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BRIDGE HEALTH MONITORING USING ACCELERATION MEASUREMENTS AND THE CONCEPT OF EQUIVALENT FIXED-POINT DEFLECTION

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Abstract. This paper proposes the concept of structural health monitoring of bridges using measured accelerations on the bridge and equivalent fixed-point deflections. Moving Force Identification is used to infer applied forces from measured accelerations. Given the statistical repeatability in the weights of heavy vehicles at a given site, any inferred change in mean weight can be used as a damage indicator. Equivalent fixed-point deflection (or force) was found to be computationally stable. In effect, this focuses on the static part of the signal – the measured acceleration is being transformed into what is essentially a static parameter.

Using the equivalent deflection from a group of trains without knowing their bogie weights, the normalised influence line is calculated and used as an indicator of structural condition. Simulations show that the equivalent deflection contains only a small dynamic component. As the deflection is the result of multiple applied loads, an influence line is found from the deflection, i.e., the component corresponding to a single point load. Using acceleration data from a simply supported railway bridge, the shapes of equivalent deflection influence lines are obtained from different groups of trains and show very good repeatability. Subsequently, this highly repeatable influence line is proposed as an indicator of certain types of bridge damage.

Key words: Bridge damage detection, structural health monitoring, influence line, equivalent deflection, acceleration.

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1 INTRODUCTION

Many damage indicators (DIs) have been proposed in the field of structural health monitoring (SHM) [1, 2]. It is generally agreed that a DI should be sensitive to damage and insensitive to noise and environmental effects [3, 4]. While not always achieved, a DI should ideally determine the presence, location and magnitude of damage. DIs can be classified as dynamic or static, with the dynamic indicators being further sub-divided into those based directly on the dynamic parameters of the structure and those that use transforms of the response. The DI proposed here is a pseudo-static indicator of damage, i.e., it derives from an acceleration measurement but uses an equivalent deflection, a static response, to monitor the condition. The disadvantage of a pseudo-static approach is that the response is affected by the weight of the passing vehicle. However, unlike acceleration, deflection is relatively stable and the variability in vehicle weights is countered by averaging the responses from many vehicles.

2 CONCEPT

Using an acceleration signal directly for SHM is problematic as the response oscillates and its 'magnitude' is difficult to measure. Deflection or force are more stable responses and are easier to relate to the bridge condition. In this paper, Moving Force Identification (MFI) theory [5] is used to calculate an equivalent deflection, defined as the imposed deflection signal at a point which would generate the measured acceleration. Conventional MFI [6-8] calculates the force signal corresponding to a measured acceleration and the principle is similar.

The equation of motion of the bridge, represented here as a beam, is:

$$[M_b]\{\ddot{u}\} + [C_b]\{\dot{u}\} + [K_b]\{u\} = [L]\{g(t)\} \tag{1}$$

where, $[M_b]$, $[C_b]$ and $[K_b]$ are the mass, damping and stiffness matrices of the bridge, respectively. The vectors, $\{u\}$, $\{\dot{u}\}$ and $\{\ddot{u}\}$, represent the bridge deflection, velocity, and acceleration signals, $[L]$ is a location matrix and $\{g(t)\}$ is a vector containing the magnitude of the dynamic forces acting on the bridge. The equivalent deflection, $\{\Delta(t)\}$, at a fixed point is defined by:

$$[M_b]\{\ddot{u}\} + [C_b]\{\dot{u}\} + [K_b]\{u\} = [K_b]\{\Delta(t)\} \tag{2}$$

Equation (2) can be rearranged, and the equivalent deflection signal found as:

$$\{\Delta\}_{j+1} = \{\Delta\}_j + \{r\}_j \tag{3}$$

where $\{r\}_j$ is the first derivative of the deflection. In state space, this becomes:

$$\{\tilde{X}\}_{j+1} = [\tilde{M}]\{\tilde{X}\}_j + [T]\{r\}_j \tag{4}$$

where

$$\{\tilde{X}\}_{j+1} = \begin{Bmatrix} X \\ \dot{X} \\ g \end{Bmatrix}_{j+1} \tag{5}$$

$$\{X\} = \begin{Bmatrix} u \\ \dot{u} \end{Bmatrix} \tag{6}$$

and

$$T = \begin{bmatrix} [0] \\ [0] \\ [I] \end{bmatrix} \tag{7}$$

To evaluate the vector $\{r\}_j$, an error function E is defined based on $\{\tilde{X}\}_j$ and $\{r\}_j$,

$$E(\{\tilde{X}\}_j, \{r_j\}) = \left([Q]\{\tilde{X}\}_j - \{d\}_j, [W]([Q]\{\tilde{X}\}_j - \{d\}_j)\right) + (\{r\}_j, [B]\{r\}_j) \tag{8}$$

where $[B]$ is a regularization term. The matrix $[Q]$ is used to select data from the state variable $\{\tilde{X}\}_j$ to match the acceleration measurements $\{d\}_j$. To get the vector $\{r\}_j$, Equation (8) is minimised using a procedure from the literature [8].

3 THE BRIDGE

The concept was tested using the Norton railway bridge in Staffordshire, the United Kingdom – Figure 1. The bridge, built in 2015, is a composite structure made up of two I-shaped steel plate girders and a cast-in-situ reinforced concrete deck slab. The main girders are connected by cross beams near the bottom flanges. The superstructure is 2.2 m deep and 7.3 m wide, carrying two railway tracks and resting on two cantilever-type abutments. It is skewed at 22.6º to the span. A detailed description of the bridge can be found in [9].

Figure 1. Norton test bridge

The bridge has been instrumented with 290 sensor nodes by the Centre for Smart Infrastructure and Construction [10], a research group in the Department of Engineering at the University of Cambridge. Sensors include axle detectors, installed at the bridge ends and accelerometers, installed on the West main girder at the end supports, quarter- and three quarter-span locations.

The axle detection system comprises of SF30/C high-speed laser rangefinder sensors made by LightWare and installed on the guardrails at the Southern and Northern ends of the bridge, pointing in the transverse direction slightly above the rails. When an axle crosses the sensor location, it cuts the beam, causing a spike in the time history of this signal that is used to identify its presence. The accelerometers are triaxial high-grade QMEMS that can sense gravity. Data from the accelerometers was acquired at a 200 Hz sampling rate using the National Instruments cRIO datalogger.

About 70 trains pass over the Norton bridge every day, predominantly regional and suburban passenger trains, with some freight trains using the line at night. For this study, data was acquired from 2nd June to 10th September 2022. In that period, there were 1008 crossings of British Rail Class 350 trains – Figure 2. The British Rail Class 350 is an electric-multiple-unit passenger train comprising of a 4-car set formation. Each car consists of two bogies spaced 14 m apart, each of which has double axles spaced at 2.59 m. Typical measurements are illustrated in the figure.

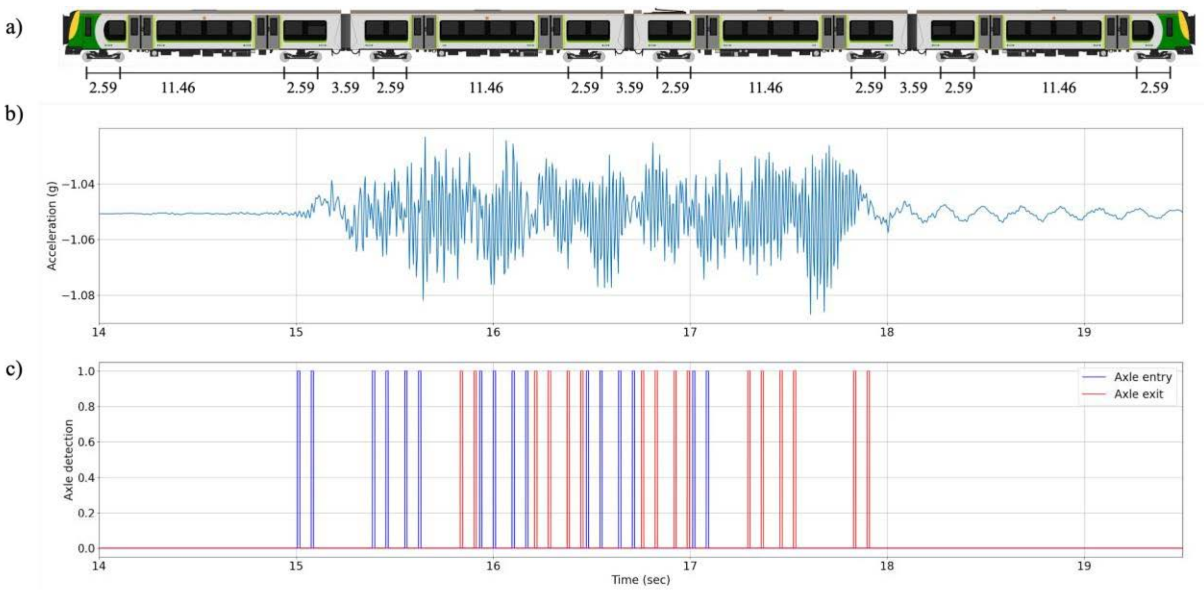

Figure 2. British Rail Class 350 train and measured responses: (a) Train axle configuration, (b) Vertical acceleration time history signal from the quarter-span location, and (c) Axle detection time history signal from the Southern bridge end

4 RESULTS

To allow the equivalent deflections to be calculated, the bridge properties were estimated. The mass per unit length of one girder is considered to be 16910 kg/m and the bridge damping ratio is assumed to be 3%. Those properties are used to obtain the matrices in Equation (2). The damping matrix is generated according to the assumption of Rayleigh damping [11]. Different values of the bridge flexural rigidity were tested for the calculations. The equivalent deflection was found to be largely insensitive to the value assumed.

The equivalent deflection is the equivalent response to the loading from all axles present on the bridge at a given time. To remove the effect of axle configuration, an influence line (IL) is calculated using an iterative procedure [12]. In this case, the IL is the equivalent deflection response to an axle of unit weight – in effect, the response is broken up into components corresponding to each axle load. The magnitude of the IL is sensitive to the train weight, so it is normalised and a single curve is found for a large group of trains – in this case there are 325 trains per group. This process is repeated using three different groups of train data. The data are divided into three groups by date: Group 1 (2nd June to 5th July), Group 2 (5th July to 22nd Aug.), and Group 3 (22nd July to 20th Sep.).

The normalised ILs are illustrated in Figure 3 and it can be seen that the repeatability is excellent. As it is normalised, this IL is unsuited to the detection of a loss of stiffness. However, other types of damage, such as bearing failure, have a strong influence on IL shape and this function seems well suited for early detection.

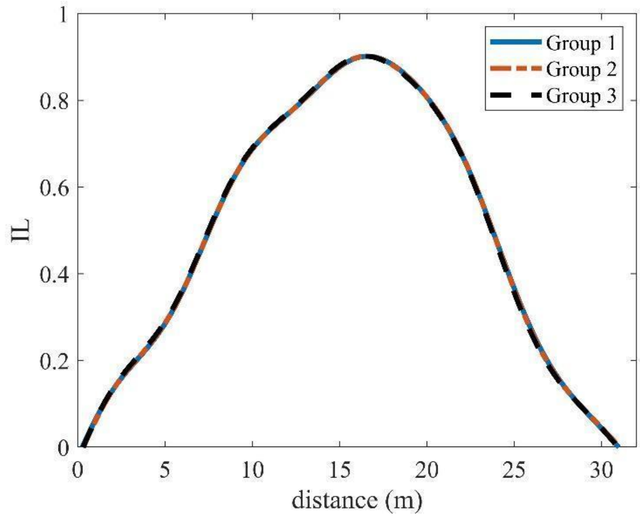

Figure 3. Normalised influence line at ¾-span (S-N) for three different groups of trains

5 CONCLUSIONS

The concept of equivalent deflection is introduced as a bridge damage indicator. Equivalent deflections, defined as the deflections at a point consistent with the measured accelerations, are found using Moving Force Identification theory. They are a pseudo-static response and therefore are more stable than raw accelerations. Acceleration measurements from a bridge in the United Kingdom are used to calculate the equivalent deflections corresponding to passing trains. The signals are decomposed to determine the normalised influence line. The shape of this influence line is shown to be highly repeatable for groups of 325 trains and is proposed as an indicator of certain types of bridge damage.

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