Development of a Prototype Remote Structural Health Monitoring System (RSHMS)

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Key words: Structural Monitoring, Digital Signal Processing, Signal Extraction.

SUMMARY

The Engineering and Physical Sciences Research Council (EPSRC) of the UK awarded a three-year contract to The University of Nottingham and Cranfield University to collaboratively investigate the feasibility of using computational simulation and GPS sensors for structural health monitoring (SHM). This paper is one part of this joint research between two parties. In the project, GPS and triaxial accelerometers are two kinds of basic sensors which are extensively used in the structural deformation monitoring of different scale bridges. This paper consists of two parts. The first part is a comprehensive review to the prototype RSHMS, including hardware configuration, accuracy assessment to the proposed sensor system, an real-time adaptive filtering algorithm developed for data integration of different sensors, field data acquisitions and various deformation analysis approaches. The second part is a brief discussion on a specifically developed finite element (FE) model for predicting theoretical dynamics by the project partner, Cranfield University. The real dynamics of the structures under different environments are compared with predicted ones. Results demonstrate that it is possible to use modern satellite positioning technology augmented by other sensors to realise highly accurate structural health monitoring with less human intervention.

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1. INTRODUCTION

In 2001, the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham was awarded a major grant to investigate the feasibility of using GPS and other sensors to remotely monitor structural health condition in real-time, particularly on an operational bridge, without on-site inspection (Roberts et al. 2003). The project partners include Cranfield University, Leica Geosystems Ltd, Network Rail, WS Atkins, and other industrial collaborators. Extensive hardware devices were either purchased or made available to achieve difference functionalities of proposed system. Meanwhile, various software packages have been developed during this project period for different data collection and processing purposes. Trials were conducted on the Wilford Footbridge over the River Trent in Nottingham, the London Millennium Bridge over the River Thames and the Humber Bridge over the River Humber in Hull. The research has been published in prestigious journals and conferences. International cooperation in wider areas with the University of New South Wales in Australia, Tongji University in Shanghai, China and the Chinese Academy of Surveying and Mapping has been initiated. In this paper, the hardware and their functionalities are introduced in the Section 2. Software packages developed for data fusion, satellite geometry simulation, real-time data synchronisation and collection of GPS and accelerometer data, web based RTK correction transmission, structural dynamic extraction and an FE model for the Wilford Bridge, are presented in the Section 3. Results from the Wilford Bridge with different dynamic characteristics are discussed in the Section 4. Also included in this section is the comparison of theoretical dynamics prediction from an FE model and those extracted from field measurements. This paper demonstrates that it is feasible to detect structural dynamics using a computational model and GPS sensors.

2. HARDWARE OF RBHMS

Leica Geosystems won the bid for the invitation to tenders and became the major GPS sensor supplier for this project. Ten 10 Hz Leica SR510 single frequency GPS receivers were purchased, particularly for this project. Four Leica 10 Hz dual frequency GPS receivers System SR530 purchased before were also used in the project. Leica antennas AT501 (SF), 502 (LDF), AT503 (LCH) and AT504 (CH) are extensively used in the project. Since the vibration frequencies of short span bridge can reach several tens of Hertz, current GPS receivers cannot be effectively used to detect such bridge dynamics. Figure 1 shows the first natural frequencies of railway bridges against their spans. For detecting higher bridge vibrations, GPS receivers with sampling rate lower than 100 Hz are obviously incapable in this case. Accelerometers are designed to sense high structural dynamics. It can accurately detect vibration frequencies up to several hundred Hertz or even higher. However, it has problem to accurately detect 'very low' vibrations which are evident for long span structures and the force measurements have to be double integrated to obtain relative displacements. For instance, the first natural vibration frequency in vertical direction of the Humber Bridge is 0.116 Hz (Brown et al. 1999), and the Tsing Ma Bridge in Hong Kong is 0.117 Hz, with the main spans of 1, 400 m and 1, 377 m long (Xu and Ko 1997), respectively. From above analysis, it is apparent that the high dynamics of bridges (f>10 Hz) cannot be detected by current GPS receivers. However, the lower vibration frequencies of the same structures cannot be identified by a triaxial accelerometer. Integration of GPS and triaxial accelerometer can extend measurable frequency bands from very low to very high and hence a more reliable deformation system. A cage housing a GPS antenna and a triaxial accelerometer for this purpose was designed to achieve seamless senor integration (see Figure 2).

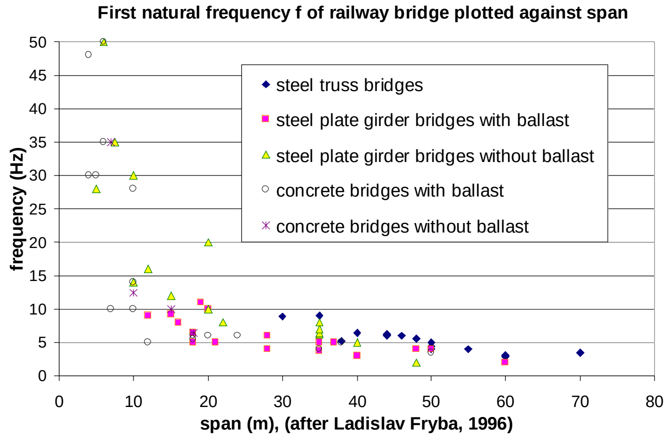


Fig. 1: Natural vibration frequencies of railway bridges

Fig. 2: Cage for Housing GPS and Accelerometer

Two kinds of triaxial accelerometers are tested and Kistler's K-BEAM® 8393A2 ±2*g* triaxial accelerometers were eventually chosen for this project. Details about the specs can be found from website: www.kistler.com. To convert continuous analogous signal to a digital one, 16 bit A/D converters were used. GPS satellite geometry and its implications for precise engineering applications in the middle and high latitude areas are analysed by (Meng et al. 2004). For instance, due to an inclination of 55° of the GPS satellite orbits, the satellite distribution across the sky in mid- and high latitude areas is uneven. Observations in the northern sky quadrant (roughly between azimuths 315° and 45°) are only possible from the satellites close to the zenith or near the horizon as shown in Figure 3. Since for most engineering applications, uniform 3D positioning precision is important for correct geodetic data interpretation. Simulation indicates with the inclusion of low elevation angle satellites in the data processing, the dilution of precision (DOP) will greatly be improved but the measurements might be contaminated by the errors sources related to transmission media near the earth surface and cause a total precision degradation. To solve this problem ground based pseudolites can be employed to strengthen the satellite geometry. Since pseudolites can theoretically be installed anywhere with a line of sight to the receivers they can be used to improve the positioning precision in specific directions according to the actual observation scenario. As demonstrated by (Meng 2002), pseudolites set up on the north side of a rover station with low or even negative elevation angles will improve north and vertical positioning precision due to strengthened transmitter geometry. To further investigate feasibility of using pseudolites for precise engineering application an IntegriNautics IN200 pseudolite transmitter and NovAtel GPS/pseudolite receivers were purchased. JNS100 marks a new generation of high precision GPS boards in a small size and it is able to output raw data and position solution 100 times per second without interpolation. To compare the GPS output with accelerometer, two Javad JNS100 Hz single frequency receivers were recently purchased. Further tests are on the way.

Development of a prototype monitoring system is the core of this research. Real-time transmission of RTK corrections to a series of rovers installed at various critical bridge sites is a prerequisite of the proposed system. In the past, radio modems have been widely employed for this purpose. However, this kind of data link is single-directional and the real-time positioning solutions cannot be transmitted back to the control centre for further analysis, which is crucial for detecting structural problems after collecting each site deformation information. Also this technique requires a line-of-sight between the reference(s) station and rovers, which proves to be unrealistic for all bridge sites where bridge deck, supporting towers or other surroundings might obstruct the signal transmission. Other disadvantages of radio modem based RTK correction transmission have been explored by Omar and Rizos (2003).

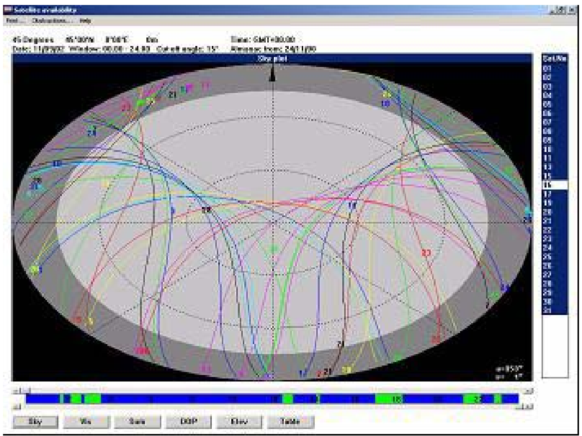


Fig 3: Deficiency of GPS Geometry

The Internet provides an alternative way to transmit timely and reliable RTK or DGPS corrections for many geodetic, engineering, maritime and military applications. For instance, Jet Propulsion Laboratory (JPL) in the USA developed a Global Differential GPS (GDGPS) system to generate and disseminate over the open Internet special 1s global differential corrections to the broadcast GPS orbits and clocks/
(http://gipsy.jpl.nasa.gov/igdg/)

Using this facility, stand-alone users equipped with dual frequency receivers can achieve real-time positioning at an accuracy of dm level globally. Researchers at Delft University in the Netherlands further proved JPL claim by conducting static and kinematic tests. The experimental results show that positioning accuracies of 10 cm in horizontal component and 20 cm in vertical component, with a latency of 7~8 seconds, can be achieved using Internet-based DGPS disseminated by JPL (Kechine et al. 2004).

However, there are very few Internet-based RTK GPS studies so far, especially there is a lack of research in the investigation of high rate correction transmissions to a series of rovers for the application in monitoring of structural deflection (Meng et al., 2004).

This research attempts to develop a prototype remote bridge health monitor system using currently available techniques. Figure 4 shows the basic hardware configuration. The designed system consists of three segments, i.e. reference station(s), rover station array, and control centre, denoted as 1, 2 and 3 in the figure, respectively. The reference station(s) comprise one or more GPS receiver(s) and the Ethernet to serial convert(s) acting as data server(s). The rover array consists of GPS receivers installed at critical sites on the bridge deck and pairs of Ethernet to serial converters attached to each GPS receiver to receive and disseminate date from and to the Internet. The host PCs at a control station has an Internet access to "listen" to the positioning solutions. The functionalities of each component include to disseminate RTK corrections to the rovers via the Internet connections (Segment 1), receive RTK corrections and conduct RTK positioning and send the positioning solutions back to the Internet (Segment 2), and capture positioning solutions of each rover and analyse the structural dynamics (Segment 3).

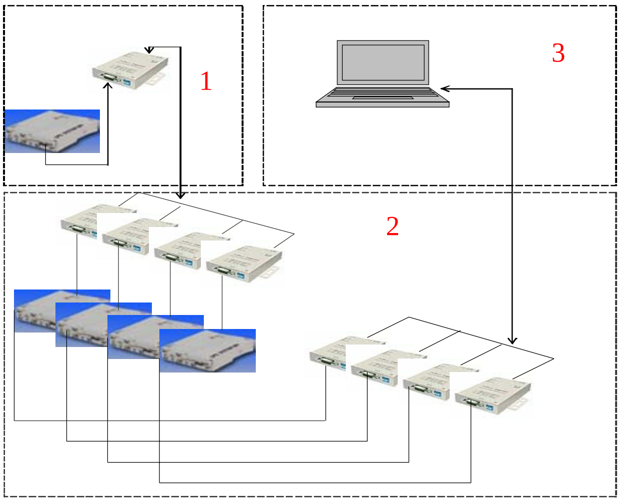


Fig 4: Configuration of Web Based RTK GPS

3. SOFTWARE DEVELOPEMENT

To investigate the improvement with the inclusion of several ground based pseudolites and future Galileo satellites, and also determine the optimal locations for these pseudolites, an integrated GPS/Galileo/pseudolite simulator was developed. For example, the global maximum GDOP before and after the inclusion of Galileo satellite are shown by Figures 5 and 6. It can be seen that the maximum GDOP values are less than 4, compared to that the maximum GDOP values are higher than 4 in most areas, which can guarantee the positioning quality on the base of 24 hours.

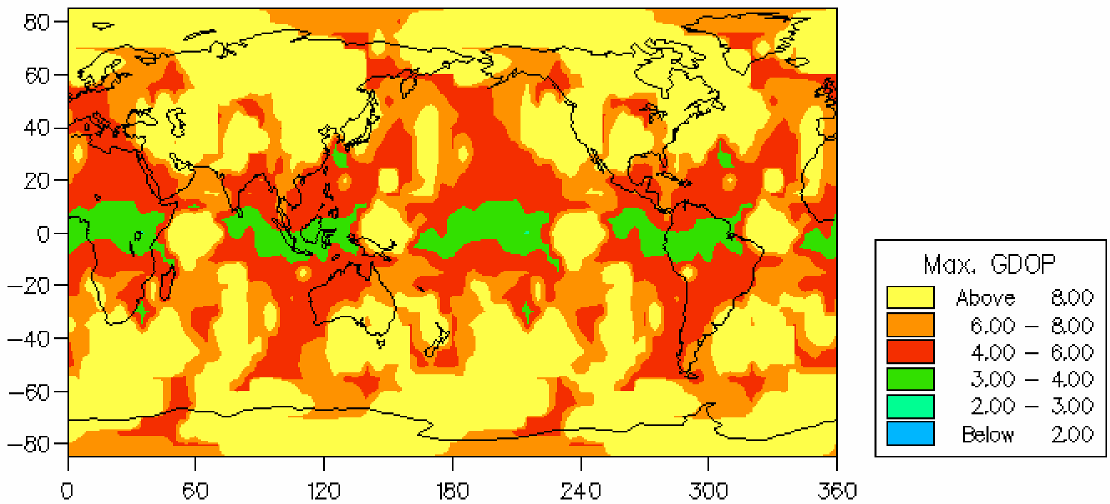


Fig. 5: Global Maximum GDOP of GPS only System

Real-time adaptive filtering technique is developed to mitigate multipath, extract relative tropospheric delay and integrate GPS data with accelerometer measurements. Through the coordinate comparison of two days measurement at same observation site the multipath signatures can be characterised and effectively removed. For instance, for different deformation amplitudes, the ratios in mitigating multipath are different due the changing nature of multipath. For short span bridges of several tens of meters, multipath can occupy up to 80% of total amplitude of the time series, whilst for longer span bridges of several hundreds of meters, multipath only forms about 30% of total time series. It is evident that the algorithm can be effectively used to reduce the multipath noise in the deformation time series and supply a better understanding to the real structural dynamics.

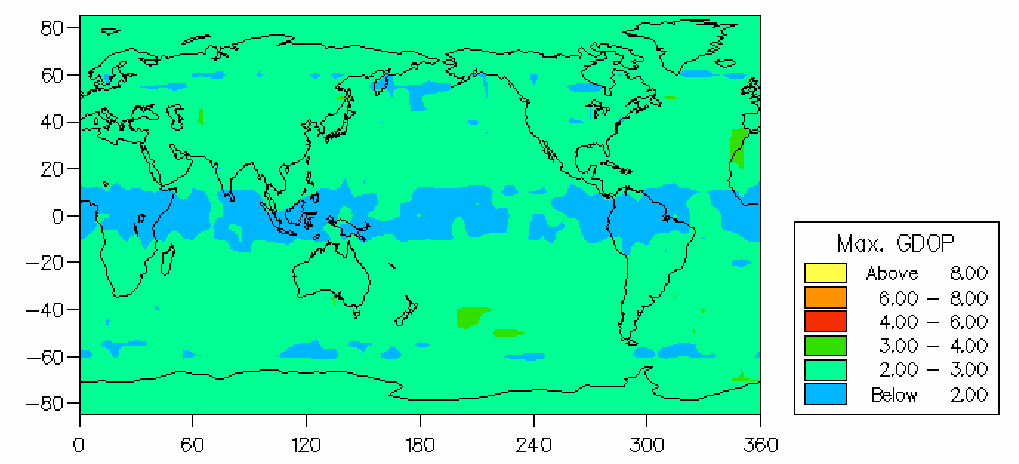


Fig. 6: Global Maximum GDOP of GPS/Galileo Systems

Synchronising GPS data with accelerometer measurements is important in the design of a filtering technique based data fusion system. Figure 7 shows the schematic of synchronisation software package developed. GPS pulse per second (PPS) signal is used to trigger the data collection of a triaxial accelerometer, whilst GPS NMEA messages are captured by a host laptop and stamp on the accelerometer data.

For achieving web based Internet RTK GPS, a dedicated VC++ software package is developed for the following purposes:

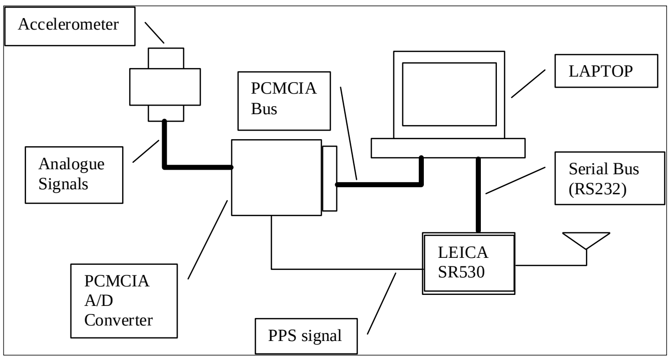


Fig.7: Synchronisation of GPS and accelerometer

- Control the data capture of NMEA message sent by rover receivers, using User Datagram Protocol (UDP), from a host PC running this developed software;
- Real-time coordinate transformation from WGS84 to a local coordinate system (OS) and then to a engineering coordinate system;

– Create and retrieve a multipath template database;
– Real-time multipath mitigation using moving averaging or adaptive filtering where appropriate; and

– Real-time result visualisation.

Figure 8 is the interface of this system. Three rovers are used to capture the RTCM corrections from the Internet in this case. The real-time 3D positioning solutions are also saved and further exploited to mitigate multipath.

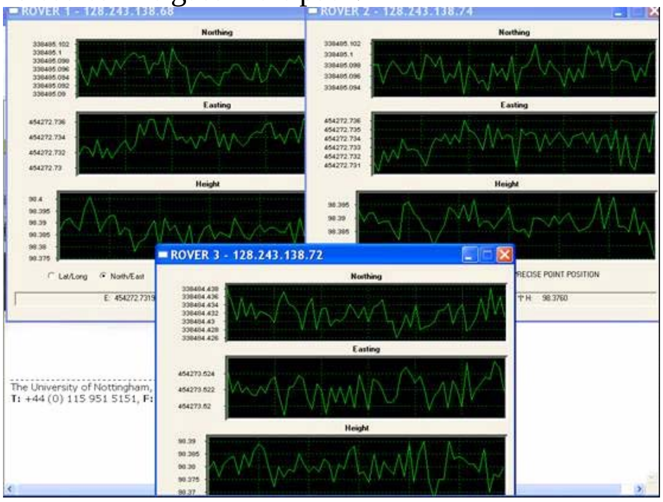


Fig. 8: Interface of Web RTK GPS

4. UPDATING AN FE MODEL WITH FIELD MEASUREMENTS FROM GPS AND ACCELEROMETERS

Various Digital Signal Processing (DSP) software packages are developed to extract 'real' deformation signals from the time series contaminated by different noises.

For example for investigating the efficiency of multipath mitigation, spectral analysis is applied to the desired signal, reference signal, filtered multipath and cleaned data set, which are first, second, third and fourth rows in Figure 9. The output of this spectral analysis is shown in Figure 10. It is apparent that after applying adaptive filtering to these time series, multipath has been isolated from the original signal, which is expressed as a very flat spectral output.

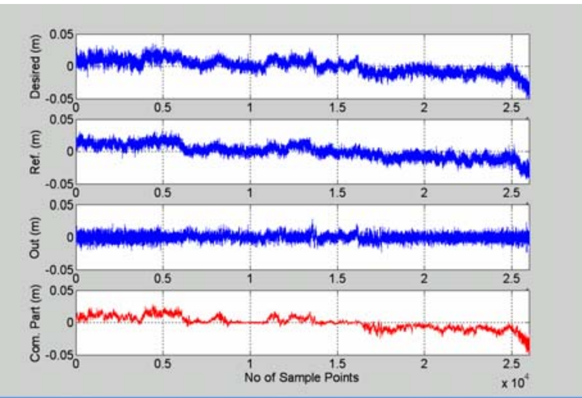


Fig. 9: Adaptive filtering for Multipath mitigation

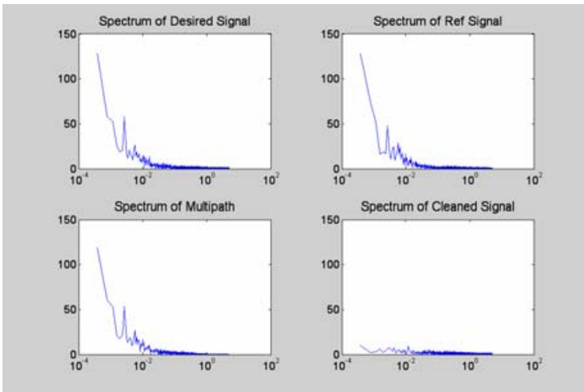


Fig. 10: Spectral Analysis of Time Series

Bandpass filtering technique has been employed to analyse the structural vibration frequencies and these dynamic characteristics can then be used to update a computational Finite Element models.

The Wilford Bridge over the River Trent in Nottingham is a footbridge about 4 km away from the University of Nottingham campus, held up by two sets of suspension cables restrained by two massive masonry anchorages (Figure 11). It has a span of 68 m long and 3.65 m wide and consists of a steel deck covered by a floor of wooden slats. It has been used as a test bed by the IESSG since 2000. Many trials have been conducted using GPS, accelerometers, pseudolites, total station and laser scanner in the last couple of years.

Fig. 11: Wilford Bridge over the River Trent

Figure 12 is the result after apply a bandpass filter of frequency band from 1 Hz to 4.5 Hz. Since the multipath frequencies are relatively slower than this filter frequency band, the signature of multipath with frequencies lower than 1 Hz is totally removed from the vibration time series. The first natural frequency identified is 1.733 Hz, and the second frequency is 2.117 Hz, which is the maximum of all valid frequencies detectable by 10 Hz GPS receivers. To prove the correctness of this result, the accelerometer measurements collected at the same time as GPS are analysed using a bandpass filter with frequency bank from 1 Hz to 39.8Hz and the results are shown in Figure 13. Similar results are obtained and these results can be further exploited to update a theoretical FE model.

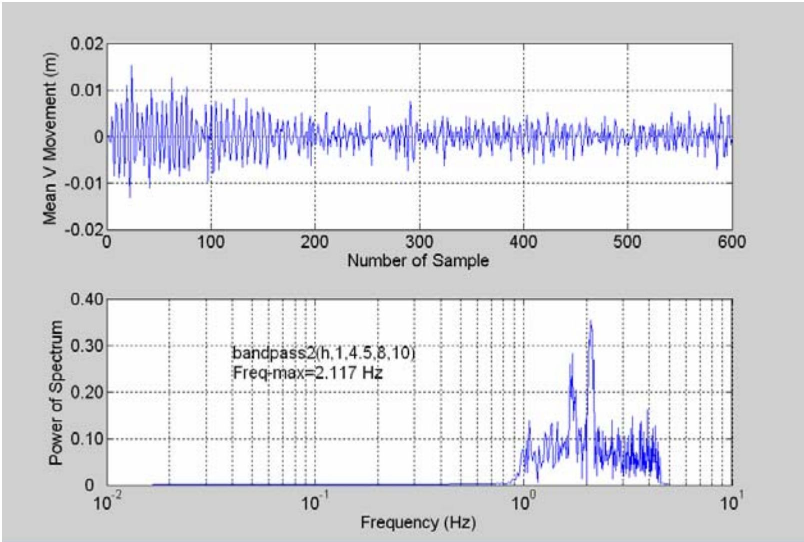


Fig. 12: Extraction of Bridge Dynamics from GPS Data

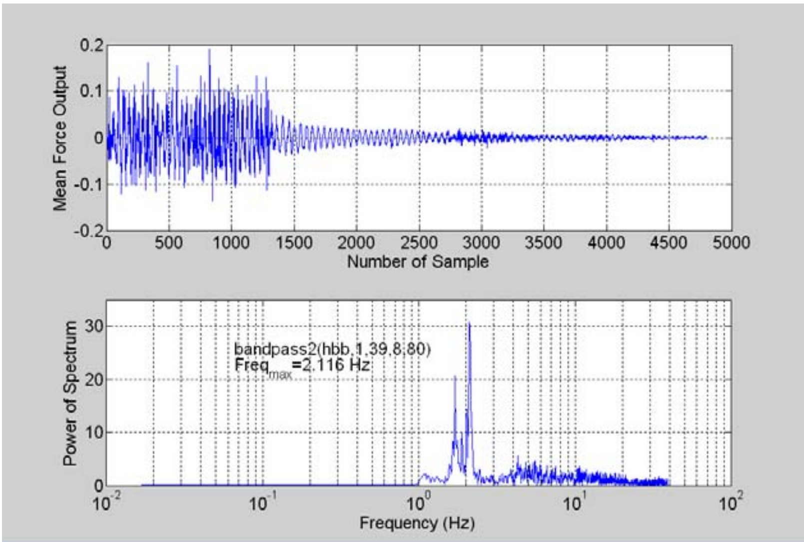
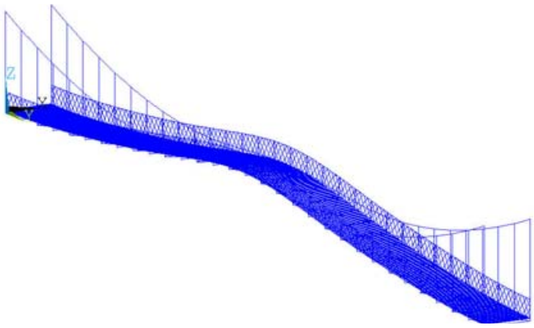


Fig. 13: Extraction of Bridge Dynamics from Accelerometer Data

An FE model was developed for the Wilford Suspension Footbridge by Cranfield University. Figure 14 shows the first mode shape with vibration frequency of 1.733 Hz, which is the same as that detected by both GPS and accelerometer sensors. However, the second vibration frequency cannot match with the computed one. This is the meaning to use field measurement to update a theoretical model until a more reliable FE model is achieved to diagnose potential structural failures.



Frequency	Full Bridge
1	1.733435454
2	2.5345565
3	4.492791804

Fig. 14: Computational Model and Natural Vibration Frequencies

5. CONCLUSIONS

The authors introduce a monitoring system designed for detecting the dynamics of civil structures. The hardware and software and their functionalities used by this system are presented in the paper. For investigating the actual structural dynamics and validating developed system, trials on the Wilford Bridge are analyzed and compared with a dedicated FE model for this bridge. It demonstrates well match between field testing data but little discrepancies with a computational model. To obtain a more accurate FE model, reliable updating technique need to be further developed. Also noises in the field testing data are required to be well addressed.

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