherwise, some difficulties will occur in identifying modal parameters. In normal DFT analysis the frequency resolution cannot satisfy this condition. So in signal processing, the Band-Selectable Fourier Analysis i.e.Zoom FFT have to be employed. In our test below 8 Hz, the resolution reached 0.025 Hz. It is guaranteed that there are enought measured points to carry curve fitting. For higher frequency resolution with 0.05 Hz, better results can be reached. As frequency spectrum is continuous, the resolution can be adjusted in time and it always can be satisfied through Zoom FFT.

Modal parameter identification is to use theoretical curve with variable modal parameters to fit the measured curve of transfer function. The variable parameters can be seen as practical modal parameters, if it can make the residual error to reach a minmum. Identification may be based on complex modal formula. It also may be based on simpler real modal formula.

As dams worked on are in elastic stage, damping is light, so the result obtained from the two methods have no obvious difference. We compared some practical examples and the two results are also consistent.

EXAMPLES

Example 1 Xiang Hong Dian is a concret arch dam with fixed center and radius. It is 87.5 m high and 361 m in length at crest. The thickness of dam is 5 m and 39 m at the crest and base respectively.

Various methods were used in prototype test of this dam such as excitation by shaker, impulse and ambient vibration. In steady excitation identification methods of tradition and transfer function were employed at the same time. Frequency response curve and transfer function of station at centre on dam top got from different excitation manners are shown in Fig.5.

To satisfy the need for modal identificaiton Zoom FFT was carried out in signal processing as inpulse excitation. The resolution is 0.0246 Hz in range 3.5-8.5 Hz and 0.06 Hz in range 7.5-20 Hz. The amlitude and coherence function of station at quarter point on top arch are shown in Fig.6. In this figure the fitting curves are also shown and it can be seen that the fitting is excellent. The Nyquist plot and its fitting curve for range 7.5-20 Hz is shown in Fig.7. In Fig.8 the shape of central cantilever of the dam is showm from different modal identification method corresponding 8.2 and 9.5 Hz. In calculation there should be a node on the cantilever and this node is missed in traditional method. If the transfer functions are employed this node can be identified both in steady and transient excitation. Comparing the results got from identification by impulse and shaker with FEM calculation it can be seen that these results are quite consistent (Ref.2). Modes identified by impulse are more than by shaker.

Example 2 Chencun dam is also a gravity arch dam. It is 76.5 m high and 411 m in length at crest. The thickness is 8 m at the crest and 53.5 m at bottom.

Diffrent test methods are also employed on prototype test for this dam and the excitation by small rocket was used for the first time. In ambient vibration only a few modes appear and the some peaks are difficult to identfy. When using two synchonized shakers for excitation only two symmetric modes and two antisymmetric modes are identified. When the dam is excited by the rocket the frequency responce curves and transfer function show the peak values corresponding modal frequency very clearly. Seven modes at least may be identified only for symmetric modes and it is consistent with result from FEM calculation. In Fig.9 the frequency response curves for centre on dam top are shown. These curves are obtained from ambient vibration, impulse excitation and shaker. It may be seen that the effect of impulse is satisfactory.

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2. Clough, R.W., and etc., Vibration Behavior of Xiang Hong Dian Dam, 8th WCEE, San Francisco, 1984.

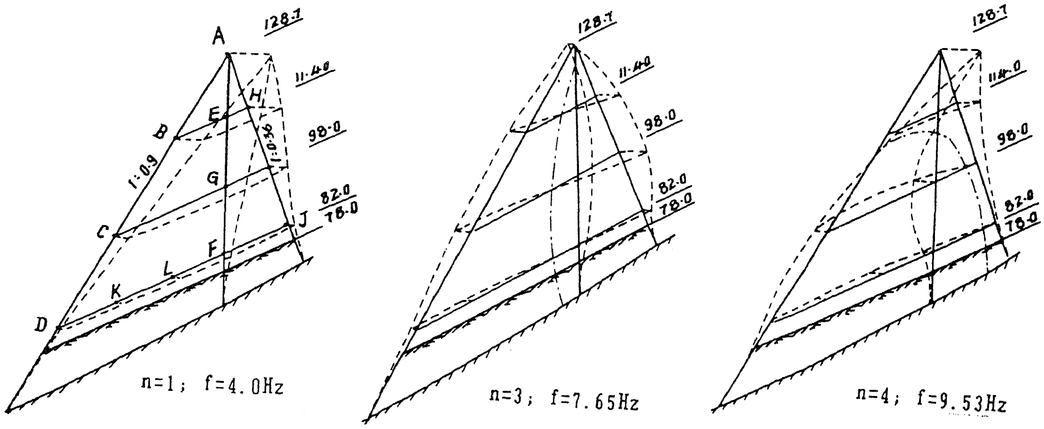


Fig. 1

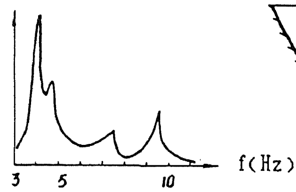
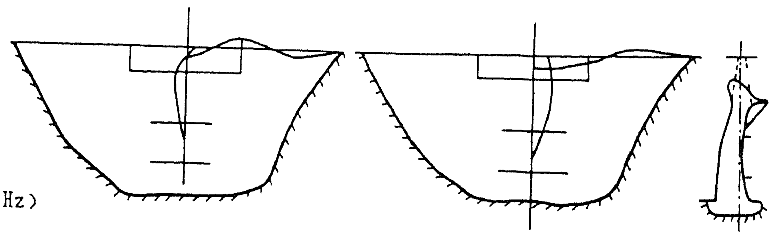


Fig. 2



f=9.72Hz

f=5.50Hz

Fig. 3

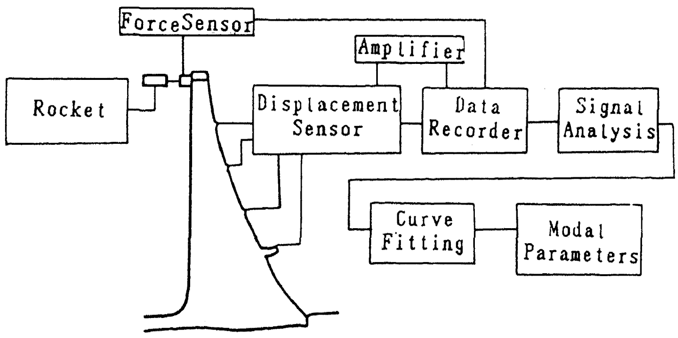


Fig. 4

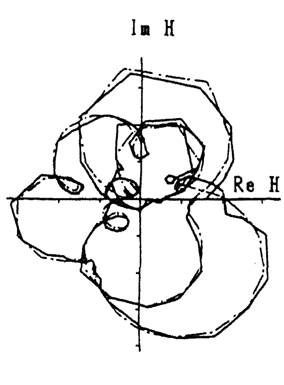
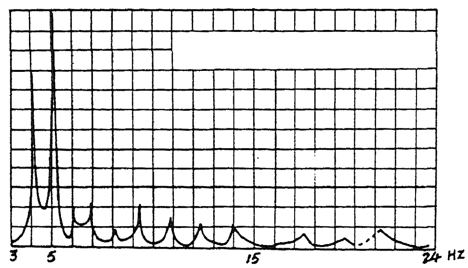
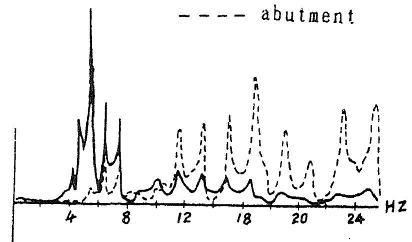


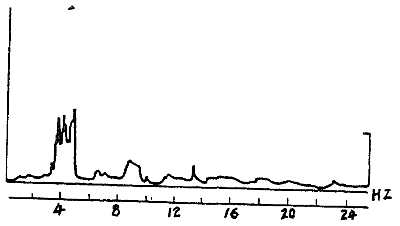
Fig. 7



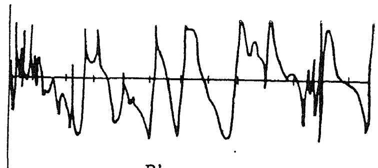
Response curve for steady excitation



Amplitude



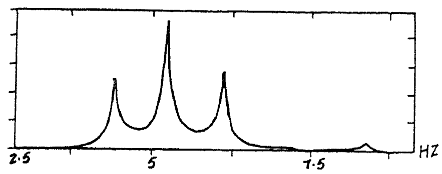
Response curve for ambient vibration



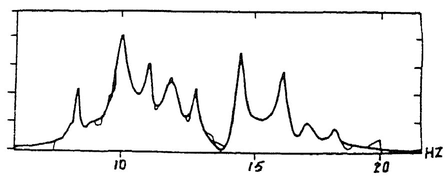
Phase

Transfer function for impulse

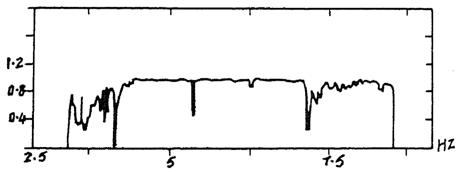
Fig. 5



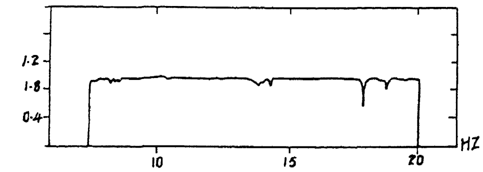
Amplitude



Amplitude



Coherence



Coherence

Fig. 6

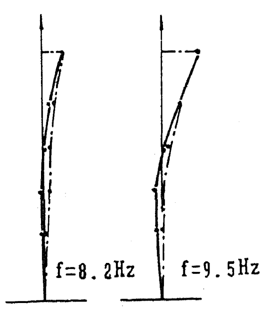


Fig. 8

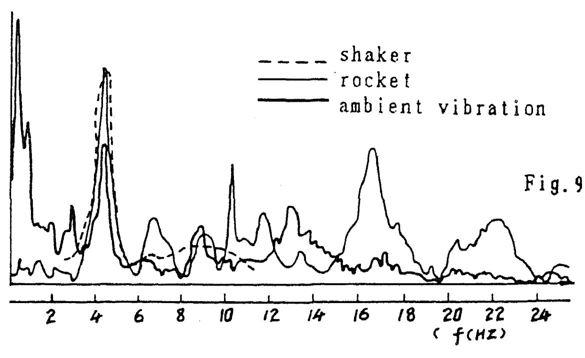


Fig. 9