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DYNAMIC BRIDGE TESTING SYSTEM (DBTS) FOR THE EVALUATION OF DEFECTS & LOAD CARRYING CAPACITY OF IN-SERVICE BRIDGES

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A Paper by J S Higgs & D J Tongue

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Introduction

This paper outlines the experience gained in the development of a relatively simple field application technique to a sophisticated method of determining the load carrying capacity and integrity of in-service bridges.

The paper summarises the test methods and details of some of the structures tested and results obtained. The technique now gives bridge managers and bridge designers a useful tool for inclusion into bridge management programs. The techniques range from tests on single in-place structural members such as beams and columns to complex lattice structures.

Background

In a review of 143 major bridge failures worldwide between 1847 & 1975 it was revealed that over 50% of the failures were due to foundations, 15% to poor workmanship and defective materials and 10% due to overloading, the remaining 25% being due to structural deterioration of one type or another (Baxter & Higgs, 1986).

Piled foundation evaluation by non-destructive methods such as seismic and vibration testing is widely documented using such techniques as vibration testing (Davis & Dunn, 1974); transient vibration (Higgs & Robertson) and non-destructive test methods (Tongue et al, 1984). However, in order to address the problems of assessing bridge decks, beams, piers and column members, further development of the techniques was necessary in order to make them less dependent on highly skilled interpretation, and thereby more economic.

Initial Development of a Measurement Concept

The first approach was to measure bridge deck stiffness by a technique similar to a transient vibration test and correlate this to an available bending moment or a load test- This method can only be used in conjunction with limit state criteria if all the tested bridges are of similar design and construction otherwise extrapolation or interpolation of any resulting correlation would be extremely risky.

However, this preliminary approach soon foundered in practice due to the fact that a substantial impact was required to obtain the necessary deflections. Small deflections arising from inadequate impact energies were greatly affected by the type of surface dressing, localised movement, truck noise and other factors giving uncertain results
The second approach was to use simple models and to consider the basic physics of vibration of beams in bending. The resonant frequencies of a simply supported beam are given by:

$$Frequency = \frac{i^2 \pi}{2L^2} \sqrt{\frac{EI}{M}}$$

Where:

I	= Harmonic Integer
L	= Length
E	= Young's Modulus
I	= Moment Inertia
M	= Mass per Unit Length

It can be seen that EI is directly proportional to the square of the frequency thereby allowing a direct estimate to be made of the global EI from measured free vibration frequencies.

Modal Analysis Methodology

Modal analysis techniques have been used for many years particularly in the aerospace industry. With the advent of specialised digital data acquisition and monitoring equipment7 they have become viable methods of determining the in-service condition of structures.
Recently, research bas been conducted to see if the same techniques can be applied to identify the condition and serviceability of bridges, viaducts and wharves. The research showed a great deal of promise (Grace & Kennedy, 1988; Flesch, 1988 & 1992) and was in line with the research and developments of one of the authors (Higgs, 1988).

The principal hardware and software requirements for implementation of a modal analysis technique can be summarised as:

a) A means of applying a dynamic force sufficient to excite the structure at one or more pre-selected locations

b) Hardware and software capable of acquiring simultaneous measurement of the resultant dynamic response of the structure at pre-defined positions.

c) Software capable of analysing the database of input and output information to produce individual modal characteristics which would include:

    i) Frequency and mode shape of all relevant modes together with their degree of participation in the resultant response

    ii) Although not strictly a result of modal analysis, deflections of the structure, by integration of the velocity/rime data this would then allow estimates to be made of the degree of fixity associated with supports or bearings

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Dynamic Excitation

In research and laboratory applications of modal analysis, particularly of complex machinery, dynamic excitation is often provided by a linear hydraulic or eccentric mass shaker. Experience gained in testing over 140 bridges indicates that simpler means of excitation are suitable for 90% of all bridges. Attaching shakers to bridges is a complex and costly method and is only practical for research purposes or for extremely complex structures.

After using a number of different methods, it became apparent that the preferred method of exciting a bridge was a simple drop weight for measurement of the bridge in its free un1oaded state, and a known loaded truck travelling at various speeds for measurement in its loaded state. These two methods can usually excite all the necessary modes required to detect any defects and measurement of the' global' El of the deck of the bridge.

Dynamic Response

There are many methods of measuring the dynamic response of a structure, including strain gauges and displacement transducers, the instruments being placed at several representative locations on the structure. One of the traditional methods of data acquisition is by use of multi-channel spectral analysers which provide both, data capture as well as frequency spectra analysis. Generally such instruments provide frequency domain transformations of the data in the form of cross spectra via in built Fast Fourier Transform (FFT) hardware.

One of the principle disadvantages of using spectrum analysers is the expense of even a four channel machine, with the contingent difficulty and expense of moving the transducers to all the positions required to obtain sufficient data to produce meaningful mode shape data.
For a system to be cost effective, it must be a multi-channel system capable of testing a single bridge span in one pass. The transducers must be robust, capable of working under severe conditions and inexpensive. These constraints led to the development of a sixteen channel velocity transducer based system.

Velocity transducers comprise a magnet suspended in a coil and when the body of the transducer moves as a result of vibration, an electrical signal is generated (typically of the order of a few thousands of a volt) which is proportional to the velocity of the movement. These transducers are available off the shelf and exhibit defined characteristics.

The conditioned signal is fed into an analogue to digital (A to D) converter housed in a micro computer. This digitises the continuously varying voltage signal at a frequency of around 60 kilohertz (KHz), thereby providing a stream of digital data which represents the input waveform over this period of time. Data records are saved in one second time slices.

Replicate records are averaged to reduce the influence of noise and thereby provide a more accurate frequency analysis. Because data capture on each channel is effectively simultaneous (less then a l/6000th second between channels) both the amplitude and phase characteristics of the resultant response can be determined for each of the measurement locations to this level of accuracy.

In order to make use of the modal measurements and analyses, it is necessary to produce a model of the bridge being tested. This model can vary from a simple arithmetic calculation of the' global' El to a full dynamic finite element model allowing calculation of frequencies and mode shapes up to the l00th spectral peak or beyond.

This area is very much currently active research and a great deal of progress has been made (Stetson & Harrison, 1981; FUH & Bennan., 1986 Research Project Vic Roads, 1992). A great deal of research is also taking place into parameter optimisation techniques. These utilise a finite element model which is subsequently tuned from data produced from the structure's response to excitation.

Once a suitable model has been produced then the modal analysis results can be compared to the expected or calculated behaviour of the model.

This fitting of the model and modal analysis results enables an appraisal or rating of the bridge in its present condition or for revised loading. The interpretation can be based on either ultimate limit state or serviceability limit state criteria depending upon the level of sophistication of the modelling that is adopted (Baxter, 1990).

The raw data can be analysed in a number of different ways. For the determination of response shapes, each signal trace is integrated to produce an equivalent displacement trace. At this stage a hard copy can be obtained of the displacement at each of the transducer locations, and the data can also be played back at different speeds so that the responses can be examined in detail for each measurement location.

Mode shape estimation requires further processing via Fast Fourier Transform (FFT) of the displacement shapes. The energy density, frequency spectra obtained from the Fast Fourier Transform are then scanned across all channels, ie. , spatially so that for each identified mode an animated frequency response shape display can be generated. These response shapes have been shown to be an accurate indication of the mode shapes (Haritos, N et al, 1993) refer Figure A.

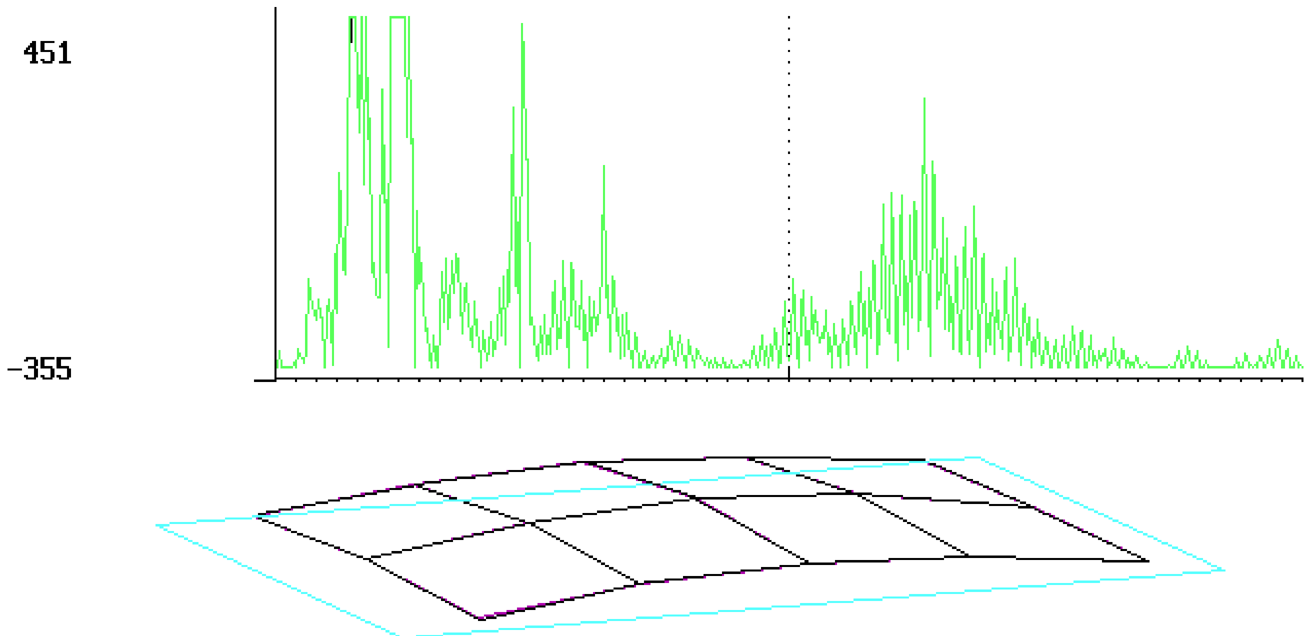

Figure A Mode shape of bridge under dynamic excitation

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The standard equipment set up uses 16 transducers. By strategic location of these transducers on the bridge deck, it has been possible to determine not on]y flexural modes, but also some lower plate and tensional modes, and to estimate support restraint, thereby allowing identification of bearing problems

Data Analysis

Many structural units (which would include simple forms of bridges) can be modeled as beams with a range of end support conditions. The simplest condition of end support *is* the simply supported condition for which the flexural frequencies can be determined from the formula noted earlier.

To identify the fundamentals and harmonics of the various modes and to measure the corresponding frequencies, the time domain records must first be transformed into frequency domain data by the use of an *FFT* algorithm. Plots of spectral energy density obtained in this way are seen to comprise of a series of relatively sharp peaks embedded in a great d~ of noisy background information. Some of the peaks will occur at frequencies which correspond with the natural frequencies of the superstructure, but others may not be so easily identified, and may be caused by vehicle suspension dynamics or even plate vibration caused by the vehicle exhaust noise.

There may also be additional (non-flexural) modes present, eg., torsional and plate modes, but simplistic modeling is not appropriate for these types.

Clearly, in an undamaged condition, the more frequencies which can be identified, the more precisely that El can be estimated.

Replicate records are taken from repeat measurements on each transducer and are used to reduce the effects of noise and improve on the identification of superstructure frequencies.

Effect of End Support Conditions

The simple beam flexural formula for frequency is modified slightly for different end conditions, but the number of known and unknowns does not. For example, for a beam with encastre supports the appropriate revised formula becomes

$$Frequency = \frac{(2i+1)^2 \pi}{8L^2}\sqrt{\frac{EI}{M}}$$

Determination of Mass per Unit Length (m)

The simple beam vibration formula includes a term for the mass per unit length (m). As a means to provide an estimate of (m), the structure can in some instances be measured, but generally dimensions are taken off from drawings. These methods are appropriate in some circumstances, but may lead to significant errors if the drawings are incorrect or records of the as-built structure and the material density is significantly different to the value assumed (especially in the case of timber structures). These problems can be largely overcome by determining the influence of an additional mass in providing a frequency shift which can be ascertained, and then used to provide an implied value of" m " -

Effect of Deterioration/Damage

In both of the above cases the simplified model will be perturbed when the beam contains non-uniform properties in El, (such as when it has suffered damage) or when the end conditions cannot entirely be described as either encastre or both simply supported. This will have the effect of altering the simple relationships between the various natural frequencies, so that natural frequencies on their own would not be sufficient in the modeling process. However, this is where information on response shapes that can also be obtained from these multiple point measurements can greatly assist with the identification process.

On more complex structures such as aircraft and aerospace vehicles structural integrity monitoring involves a close study of dynamic response records obtained from systems exhibiting departures from their expected performance characteristics over long periods of time result in identification of the causes of these departures. The ratios of the sequence of identified modal frequencies: f1, f2, f3, f4 etc., can provide an indication of structural change since the time when the last set of measurements were taken and may be used as a simple criterion for 'flagging' the occurrence of such changes. We believe that *this* system could be used for extended periods but as yet no case studies have been published to “support" this theory.

Determination of Load Capacity

An estimate of the' global ' El value of the simple bridge model under consideration in combination with the support conditions, allows an extension of the simple beam model for the purposes of estimating load capacity -

However, confirmation that the structure actually behaves as modeled or as designed, in itself gives significantly increased confidence in the structural model used. This confirmation is based on the FEA and FEM model timing, whereby the FEM is compared to the FEA or initial design of the bridge. This therefore allows higher confidence to be placed in the calculated load capacity based on that model or design, irrespective of whether that capacity was estimated using deflection or ultimate limit state principles.

Verification of the System --Princess River Bridge, Tasmania.

Traditionally, bridge performance assessment was carried out by load testing, using the deflection criteria obtained in a limit state design- These tests only determined whether the anticipated deflection under a dead load was as expected- Bridges are dynamic structures under traffic loading and though the dead load tests were useful they did not find any of the defects that may have been present under dynamic loading. ,

The systems described in this paper have been developed and enhanced over a number of years. Over this period over 140 bridges have tested and consequently a large database of verifications has been produced. Unfortunately much of this work was carried out under confidential contract and is therefore unavailable for publishing however the results of measurements on the Princess River Bridge Tasmania provide useful evidence of the success of the techniques.

This project was a joint research project funded by Vic Roads, Australia in association with ETRS Pty Limited with auditing by Melbourne University and was carried out between 1990 and 1992. The object of the research project was to find a cost effective method of estimating the load capacity of in-service bridges. After a literature review (Baxter, 1990) and an initial testing program (Tongue, 1991) a bridge was tested to destruction in Tasmania. The Princess River Bridge was being inundated by the flooding due to the new King River Hydro Electric scheme. Due to the generosity of the Tasmanian Department of Roads (TDR) it was possible to use the system in a comprehensive evaluation. At the same time the TDR carried out a load test to destruction of the bridge, so enabling the system to be correlated against the conventional techniques (McGee R? 1992).

One of the primary requirements of the system evaluation was to establish the accuracy with which flexural modes up to the 5^{th} could be measured. The results were to be compared against a finite element model of the superstructure.

The basis of the evaluation was to determine whether the Dynamic Bridge Testing System (DBTS) could determine the true mode shapes of the bridge. The test was also used to determine whether the hardware and software in the DBTS system gave sufficiently accurate results, with Melbourne and Wollongong University carrying out comparative analyses to assess this aspect

The program was also designed to determine the degree of agreement between the estimated actual flexural rigidity (E1) from the system and that obtained from load tests and finite element modeling. This aspect was covered at the conclusion of the project in an unpublished report (ETRS, 1992).

The final part of the project at the Princess River Bridge was to see if the mode shapes could detect defects introduced into the bridge, such as removing handrails, cutting of one layer of reinforcement in one beam and eventually cutting out the whole of the bottom reinforcement in two beams (induced defect). ,

Frequency & Mode Shapes

The system accurately measured the first four major frequency and mode shapes to within 0.2% of the FEA model (refer Table 2 below). The majority of the secondary mode shapes were linked to the handrails, and as the transducers were placed on the deck the DBTS system was not measuring the secondary handrails/mode shapes.

MODE	FE RESULTS Frequency (Hz.)	TEST RESULTS Frequency (Hz.)	MODE SHAPE DESCRIPTION
1	16.5	17.6	1st bending
2	22.8	22.0	1st torsion
3	28.5	28.2	1st diaphragm, edge flap
4	38.6	-	2nd diaphragm, handrail
5	51.5	-	Handrails only
6	51.7	-	Handrails only
7	51.9	-	Handrail, edge flap
8	55.0	-	Handrails only
9	58.1	65.9	2nd bending
10	62.0	-	Handrails

Table 2 Comparison of Model & Modal Frequencies

The second columns of results gives the frequency of the mode shape indicated in Column 1 and obtained from an FEA model produced by the FEA package "Strand 5 n. The third column indicates the frequency of the same mode shapes measured from the tests on the bridge.

Accuracy of Results

Melbourne & Wollongong Universities took measurements simultaneously with the measurement obtained by the DBTS™. Due to a lack of fiscal support neither University was able to carry out a full audit of the tests, though Wollongong processed their data sufficiently to declare that frequencies and mode shapes were in agreement with their data as in Table 2 of this paper.

EI. Measurements

Accuracy of the various diagnostic methods. The results are shown in Table 3 and it can be seen that the DBTS system obtained "El" values within 3% of the static field tests

Test Method	EI Value ($N.m^2$)	Formulation
Dynamic field tests	1.3×10^{10}	$EI = (2\pi f)^2 M \iota^4 l^4$
Dynamic FE methods	1.15×10^{10}	$EI = (2\pi f)^2 M \iota^4 l^4$
Static fields tests	1.26×10^{10}	$EI = Wl^4/48y$
Static FE methods	1.23×10^{10}	$EI = Wl^4/48y$

Table 3- Comparison of "El" Values using the Various Methods Employed at the Princess River Bridge

Notations from the table are as follows: -

EI	Stiffness (N.m2)
E	Young's Modulus (MPa)
I	Second Moment of Area (m^4)
F	Natural Frequency (Hz)
M	Mass per Unit Length *(kg/m)*
L	Length (m)
W	Uniformly distributed load *(N/m)*
y	Distance from Neutral Axis (m)
ι	Integer

The DBTS values were determined by assuming that the bridge span is pinned at both ends (ie. , simply supported) and by calculating the mass of the bridge as being 9 tonne.

Test Methods

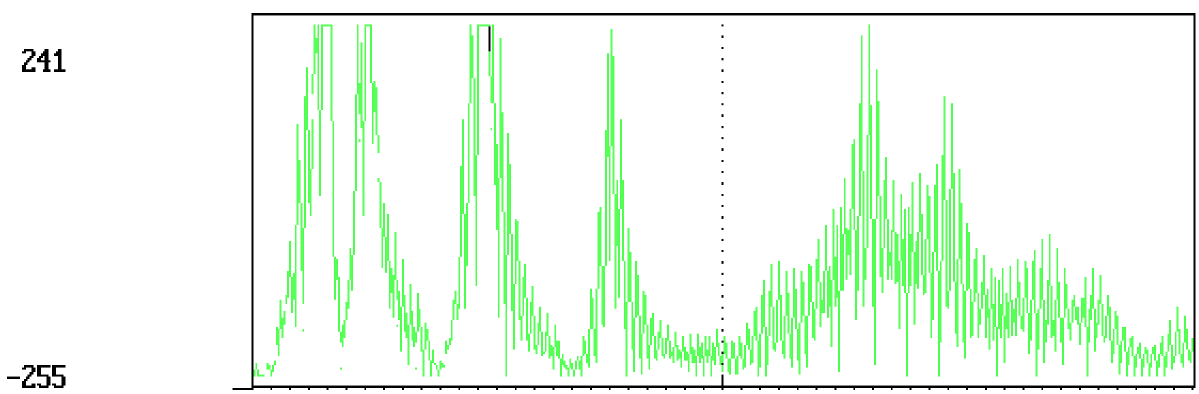
1) Calculation of "El" value from DBTS system tests
2) Theoretical estimation of "El" value from "Strand 5" FEA in a dynamic mode.
3) Measured values of "El" from dead load test on the bridge
4) Theoretical estimation of "El" value from "Strand 5" FEA in a static mode.

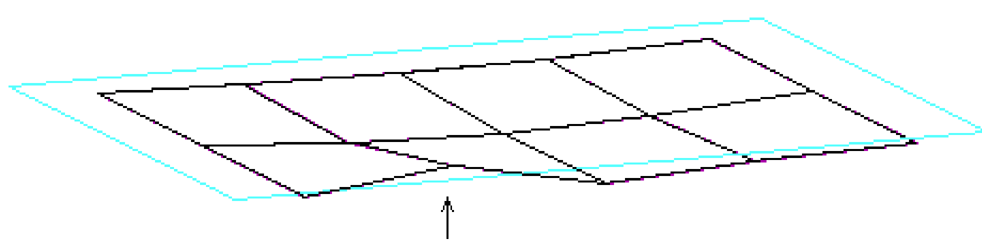
Detection of Defects

This aspect of the program was the most significant as the mode shapes readily identified the introduced defects. The first defect identified was the removal of one section of handrail from one side of the bridge.

Reviewing the spectral data onsite., without the benefits of any sophisticated analysis., it was immediately apparent that there was a shift in frequencies in the 60 Hz band. Examination of the calculated mode shapes readily identified the change.

The mode shapes also indicated when the bottom three bars from one beam had been cut and, of course, the further detects induced after this detect.



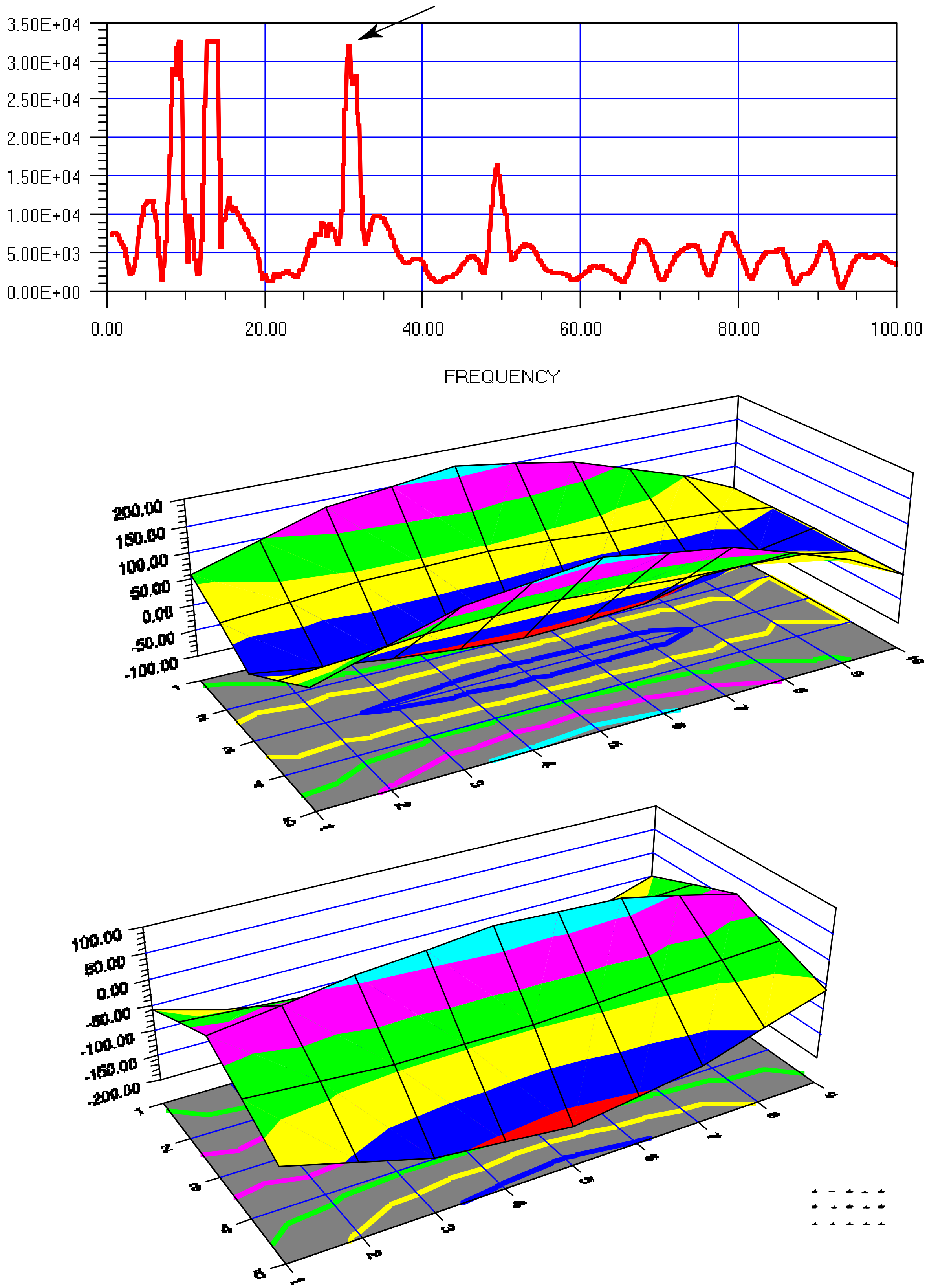


The project conclusively demonstrated that DBTS measured vibration data accurately; it identified the first five flexural modal frequencies accurately; gave satisfactory estimates of the deck flexural rigidity , and was able to detect each of the defects purposefully introduced. The bridge was initially in good structural condition, and was very stiff. In consequence it was not possible to excite it sufficiently by means of a mobile vehicle, but the impact system of a drop weight, nevertheless, proved quite adequate

Further Developments

Since completing the Princess River bridge project, further development has continued and the DBTS is now able to display animated mode shapes in two planes which significantly enhances the ability to visually detect defects (Figure 5)- The system can also link the 16 transducers in as many locations as required so multi span bridges can be tested and observed as one (Figure 6).

Figure 5 – Mode shapes in two planes on a bridge deck



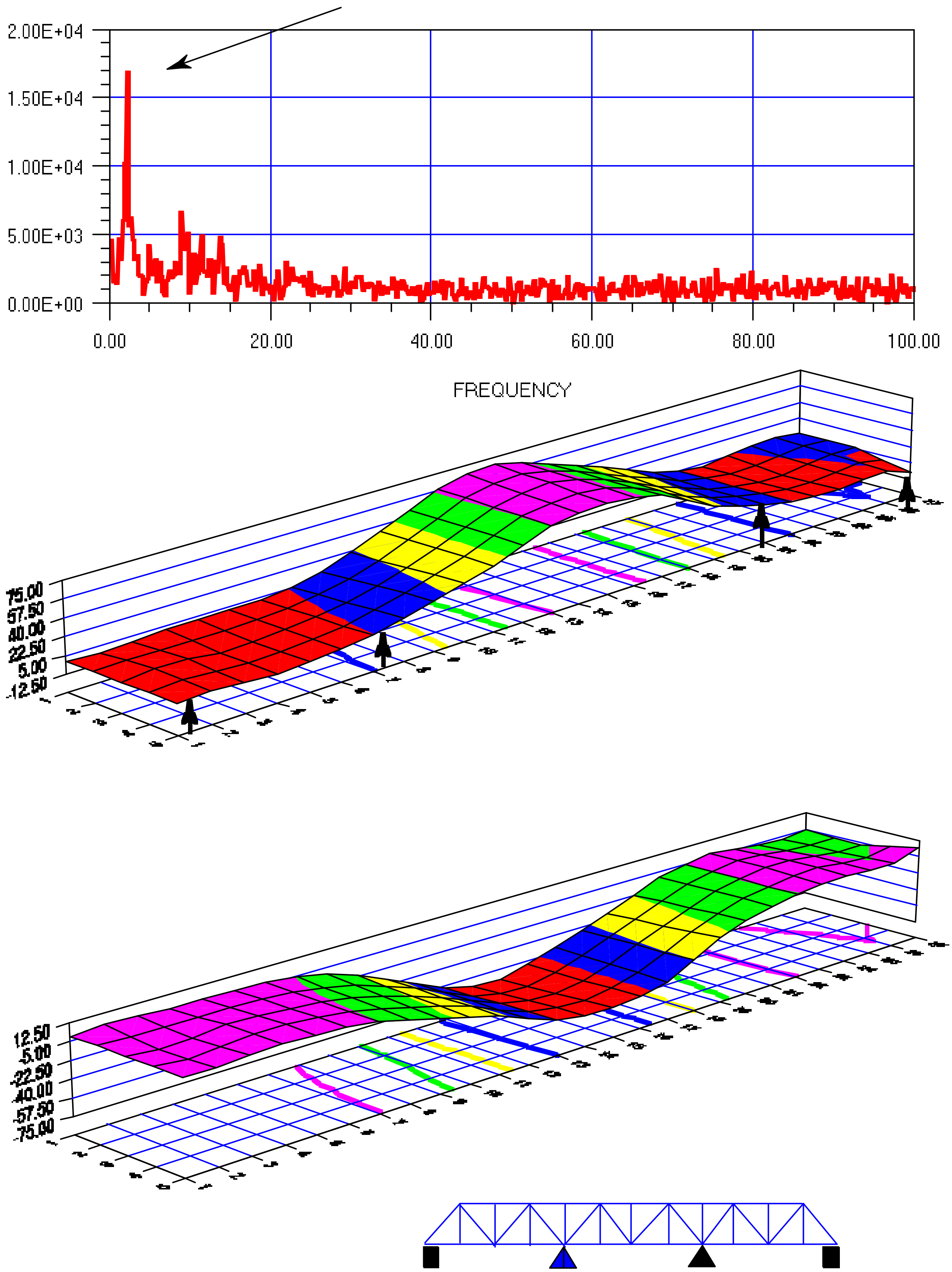


Figure 6 – Multi span bridge linked date to give 128 mode point plot.

Conclusion

The Dynamic Bridge Testing System (DBTS) described in this paper has been demonstrated to be capable of addressing the following aspects of in service bridge deck systems

- Identification and display of principle flexural modes. Comparisons with finite element models have shown excellent agreement up to at least the 5th mode
- Estimation of the actual dynamic rigidity of the bridge deck (EI)" to within approximately 10% (generally better) of the static (load test) value
- Identification of structural defects which have a significant effect on actual performance
- Detection of structural imbalance which may result in unanticipated torsional behavior
- Estimate of the degree of fixity associated with bearings, and through this, estimates of the actual load distribution through piers, abutments and other support elements.

The system in its current form using 16 transducers is efficient and cost effective; a single span concrete bridge can be measured without difficulty of access in about 4 hours with limited traffic disruption and with an approximate budget of 2,000 Pounds Sterling. This allows DBTS to be incorporated in bridge management and repair assessment strategies without penalty, since it can replace come of the existing time consuming and costly methods.

The system has been successfully used throughout South East Asia and Australia on concrete, steel, steel composite, timber, masonry and cast iron structures and can therefore deal with most of the structures likely to be found on European road').

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