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WIRELESS DRIVE-BY-VIBRATION SENSING FOR HEALTH MONITORING OF SHORT-SPAN BRIDGES

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Abstract

To provide reliable monitoring of short-span rural bridges, ambient excitation measurements using wireless sensing and drive-by measurements has been suggested to nondestructively estimate the remaining load capacity of these bridges. The recommended procedure includes dominant mode system identification and using ambient traffic excited vibrations measurements to determine bridge load capacity. This approach (dynamic load rating technique) represents a simple, first order approximation to the remaining load capacity. The technique is further improved by coupling with wireless sensors to form the basis of a Wireless Drive-By-Network (WDBN) sensing technique. This paper reports the underlying philosophy, wireless sensor placement and system design and results from preliminary studies on six different bridges in Alabama, USA.

INTRODUCTION

This paper describes a research effort to develop a dynamic load rating (DLR) technique for application on US county bridges. The new technique is based on the serviceability deflection limit of a bridge and its relationship to ambient vibration measurements taken from the bridge [1][2]. Many bridges in the US face deficient ratings indicating a need for significant work or even replacement [3][4]. Limited funding, however, makes it impossible to replace all the bridges with insufficient carrying capacity. Also, many bridges rated as insufficient by traditional rating methods turned out to be perfectly serviceable. Some were reported as capable of withstanding more than 10 times the posted load [5]. It is well-documented that current rating and inspection techniques have limitations in predicting the load capacity of these bridges [6]. New techniques are therefore needed to test the loading capacity of those bridges.

There are currently two commonly used rating systems. One is based on visual inspection results and the other relies on static analytical methods. The rating of bridges is a score-based system, where inspectors are required to rate various components of a bridge such as: the condition of the steel girders, the condition of the asphalt pavement, the cracking of the concrete, the corrosion of the piers, conditions of the bridge bearings, etc. Most of those indicators are independent quantifiers. An integration of the scores using rationalization becomes necessary to come up with a general health condition rating. The rating method recommended by AASHTO does not require any field measurements of the remaining strength of the bridge or its components [7]. The rating method can be based on LRFD (Load Resistance Factor Design) or ASD (Allowable Stress Design). The method requires subjective input from an inspector. If the results of a typical inspection and evaluation process lead to the conclusion that a structure is not sufficient and a replacement is appropriate, a detailed consideration of actual load capacity is generally justified. The major drawback of current bridge inspection approach remains that the input needed is almost completely independent of the existing condition of the bridge, since the actual damage state is not directly quantified. A second drawback is that any change of conditions is most likely to be a function of the inspector's visual inspection. As a result, a highly experienced inspector is needed. Many times, the same bridge may be classified as safe or unsafe by different inspectors.

Currently, bridge load testing is the only true validation to give a clear picture of the condition of the bridge, especially when deflection is measured. Deflection and strain may involve integrated parameters that could realistically reflect the loading capacity. However, static testing is not easily conducted; it requires stopping traffic and may involve several personnel to test a bridge. In most cases, a special test truck will be required to park on the bridge as static load. A very important reason to load test bridges is to determine the ultimate load-carrying capacity of a bridge. The difficulty is that the information relating to some of the important variables that affects the capacity of a bridge is not generally available to those in charge of making this assessment. Due to the potential danger of damaging existing bridge, large scale tests to ultimate capacity are usually avoided.

As shown in Figure 1, load-deflection behaviour of a bridge can be idealized as a linear-nonlinear curve. The design load of the bridge is usually much lower than the ultimate load carrying capacity when the bridge is well designed. As a result, there is little surprise why some bridges could carry static proof load of about 70 metric tons when posted with a two metric tons load limit [5]. There is no detailed or convincing data from which a correlation between the inspector rated safety standard and actual load capacity can be drawn. Even if a bridge test is conducted, different results may occur from different testing procedures. Hence, no reliable data exists regarding the actual load capacity of a bridge.

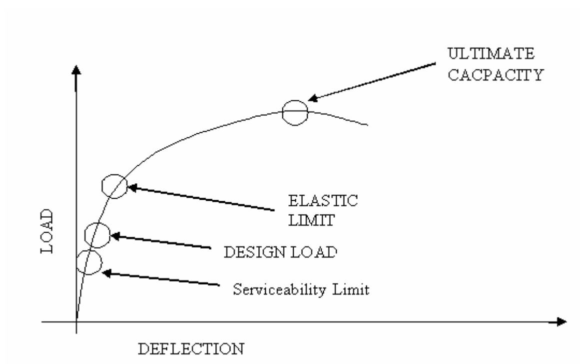

Figure 1. Idealized Load-Deflection Behaviour of a Bridge (NCHRP, 1998).

WIRELESS DRIVE-BY-NETWORK SENSING FOR BRIDGE RATING

The proposed DLR technique is intended to address the shortcoming of static load testing and to provide an inexpensive solution to monitoring bridges. The idea is to detect the vibration property of a bridge during normal operations. The proposed method is safer compared to static load testing on a real bridge, since it does not require the placement of large load on a bridge. The method is also more convenient than static load testing, since it does not require stopping the traffic in order to conduct the test.

The DLR technique idealizes the bridge as a mass-loaded spring with spring constant, k (see Figure 2). When a vehicle passes over the bridge, a load P is exerted causing the bridge to deflect δ. Under linear elastic assumptions, the load P on the bridge is then equal to $\delta * k$. By measuring the vibrations under ambient conditions, the bridge's fundamental vibration frequency, f, can be determined as a function of its mass and stiffness and used to back calculate the remaining bridge stiffness, k'.

Figure 2. Bridge Modeled as Mass-Loaded Spring.

The remaining loading capacity, *P'*, can be then determined if the deflection is maintained as a constant such as by using the AASHTO (American Association of State Highway and Transportation Officials) deflection limits $\delta_{allowable}$ [7]:

$$P' = \delta_{allowable} \cdot k' \quad (1)$$

To formulate the effective bridge spring model, a Single Degree of Freedom (SDOF) system is established to account for vehicle motion, boundary condition, thermal expansion and prestress effects [8]. The dynamic equation of motion for the SDOF model can be stated as:

$$M * X(t)'' + C * X(t)' + K * X = F(t) \quad (2)$$

where M is the effective mass, K is the effective spring constant, C is system damping and F(t) is the forcing function:

$$M = \int_0^L m(x)\varphi^2(x)dx \quad (3)$$

$$K = \int_0^L EI(x)\{\varphi''(x)\}^2 dx \quad (4)$$

$$C = \int_0^L c(x)\varphi^2(x)dx \quad (5)$$

$$F(t) = \int_0^L p(x,t)\varphi(x)dx \quad (6)$$

$X''(t)$ is acceleration of mid-point in bridge, and $\varphi(x)$ is the mode shape function. To account for vehicular mass effect, m_{vi} and considering thermal expansion and pre-stress loads, the SDOF model can be revised as:

$$(M_b + m_{vi}) * X(t)'' + C_b * X(t)' + (K_b + K_p + K_t) * X = F_i(t) \quad (7)$$

where *i* represents load location; M_b is bridge mass; K_b is bridge stiffness; K_p is stiffness change due to pre-stress and K_t is stiffness change due to temperature loading effects.

The baseline frequency for the existing structure can be determined through full-scale modal test on the bridge. Assuming the bridge did not lose significant weight (<10 percent), the drop in stiffness can then be determined by comparing the present vibration frequency with initial frequency value. Load capacity can then be calibrated with known vehicle speeds and types. Through parametric studies, the vehicular effects including suspension system considerations and temperature effects are then used to generate different coefficients (see Table 1) that can be used to modify the measured vibration frequencies:

$$f_c = \lambda C f_n \quad (8)$$

where f_c is effective frequency; f_n is the actual measured natural frequency; C is total effect coefficient; and λ is boundary effect coefficient.

Table 1. Effect Coefficients [9]

Types of Effect	Situations	Effect Coefficients
Vehicle speed (c1)	$0 \le V \le 90$ Mph	1~0.95
Vehicle weight (c2)	$0 \le V \le 20$ tons	1~0.94
Vehicle Wheelbase (c3)	$l/L \le 0.15$ in or $l/L \ge 0.2$	0.94
	$0.15 < l/L < 0.2$	0.99
Temperature (c4)	Calibrate for location	1.1~0.9
Other effects (c5)	Vehicle suspension systems	0.95~1.05
Note: C=c1*c2*c3*c4*c5		

The Wireless-Drive-By-Network (WDBN) sensing concept is captured in the following schematic drawing (see Figure 3), where the vehicle is shown equipped with a laptop for data acquisition. The unique feature of this model is the induced vibration due to the vehicle crossing; for remote sites with little traffic, this approach is logical, but technically challenging for two reasons: 1) the data logging has to be ready for very short-span bridges and 2) excitation may not be representative of the system response.

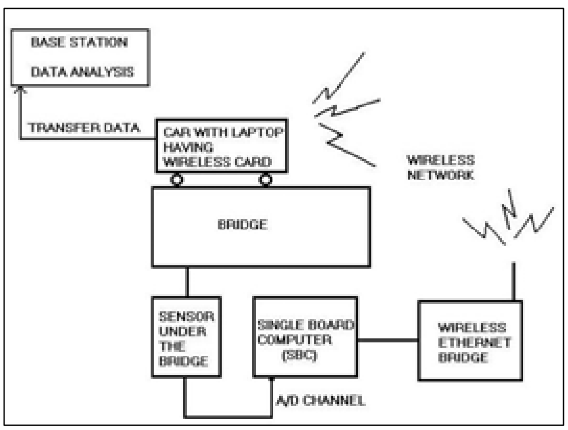

Figure 3. Block Diagram of WDBN System [10].

CHALLENGES IN WDBN SYSTEM DESIGN

Key challenge in WDBN system involves the selection of appropriate remote sensing technique. Experiences with both FM radio wave and cellular technologies indicate the difficulties in establishing signal sighting from sensors installed under the bridges. Current DLR approach requires a single sensor setup and the capture of the first bending vibration mode, thus limits the number of sensor positions. To optimize the capture of first bending mode and at the same time, minimize torsional mode amplitudes, it is essential to place the sensor at the centre girder of a bridge. Due to the size of typical bridges, this requires an extended antenna.

Power supply is another challenge. Power requirements are very important for the proper functioning of any device. For hassle-free and safe operation of any equipment, careful considerations of its voltage and current requirements are needed. Power spikes can damage and even destroy system components. Power related problems impact the installer/designer principally in two ways: The first is merely meeting the consumer's expectations, while the second is minimizing maintenance-related issues. Depending on the manufacturer, some off-the-shelf sensors require precise system energy requirements. The power for the various components of a WDBN prototype system, for example, requires isolated power supplies (see Figure 4).

A second WDBN prototype uses a Microstrain G-Link system that has encased power supplies for the sensor only. The system allows wireless data transmission using IEEE 802.15.4 open communication with 2.4 GHz direct sequence spread spectrum radio transmission [11]. However, this system is limited to sensing range and can only be viewed underneath the bridge. Figure 5 shows the sensing system and the sensor being placed underneath a bridge.

Figure 4. Separate Power Supplies for Z-World Single IC board, Crossbow Accelerometer, and Linksys Wireless Ethernet Bridge [10].

(a) G-Link Sensor (b) Sensor Installment under Bridge

Figure 5. G-Link Sensor for WDBN Second Prototype.

BRIDGE RATING USING WDBN APPROACH

Six bridges in Alabama have been rated using the WDBN approach with ambient traffic excitation. Table 2 shows the different rated bridges and their types and span lengths. Table 3 shows the rating outcomes. To determine AASHTO-compatible load rating, a load post approach using LRFD is adopted [12]:

$$P_D^{post} = \frac{P' - \gamma_d W_d}{n(1 + DLF)\gamma_L} \qquad (11)$$

As shown in Table 3, the technique consistently provided higher load predictions than AASHTO methods. Previous studies comparing to static load tests indicate a possible 15 percent deviation from static test results [2].

Table 2. Rated Bridges in Shelby Alabama

Bridge Name	Bridge Number	Bridge Type	Span No.	Location
Cross Creek	99014	Prestressed-AASHTO III and I, simply supported	Three spans (80 ft, 80 ft and 30 ft)	Pelham, Alabama
County Bridge	042-59-216Z	Steel girder, simply supported	Four spans (50 ft, 60 ft, 50 ft, 50ft)	Columbiana, Alabama
River-Woods		Prestressed, Bulb-tee, simply supported	Single span (120 ft)	Helena, Alabama
County Bridge	000-59-100Z	Prestressed-AASHTO IV, simply supported	Single span (61 ft)	Columbiana, Alabama
County road 20	020-59-202Z	Steel girder, fixed ends	Single span (18ft)	Montevallo, Alabama
County road 47	047-59-001X	Steel girder, fixed end	Single span (32 ft)	Columbiana, Alabama

Table 3. Bridge Rating Using DLR Method

Bridge Number	Self weight (Ton)	Current AASHTO Inventory Rating (Ton)	Current AASHTO Operating Rating (Ton)	P_{total} Adjusted (Ton)
99014	420 (80 ft span) 156.5 (30 ft span)	-	-	135.7 78.9
Riverwood	626	-	-	182.6
042-59-216Z	142	29.5	56.7	61.7
000-59-100Z	207	36.0	47.9	66.9
020-59-202Z	21.39	6 – 15	9.6	11.7
047-59-001X	56.86	-	13.08	16.5

DISCUSSION AND CONNECTION TO HEALTH MONITORING

The proposed DLR technique made several assumptions in the simple SDOF model including: 1) the bridge only vibrates in a single mode; 2) the bridge support conditions do not change significantly; 3) all girders deform by the same amount; and 4) only a single vehicle passes over the bridge at any time. These assumptions may limit the application of the technique to a first order approximation of the load capacity of a bridge. There are several factors that impact on bridge vibration behaviour that are not included in current approach including the possibility of temperature effects on sensors, change of support conditions, and simultaneous multiple vehicle crossings. For practical applications, these conditions pose serious limitations to the current proposed method and demand further investigations. However, innovative approaches such as limiting the time and seasons for bridge monitoring may be imposed to ensure the validity of the test results.

The benefits of the proposed load rating technique lie in the fact that it is relatively low-cost with limited traffic intrusion, and provides to a certain confidence level the load capacity of the bridge. Such an approach can significantly reduce the inspection costs by limiting the instrumentations and traffic control requirements. However, robust sensor self-calibration and adjustment algorithms may be required to ensure that the sensor is functional at all times.

The proposed technique does not replace current inspection practices, but is suggested as a supplement to the more precise visual inspections. In the larger scheme of structural health monitoring, the proposed technique represents a low-level monitoring that can provide a possible indication of accelerated deterioration of the structure and further precision inspection can then be prescribed.

A critical component of the future of the proposed technique is a low-cost wide-range DLR sensing network that can be streamed together for real-time monitoring. A network system (see Figure 6) is proposed for Shelby County, Alabama, where clusters of bridges can be established for either scheduled monitoring or using communication hub for streaming vibration data back to DOT.

Figure 6. Possible WDBN Sensing Network for Shelby, Alabama.

CONCLUSIONS

To address the issue of an aging bridge infrastructure, a dynamic load rating technique is proposed that can produce realistic bridge remaining load capacities. The technique is based on a simple SDOF model and hence, provides a first-order approximation of bridge load capacity. Detailed theoretical equations that can be used to delineate varied conditions have also been developed and shown. Results from testing six different bridges suggest that the method provides higher estimation of bridge load capacities than current AASHTO rating technique.

REFERENCES

[1]. Chen, S.E., Siswobusono, P., Delatte, N. and Stephenes, B. J "Feasibility Study on Dynamic Bridge Load Rating" Technical Report No. 01221, University Transportation Center for Alabama, Birmingham, AL, (2003).
[2]. Siswobusono, P. "A Neworkable Load Capacity Assessment Technique for Bridge Management." MS thesis, Department of Civil and Environmental Engineering, University of Alabama at Birmingham, Birmingham, AL. (2003).
[3]. Galambos, F.C. "Highway Bridge Loadings" Engineering Structures, (1), (1979), 230-235.
[4]. Grimes, T.C. "Local roads bridge replacement prioritization database (BRPD) program." MS thesis, University of Alabama at Birmingham, Ala. (2001).
[5]. Bakht, B. and Jaeger, G.L. "Bridge Testing- A surpise Every Time" Journal of Structural Engineering ASCE, Vol. 116 No. 5, (1990), 1370-1383.
[6]. Rytter, A. "Vibration Based Inspection of Civil Engineering Structures" Doctoral Dissertation ,University of Aalborg, Aalborg, Denmark (1993).
[7]. AASHTO, "Manual for Condition Evaluation of Bridges", Second edition, Washington, D.C. (2000).
[8]. Biggs, J.M. "Introduction to Structural Dynamics", McGraw-Hill, New York (1964).

[9]. Chen, S.E. and Zhao, Z.,S. "Dynamic Load Rating of Single-Span County Bridges," Proceedings, 7th International Conference on Short and Medium Span Bridges, Montreal, Canada, (2006).
[10]. Lokanath, R. "System Design of a Wireless Drive-By Network (WDBN) for Monitoring Bridge Integrity," Report, University of Alabama at Birmingham, AL (2003).
[11]. Microstrain, Inc., "G-Link 2.4 GHz Wireless Accelerometer Node-Quick Start Guide," (2005).
[12]. Zhao, Z.S., "System Parametric and Optimization Study for Dynamic Bridge Load Rating," MS Thesis, University of Alabama at Birmingham, AL (2005).