ASSESSING THE DYNAMIC PROPERTIES AND INTEGRITY OF STRUCTURES BY THE USE OF TRANSIENT DATA

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SUMMARY

The technique of experimental modal analysis, as described in this paper, is beginning to be used in the field of earthquake engineering. This paper presents a broad outline of the method and describes the experimental procedure followed in order to extract the modal parameters of a test structure in this way. The paper is illustrated by two examples of test structures – a 1 : 200 scale model of Contra arch dam, Switzerland, and a 65 m tall prototype chimney in Bristol.

INTRODUCTION

The vibration of a linear elastic structure during an earthquake can be described by the combination of different modes of vibration each of which has modal characteristics of frequency, mode shape and damping. Once the modal parameters are known, the dynamic behaviour of the structure may be predicted. The method of modal analysis can be used to derive these modal parameters from a transient test on a model or prototype structure. The technique is based on extensive data processing, using the Fast Fourier Transform to obtain a set of "transfer functions". These describe a relationship between any two points on a structure; more specifically they are defined as the Fourier Transform of the response at one point divided by that of the force input at another. A transfer function is generally of the form illustrated in Fig 3, consisting of a number of distinct peaks, each of which corresponds to one mode of vibration of the structure.

In addition, the matrix of transfer functions, H, may be written analytically,

$$H(w) = \sum_{k=1}^{n} \frac{a_k}{iw-p_k} + \frac{a_k^*}{iw-p_k^*} , \quad p_k = \sigma_k - iw_k$$

where n is the number of degrees of freedom, w_k the kth natural frequency, i the imaginary square root of −1 and σ_k a measure of the damping associated with the kth mode. The asterisk denotes a complex conjugate. The matrices, a_k, are known as residue matrices, and contain the kth mode shape vector. Fitting the above expression to the experimentally obtained set of transfer functions yields solutions for the unknown modal parameters.

DATA ACQUISITION AND PROCESSING CONSIDERATIONS

A few of the more important practical considerations will now be briefly

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examined.

1) Frequency Resolution

The single most important factor affecting the accuracy of modal parameters is the accuracy of the transfer function measurements. It is not possible to extract the correct values of the modal parameters when there is inadequate information to process. Adequate selection of frequency resolution, sampling rate and measurement time is therefore of prime importance.

2) Aliasing

Sampling for digital data acquisition is dependent on the structure being analysed and is usually performed at equally spaced time intervals. One task is to determine the interval – too short will lead to vast quantities of data, whereas too long will lead to confusion between low and high frequency components in the original data. This latter problem is known as aliasing and is inherent in all analogue to digital conversion. The preferred method of solution is to filter the data prior to digitisation using low pass filters so that information above a selected frequency is no longer present.

3) Leakage and Windowing

To convert from the time domain to the frequency domain the Fast Fourier Transform (FFT) is used. One of the greatest sources of error is any digitally computed spectrum results from the fact that the measured (transient) signal is not periodic in the measurement period chosen and therefore violates a prime requirement of the FFT. This results in the true spectral estimate at a particular frequency being modified by power leaking from other frequency components. In a spectrum containing a number of closely spaced frequency components, leakage may smear together peaks and mask important detail. Leakage can be significantly reduced by "windowing" the sampled time history record, i.e. shaping it to become periodic.
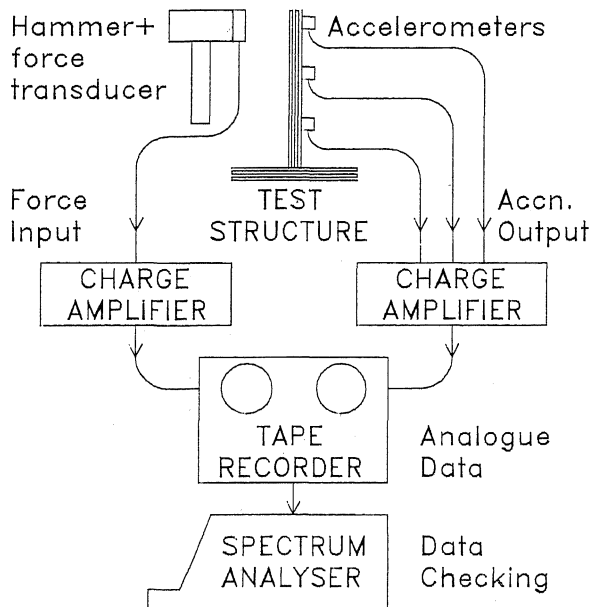
4) Measurement Noise

One of the major characteristics of any modal testing system is that extraneous noise from a variety of sources is always measured along with the desired excitation and response signals. By taking a number of averages, it may be shown that the measured transfer function more accurately estimates the true transfer function, assuming that the noise has a zero mean value and is incoherent with the measured input signal.

5) Hammer Heads

A very fast method of performing transient tests is to use a hand-held hammer, with a force transducer attached, to impact the structure. Excitation occurs with a nearly constant force over a broad frequency range. The effect of different types of head on spectral content is shown below for a PCB K291B50 sledgehammer.

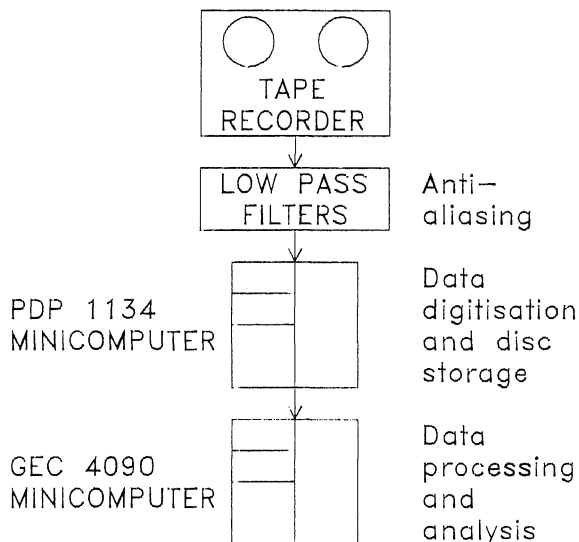FIG.1   TYPICAL HAMMER TESTING SETUP   (not to scale)

1.DATA ACQUISITION ON SITE

Hammer+ force transducer
Accelerometers

Force Input
TEST STRUCTURE
Accn. Output

CHARGE AMPLIFIER

CHARGE AMPLIFIER

TAPE RECORDER — Analogue Data

SPECTRUM ANALYSER — Data Checking

2.DATA PROCESSING AT BASE

TAPE RECORDER

LOW PASS FILTERS — Anti-aliasing

PDP 1134 MINICOMPUTER — Data digitisation and disc storage

GEC 4090 MINICOMPUTER — Data processing and analysis

Equipment Details

(a) Force transducers:
    PCB—K291B50
    B+K—8200
(b) Accelerometers:
    B+K—4344,4375
    Endevco—224C,233E
    Schaevitz—L50C
(c) Charge Amplifiers:
    PCB—480D06
    FYLDE—FE128CA
(d) Tape Recorder:
    Racal STORE 4DS
(e) Spectrum Analyser:
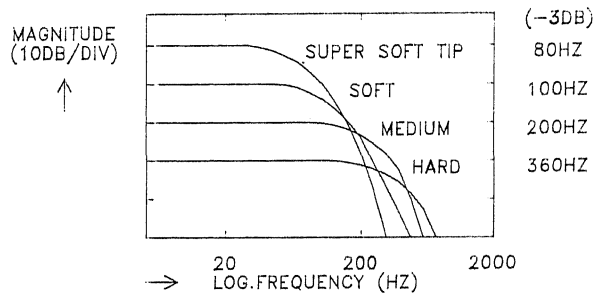   Solartron 1200

Computer Facilities

(a) Analogue to Digital Conversion
(b) Windowing
(c) Digital Filtering
(d) Mean Removal
(e) Fourier Transforms
(f) Averaging
(g) Computation of Power+Cross Spectra
(h) Statistics
(i) Frequency Analysis
(j) Modal Analysis

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MAGNITUDE                                              (-3DB)
(10DB/DIV)           ┌──────────────────────┐
                     │ ────────SUPER SOFT TIP│          80HZ
     ↑               │ ─────────── SOFT      │          100HZ
                     │ ──────────── MEDIUM   │          200HZ
                     │ ──────────── HARD     │          360HZ
 FIG.2               │                       │
 HAMMER              │                       │
 AUTOPOWER           └──────────────────────┘
                        20      200     2000
                 ──→   LOG.FREQUENCY (HZ)
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6)   On site data acquisition

Away from a laboratory base, field studies are normally performed with
severe time and financial constraints.   Advance planning and reconnaissance
are essential, with power supplies, communications and authorisations needing
to be organised.   The authors have found data checking on site to be essential
to gathering good quality data, and at least two persons are required.   During
tests on the Bristol Royal Infirmary (BRI) chimney, CB radio sets were used
successfully, one inside the chimney during hammer testing, the other situated
inside a nearby building where a "command centre" was set up housing the tape
recorder and spectrum analyser.   A typical testing set up is shown in Figure
1.

TEST RESULTS

The results obtained from both ambient and impulse tests on the BRI
chimney are presented in Figure 5.   The natural frequencies obtained from the
two tests are similar, although those predicted by a finite element analysis[6]
were found to be higher, at 0.84, 4.80 and 12.1 Hz.   The values of damping
calculated from the two types of test were found to be different;   it is thought
that this results from the higher strain levels prevalent in the ambient test.
The mode shapes obtained from the transient responses at three points on the
chimney compared well with the finite element prediction in both cases.

In the laboratory, a series of transient tests have been carried out on a
1 : 200 scale model of Contra Dam.   The behaviour of the dam was represented
by the response at 28 points along the crest, and a small, hand-held hammer
was used to excite the model.   Figure 4 gives the results obtained from such
a test with the reservoir empty.   The single-degree-of-freedom analysis, ie
fitting a circle to the vector response diagrams, was found to be sufficient
for well spaced modes, but the multi-degree-of-freedom curve fit was required
in order to obtain the modal parameters for closely spaced modes.   The
frequencies obtained from the impact tests compared well with the finite
element predictions, and the mode shapes could be clearly distinguished.

CONCLUSIONS

The tests described in this paper have demonstrated that curve fitting
in the frequency domain can be used to derive the modal parameters of struc-
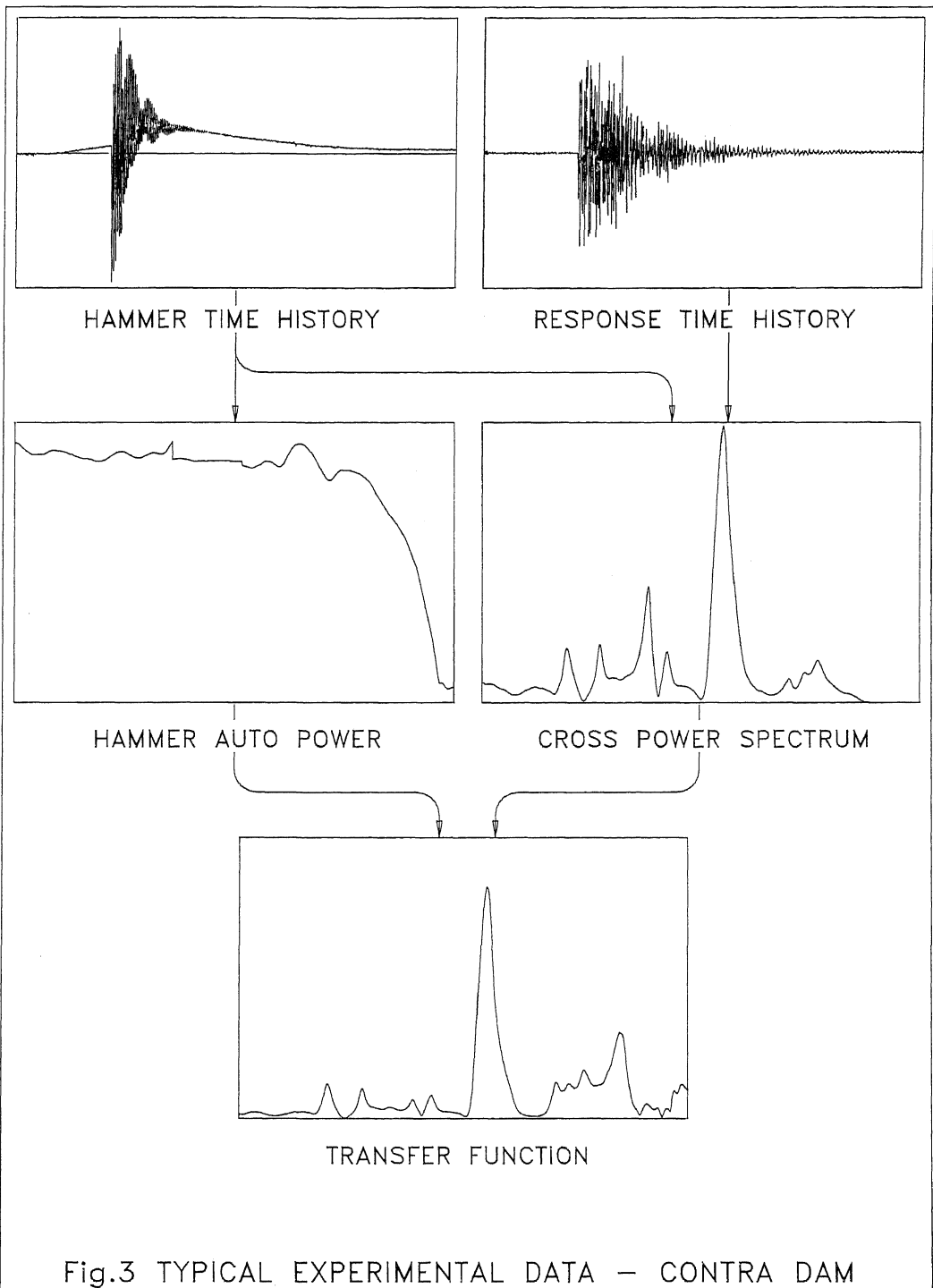tures.   The transient tests on the BRI chimney indicate that prototype

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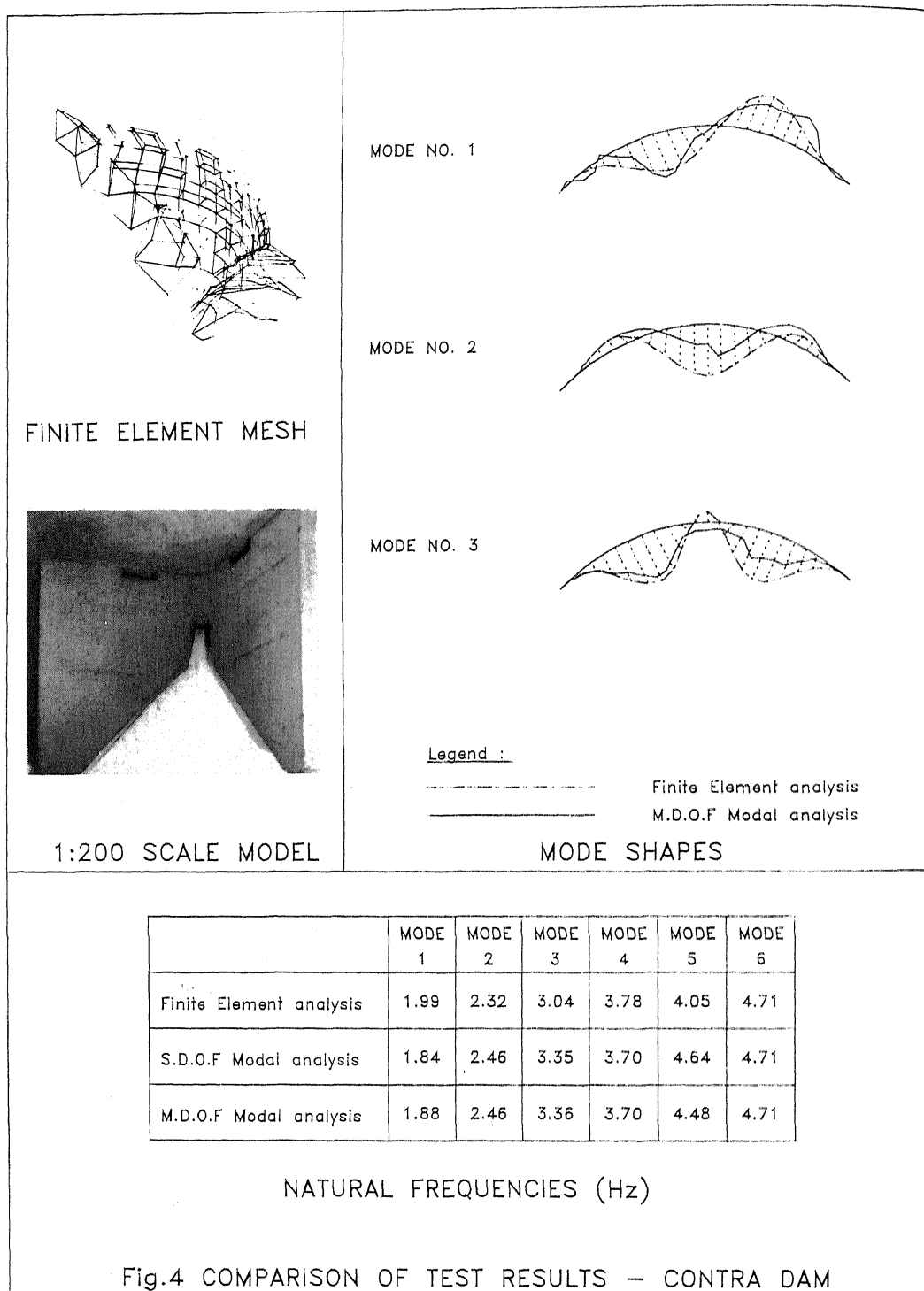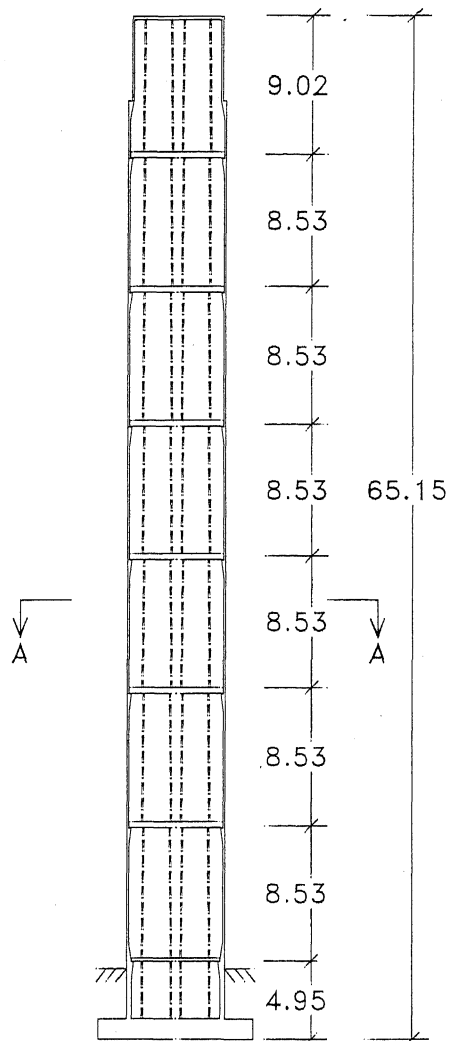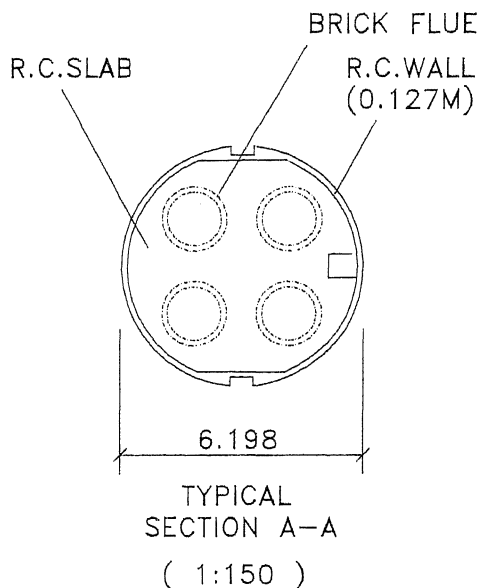Fig.3 TYPICAL EXPERIMENTAL DATA — CONTRA DAM

FINITE ELEMENT MESH

1:200 SCALE MODEL

MODE NO. 1

MODE NO. 2

MODE NO. 3

Legend :

— · — · — · — Finite Element analysis

———————— M.D.O.F Modal analysis

MODE SHAPES

	MODE 1	MODE 2	MODE 3	MODE 4	MODE 5	MODE 6
Finite Element analysis	1.99	2.32	3.04	3.78	4.05	4.71
S.D.O.F Modal analysis	1.84	2.46	3.35	3.70	4.64	4.71
M.D.O.F Modal analysis	1.88	2.46	3.36	3.70	4.48	4.71

NATURAL FREQUENCIES (Hz)

Fig.4 COMPARISON OF TEST RESULTS — CONTRA DAM

FIG.5: B.R.I. CHIMNEY

PLANS AND TEST RESULTS

(All dimensions in metres)

SECTIONAL ELEVATION

(1:400)

Dimensions (top to bottom): 9.02, 8.53, 8.53, 8.53, 8.53, 8.53, 8.53, 8.53, 4.95 — total 65.15

NOTE: Brick flues shown dashed for clarity

R.C.SLAB   BRICK FLUE

R.C.WALL (0.127M)

6.198

TYPICAL SECTION A—A

(1:150)

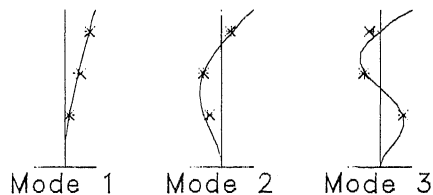## FREQUENCIES + DAMPING VALUES

from ambient vibration tests
during strong winds 2—3/9/83:

$F(1)=0.79Hz$ $D(1)=0.93\%$
$F(2)=4.36Hz$ $D(2)=1.14\%$
$F(3)=10.1Hz$ $D(3)=2.19\%$

from transient (hammer) tests
during very light winds 7/9/83:

$F(1)=0.79Hz$ $D(1)=0.95\%$
$F(2)=4.39Hz$ $D(2)=0.55\%$
$F(3)=10.3Hz$ $D(3)=0.85\%$

MODE SHAPES

Mode 1   Mode 2   Mode 3

——— =theoretical   X=ambient
(16 F.E.)   +=transient

structures may be analysed in this way, and in the laboratory the model tests on Contra Dam show that data from a large number of points may be collected and processed very quickly and with reasonable accuracy. The main advantage of this technique over steady-state sinusoidal testing of structures is its speed, particularly when the transient excitation is provided by an instrumented hammer.

PLANS FOR FURTHER RESEARCH

Tests are being carried out using a fast swept sine forcing function. This ensures that sufficient energy is imparted to the structure over the entire frequency range desired, and is expected to improve the results. Richardson [1] has shown how the structural mass, stiffness and damping matrices may be found from the transient test data. The extraction of these matrices from incomplete data, and the feasibility of their use in the integrity monitoring of large structures are under investigation.

REFERENCES

1.   M RICHARDSON, "Derivation of Mass, Stiffness and Damping Parameters from measured modal data", Hewlett-Packard, 1977.

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3.   Signal Processing and Applications Group, Cranfield Institute of Technology, Modal Analysis Package.

4.   C A TAYLOR - PhD Thesis, University of Bristol, to be published.

5.   K A RAMSEY, "Effective measurements for structural dynamics testing" Sound and Vibration, 1975.

6.   "SAPIV - A Structural Analysis Program for Static and Dynamic Analysis of Linear Systems", K T Bathe, E L Wilson, F E Peterson, University of California, 1974.

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