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Dynamic Parameter Estimation for Steel Bridges using Strain Data

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ABSTRACT: In this paper a new paradigm for estimating dynamic properties is proposed based on measured dynamic strain data, and illustrated for an actual steel railway bridge. By combining deconvolution with a frequency domain decomposition technique the frequency response function for each dynamic strain is obtained. The member dynamic characteristics estimated show significant potential of being damage estimators for "local" damage.

1 INTRODUCTION

Structural systems are known to be susceptible to damage, and undetected damage within a structure can have severe and catastrophic effects. Over the last several years, structural modal parameters like eigenvalues and mode shapes have been thoroughly investigated as damage indicators with varying degrees of success. Very often, it is seen that although these parameters do show changes, the changes are small and hence not distinctly measurable as there are measurement errors associated with instrumentation and data processing. A very good review of parameter estimation as a precursor to damage identification through modal parameters is done by Doebling, et al (1996), Farrar, et al. (2000) and Rytter (1993).

For a beam it can be shown that the curvature and strain are closely related. The mode shape curvature can hence be estimated from the modal strains. The modal curvature was initially estimated by first estimating the displacement mode shape and then finding its second derivative. It was initially shown by Pandey (1991) that the mode shape curvature's absolute value can be considered as a damage indicator. Stubbs, et al. (1992) presented an algorithm relating the decrease in the modal strain energy between two DOF's as defined as the mode shape curvature and related this index to the damage in a system. Chance, et al. (1994) found that using the measured strains directly improved the accuracy of the system, while using derived values introduced large numerical errors.

In this paper, it is shown that the strain based measurements can be used to estimate the structural modal parameters for a truss-like structure. The strain data can also be used to isolate the local parameters for each individual element which behaves as a sub-structure of the "global" system. It is then shown that the modal parameters derived from this seem sensitive to localized boundary condition changes and hence are postulated to estimate damages which are a resultant of these.

For open web girders, from experience, it is noted that most damage which occurs, occurs at the joints, resulting in boundary condition changes within the elements. It is shown in this paper that there are changes in the modal parameters which could be due to changes in these boundary conditions. The open web girder responses can be segregated into two types of response. First is the "global response" or the structural system response and the other is the "local response" or the response of the individual elements comprising the structure.

For typical beam-like structures, damage typically is a local phenomenon. It is therefore generally accepted that "local" member-level response is better captured by higher frequency modes whereas lower frequency modes tend to capture the "global" response of the structure and are less sensitive to "local" changes in a structure. From a testing standpoint it is more difficult to excite the higher frequency response of a structure as more energy is required to produce measurable response at these higher frequencies than at the lower frequencies. This limitation is not seen in open web girders, as the "local" member frequencies, which are defined in this context as the frequencies of individual elements are not significantly higher than the "global" frequencies and are seen to be excited even under normal traffic and actions.

The innovative feature of the proposed methodology is to segregate the estimated frequencies into "global frequencies" representing the behavior of the entire structure and "local frequencies" representing the behavior of individual component members behaving as sub-structure systems within the framework of the entire structure. The good correspondence between the structure natural frequency estimates from strain data at different locations in the structure also gives confidence in strain based frequency estimates as being good indicators of both structure (global) and member (local) behavior.

2 BACKGROUND

The partial differential equation of a beam, vibrating naturally with a frequency ω is given by:

$$\frac{\partial^2}{\partial x^2}\left[E(x) * I(x)\frac{\partial^2}{\partial x^2}\big(w(x,t)\big)\right] + \rho A(x)\frac{\partial^2 w(x,t)}{\partial t^2} = 0 \tag{1}$$

where ρ is the density and E the Young's Modulus, and A is the area and I the moment of inertia of a cross-section. This can be written in terms of the modal displacement W(x) as

$$EI\frac{d^4W(x)}{dx^4} = \rho A\omega^2 W(x)\,. \tag{2}$$

Using a weighted function δV(x), signifying a displacement field, it is possible to convert the above member level equation into a structural level equation such as:

$$EI\int_{x_k}^{x_l}\frac{d^2W}{dx^2} * \frac{d^2\delta V}{dx^2}dx = \int_{x_k}^{x_l}\rho A\omega^2 W\delta V dx + M_k\frac{d(\delta V)}{dx}(x_k) - M_l\frac{d(\delta V)}{dx}(x_l). \tag{3}$$

The member modal strain measured is proportional to the second derivative of the displacement for an Euler-Bernoulli beam. In addition to this, the essential strains which are induced on the structure due to the boundary conditions of the sub-structure which shows the structural modal effects would also be present. So, for the structure under consideration, if the structural modal effects could be removed, the resulting effects would be due to the member level vibrations.

From these, the boundary conditions and flexural rigidities could be estimated and an estimate made about the condition of the joints.

3 EXPERIMENTAL SETUP AND INSTRUMENTATION

The location of the sensors is shown for the different types of girders in Figures 1 and 2. In this paper, a "through girder" is defined as an open web girder which has the rail-track system connected to the bottom chords and an "under slung girder" is defined as an open web girder where the rail-track system is connected to the top chords. For both the girders under consideration, the U/S (Up-stream) side of the girder is strain gauged with sensors on both the top and bottom of the cross section to capture the in-plane bending of the members, while the D/S (Down-stream) side of the girder is strain gauged at the computed neutral axis. This methodology allows the differential analysis between the structural and member modes, as the structural modes exhibit predominant axial strains, while the member modes would exhibit in-plane and out-of-plane bending. The resulting signals are then passed through a fast Fourier transform to estimate their frequency content. The results have been generated for a 100 foot through girder and a 100 foot under-slung girder and their correspondences with the earlier generated results through acceleration are very good. For the analysis, 20 Trains have been considered as randomly selected over the period of 48 hour continuous monitoring.

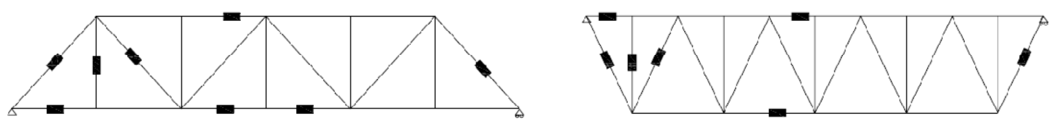

Figure 1: Instrumentation Scheme and Sensor Placement for Through and Under Slung Girder

The fundamental problem with using strain gauge data is that, unlike vibration data, there is a significant proportion of noise in the strain gauges. Also strain gauges have a large component of static data within them, which interferes in the estimation of dynamic parameters. Since the noise component is extremely high, the ambient strain data cannot be used for realistic parameter estimation as on filtering out noise, very little significant data is left for analysis. An attempt has been made here to identify the parameters from the forced vibration data. Using previously developed load identification procedures, the loads applied in the event are first identified. The measured response is then de-convoluted with this load vector to give an estimate of the impulse response. The entire process is shown below in a block diagram in Figure 2.

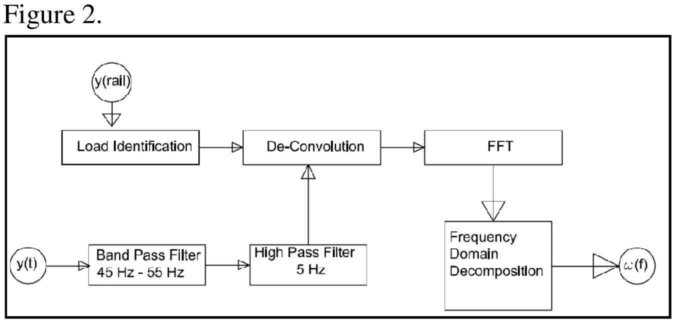

Figure 2: Schematic representation of the analysis process

4 RESULTS

4.1 Results for Through Girder

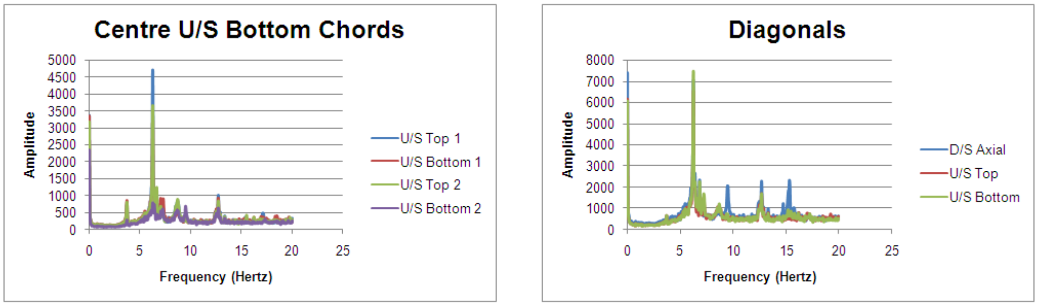

Figure 3: Frequency Content of Strain Data for various members of through girder bridge

A sample result set has been presented in a graphical pattern in Figure 3. The results from other instrumented locations were seen to be giving similar patterns of results and are being presented in Tables 1 and 2 along with a comparison of the results from the numerical models and the classical acceleration based peak picking methods.

Table 1. Comparisons of numerical and site measured structure frequency estimates - through girder bridge

Mode	*Frequency from Peak Picking in Accelerometers (Hz)*	*Frequency from Peak Picking in Strain Gauges (Hz)*	*Frequency from Numerical model (Hz)*
Mode 1	-	-	3.43
Mode 2	3.71	-	4.05
Mode 3	6.25	6.25	5.92
Mode 4	7.04	6.64	7.52
Mode 5	-	-	8.78
Mode 6	-	9.47	9.92
	-	12.71	-
Mode 7			15.38
Mode 8		18.46	17.83

Table 2. Comparisons of numerical and site measured member frequency estimates – Through Girder Bridge

	Numerical Model			*Site Measured Response*	
	First	Second	Third	First	Second
Bottom Chord Pier Side	7.95	15.95	24.05	6.84	16.17
Centre Bottom Chord U/S	9.84	19.74	29.76	7.03	17.04
Centre Bottom Chord D/S	9.84	19.74	29.76	7.23	
Top Chord	7.59	15.23	22.96		
Vertical Posts	6.75	13.54	19.84		
Pier End Raker	6.98	14	21.11	8.69	16.17
Abutment End Raker	6.98	14	21.11		
Pier Side First Diagonal U/S	6.81	13.67	20.61	6.39	14.75
Pier Side First Diagonal D/S	6.81	13.67	20.61		15.33

4.2 Results for Under Slung Girder

A sample result set has been presented in a graphical pattern in Figure 4. The results from other instrumented locations were seen to be giving similar patterns of results and are being presented in Tables 3 and 4 along with a comparison of the results from the numerical models and the classical acceleration based peak picking methods.

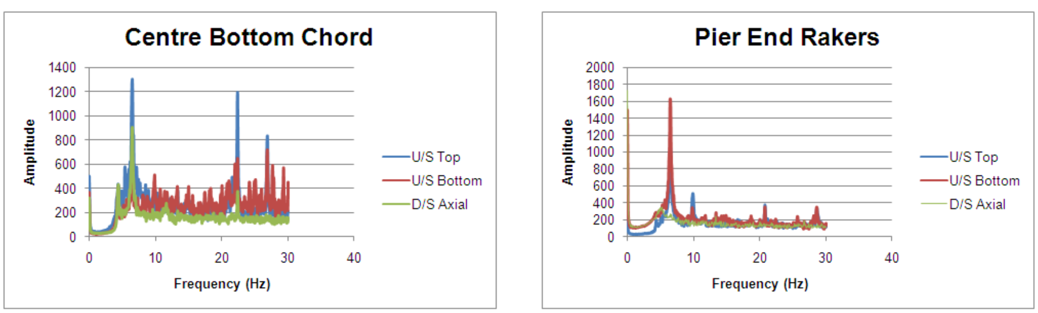

Figure 4: Frequency Content of Strain Data for various members for underslung girder

Table 3 Comparisons of numerical and site measured structure frequency estimates under slung girder

Mode	*Frequency from Peak Picking in Accelerometers (Hz)*	*Frequency from Peak Picking in Strain Gauges (Hz)*	*Frequency from Numerical model (Hz)*
Mode 1	3.91	-	4.20
Mode 2	7.42	6.45	7.35
Mode 3	9.96	9.82	9.73
	-	11.58	-
Mode 4	-	13.33	14.98
Mode 5	-	-	15.0

Table 4. Comparisons of numerical and site measured member frequency estimates – Under slung girder

	Numerical Model			*Site Measured Response*	
	First	Second	Third	First	Second
Centre Bottom Chord	17.71	35.53	53.57	15.58	-
Pier Side Top Chord	13.56	27.21	41.02	11.04	21.54
Centre Top Chord	19.88	39.88	60.13	-	-
Vertical Posts	14.87	29.84	37	-	20.03
Pier End Raker	8.44	16.93	25.53	9.87	18.66
Abutment End Raker	8.44	16.93	25.53	9.87	-
Pier Side First Diagonal	10.11	20.28	30.57	9.72	-

5 DISCUSSION OF RESULTS

The peaks from the frequency transform of the member strain data are divided into two classes of responses. The first is the “global structure response”, which are the frequencies that exist in all types of members. The second class is of frequencies which are represented locally in individual members only. These indicate the response of the specific member within the larger structure.

From Figures 3 and 4, it can be seen that the “global” responses are seen to be extremely consistent between all the members. All the members which were strain gauged, showed these “global” peaks identically, making this method of estimation a robust system for measuring the structural frequencies. This method makes accurate structure natural frequency estimates even at significantly higher frequencies and is thus a good estimator of the higher frequency vibration modes of the structure; this is illustrated in Tables 1 and 3. From Tables 2 and 4, it can be seen that with certain members, for example the first diagonal in the through girder, the two sides of the girders give significantly different responses. There is a noticeable shift in the second "local" frequency of this member, which could possibly be correlated with a change in the boundary condition. This, of course, needs further investigation, by model updating techniques.

In some members it can be seen that the numerically estimated frequency is more than the site estimated one. This would mean that the model is stiffer than the site conditions, which is generally acceptable as the numerical model as a first cut analysis has been considered as a fixed ended beam model. In the few cases where the site is showing higher responses, as in the end rakers and the diagonals, these members in reality consist of built up sections with bracings and connectors within them. These connectors have not been modeled in a first cut numerical analysis and the higher frequencies imply a higher stiffness than has been considered in the numerical model. Since more than one frequency is ideally estimated, these can be used to update the numerical model for both stiffness and boundary conditions. The process of finite element model updation and correlating the frequencies with accurately estimated boundary conditions is currently being done.

Some of the strain gauges were applied on the top and bottom flanges, while others were applied on the neutral axis. As expected, the spectral decomposition of these gave different frequency values. There were some frequencies which were only present in the strain gauges which were on the top and bottom flanges. This is expected as the bending strains, which are the essential "local" member-level modal strains would be best represented at these locations and would be significantly lower or even absent at the neutral axis location. This tendency of behavior in tune with the expected pattern gives a greater confidence in these estimated frequencies being the "local" modes and not spurious frequencies.

6 CONCLUSIONS

This work attempts to show that the strains are good structure modal parameter indicators and that they also estimate member modal parameters. It is also shown that the signal-to-noise ratios for dynamic strains are higher than those for accelerations. Furthermore, dynamic strains show more promise in damage detection as they are able to provide estimates of higher structural mode and member mode properties. It is shown that in open web girders, it is possible to estimate frequency shifts at an elemental level, which could signify member modes from strain data providing an indication of slight changes in member boundary conditions, although this needs confirmation through further study. Accurate estimates of boundary condition seem possible and are currently being explored under a model updation paradigm.

7 REFERENCES

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