Second Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

SMAR 2013

Modal Identification of Bridges Using Vehicle-Crossing Tests

M. Akköse[1], H.C. Gomez[2], and M.Q. Feng[3]

[1] Department of Civil Engineering, Karadeniz Technical University, 61080, Trabzon, Turkey
[2] MMI Engineering, 1111 Broadway 6th floor, Oakland, CA, 94607, USA
[3] Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, USA

ABSTRACT: In this study, a four-span, 224 m long, post-tensioned concrete box girder bridge supported on single column piers was subject to a series of controlled vehicle tests. Bridge acceleration response datasets were used to study the effect of truck speed and a sudden stop, on the modal identification of the bridge structure. Natural frequencies and mode shapes of the bridge were determined using the frequency domain decomposition technique for all datasets. The passing of the truck rendered difficult to identify the first bridge frequency. Conversely, the vehicle tests improved the identification of higher vibration modes. This is because the truck preferentially excites the bridge vertical response, which is associated with higher modes of vibrations, especially when a sudden stop of the vehicle occurs. Thus, carefully conducted vehicle-crossing tests provide detailed information about the bridge structure dynamics in the vertical direction. However, to identify lower modes, no vehicle on the bridge is preferred.

1 INTRODUCTION

Bridges in service are subject to a combination of various external loads, among which traffic loads are constantly imposed on the bridge structure. The dynamic response of a highway bridge is a complex phenomenon and it is less understood for curved bridges. During the past decades, various studies have attempted to study the dynamic response of curved bridges under moving truck loads. For instance, Billing (1984) presented the outcomes from a series of dynamic tests of 27 bridges in Ontario, Canada. The datasets were obtained from more than 100 truck crossings for each bridge. It was pointed out bridge frequencies identified under a single truck load are typically larger than design estimations. A similar study was conducted in Switzerland (Cantieni, 1983). Later, Kim, et al. (1996) presented the results from truck load tests conducted on seven bridges in the city of Detroit, Michigan. It was concluded truck loads on bridges are strongly site specific, even within the same geographic area. Senthilvasan, et al. (2002) conducted a truck load test on the Turbot Street Bridge, a curved bridge in Australia, using a five-axle truck. It was found the deflections and strains (due to bending moments), are not amplified by the same amount. An important observation they made is the dynamic response not always increases with the speed of the vehicle, but it depends on the ratio of the vibration period to the traverse time. Brady, et al. (2006) discussed the results from a truck load test on a simply supported bridge in Slovenia. More recently, Huang (2008) studied the deflection of a curved bridge under moving truck loads.

This paper aims to complement the body of literature for the study of bridge response under traffic loads. The paper presents the findings of a series of vehicle-crossing tests conducted on the Fairview Road On-Ramp (FRO) bridge, located in Southern California, USA. The effect of truck speed and a sudden stop on the modal identification of the bridge structure is investigated.

2 DESCRIPTION OF THE FAIRVIEW ROAD ON-RAMP (FRO) BRIDGE

The Fairview Road On-Ramp Overcrossing (FRO) Bridge (Figure 1) is located in the city of Costa Mesa on the Interstate 405, one of the busiest routes in Southern California. The FRO Bridge is a four-span and one-lane continuous concrete box girder bridge. In plan, the bridge is slightly curved with double curvature. It has a radius of curvature of 600m (1,968.5ft). The columns have circular cross-sections with a diameter of 2.14m (7ft). The bents are founded on square RC pad footings and the abutments are supported on rectangular footings. Summary plan and section details are shown in Figure 2.

Figure 1. A view of the Fairview Road On-Ramp Overcrossing (FRO) Bridge

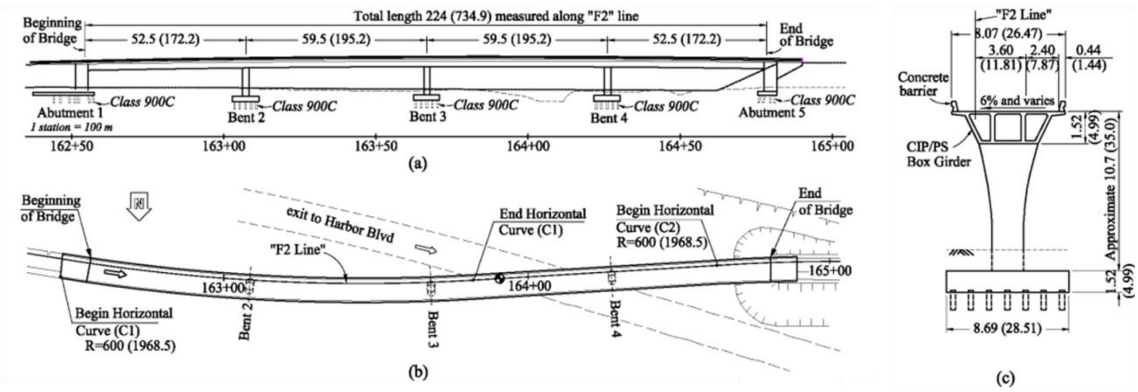


Figure 2. Structural details of the Fairview Road On-Ramp Overcrossing (FRO) Bridge: (a) elevation; (b) plan view; (c) bent typical section

2.1 FRO Bridge Monitoring System

The FRO Bridge is instrumented with a total of 21 accelerometers (Figure 3). The accelerometers are either uni-, bi- or tri-axial force-balance servo-type accelerometers. An easy access to the data recorder is possible since it is installed on the ground below the deck at the beginning of the bridge. More details on the instrumentation can be found in Gomez (2011).

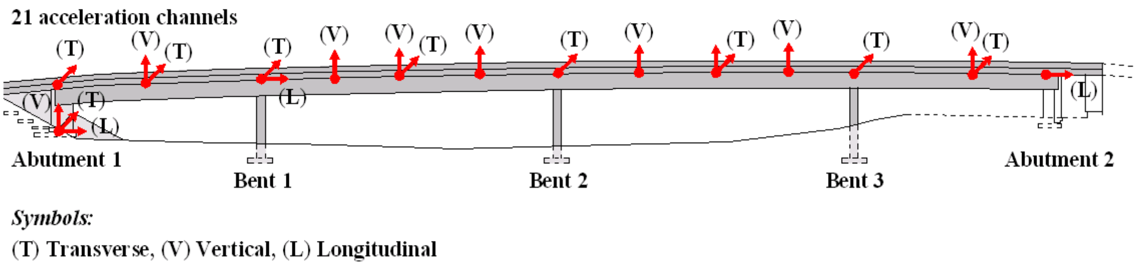


Figure 3. Sensor layout at FRO Bridge

2.2 *Description of Vehicle Crossing Tests on FRO Bridge*

A water truck with capacity of 2,000 gal, was used in the vehicle crossing tests (Figure 4). At full capacity the truck has a gross vehicle weight of 138 kN. This weight was distributed as 49 kN at the front axle and 89 kN at the rear axle. The distance from the front axle to the rear axle is 3.96 m. Although this truck is not one of the heaviest vehicles that could potentially pass on the FRO Bridge, it has a considerable mass to induce an adequate bridge response.

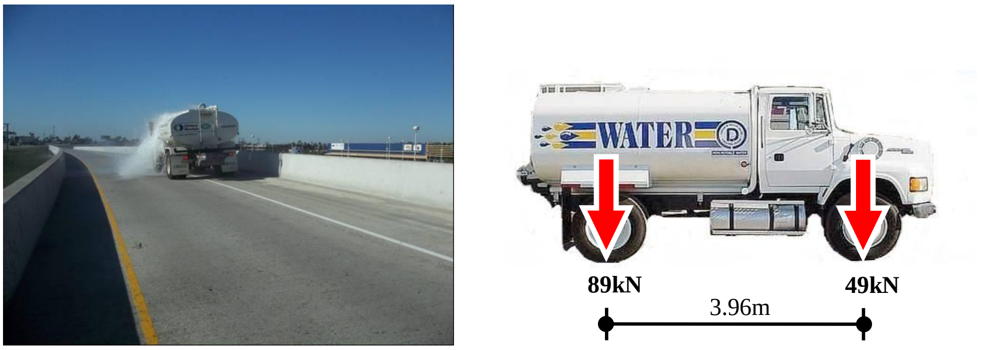


Figure 4. Truck weight and dimensions

During the vehicle-crossing tests (Figure 5), after the bridge is closed to public traffic, the truck entered the beginning of the bridge (Abutment 1) with a constant speed of 8 km/h (5 mph) and made a complete stop at the middle of the second span. After one minute, the truck started moving again at a speed of approximately 8 km/h until it arrived at the middle of the third span where it made a second complete stop. After one minute, the truck resumed the trip and left the bridge at a speed of approximately 8 km/h. Afterwards, the truck made a U-turn and entered from the end of the bridge (Abutment 5) and made two stops, one minute each, at the same locations as going forward (see Figure 5). Then, the test vehicle exits the bridge at speed of 8 km/h and completes its first round trip.

Another test consisted in driving the test vehicle at a speed of approximately 72-81 km/h (45-50 mph). When the vehicle arrived at the middle of the second span, the breaks were suddenly applied to generate an impact load on the bridge. Then, the truck proceeded at 8 km/h and left the bridge. Next, the truck made a U-turn for the final trip. In the last trip, the truck entered at the end of bridge and accelerated to reach a speed of approximately 48-56 km/h (30-35 mph). Another sudden break was applied at the middle of the third span. The test vehicle resumed the trip at 8 km/h and left the bridge.

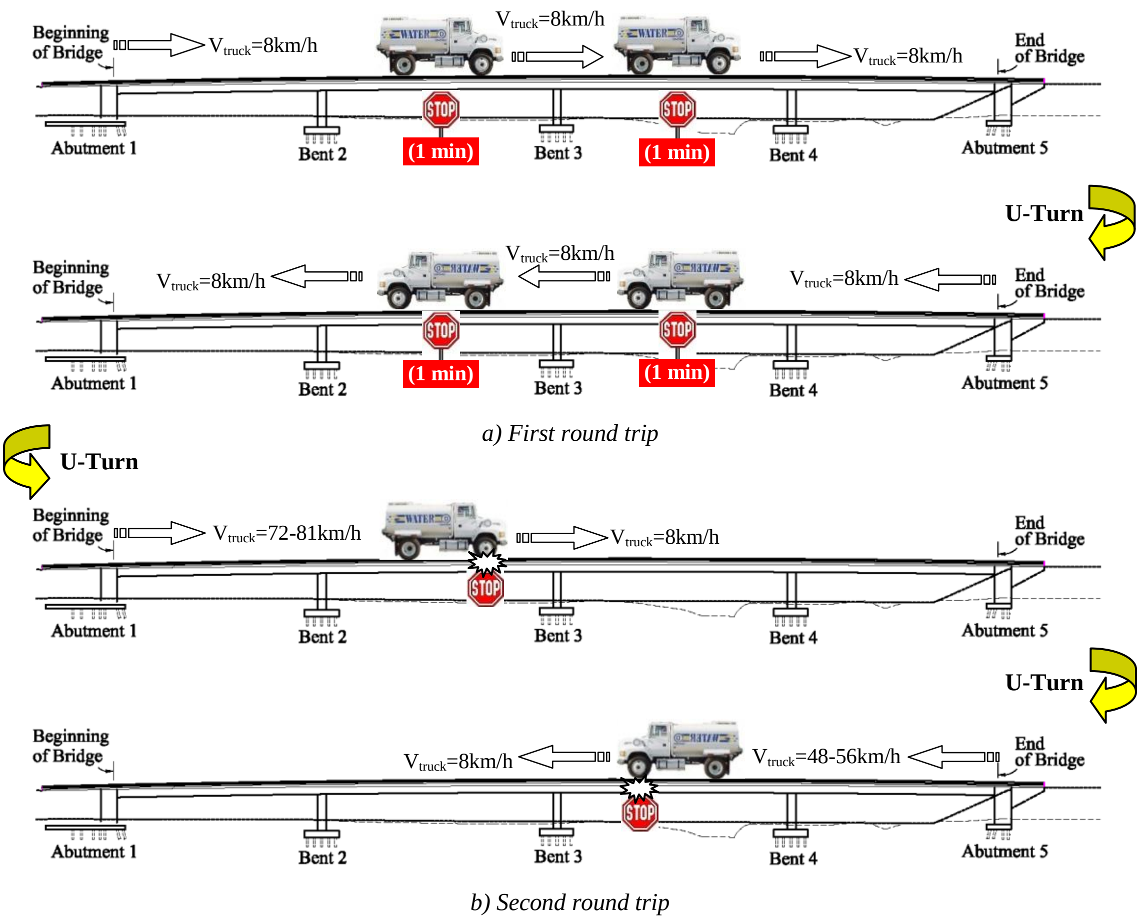


Figure 5. Description of vehicle crossing tests (total test duration was approximately 18minutes)

3 RESULTS AND DISCUSSION

Figure 6 shows the acceleration time-history response at sensor locations during the vehicle-crossing tests. It was found 7 accelerometers (#'s 9, 14, 17-21) were malfunctioning at the time of the tests. Since the accelerometers were installed inside the box girder, it was not possible to access for a detailed inspection of the sensors and the reasons for the malfunctioning were unknown. Therefore, the remaining 14 accelerometers were used to study the bridge response. Despite the malfunctioning sensors, it was still possible to attain an accurate identification of the modal parameters of the bridge. The remaining sensors provided the adequate information in order to identify the modes of vibration with high confidence.

In Figure 6, the bridge response acceleration time-histories were subdivided into nine groups, identified by colors, according to the level of acceleration. It can be observed the magnitude of the vertical response of the bridge was drastically increased (about 200%) for the tests where a sudden stop of the test vehicle was applied. Afterwards, each group of accelerations was analyzed to identify the bridge modal parameters.

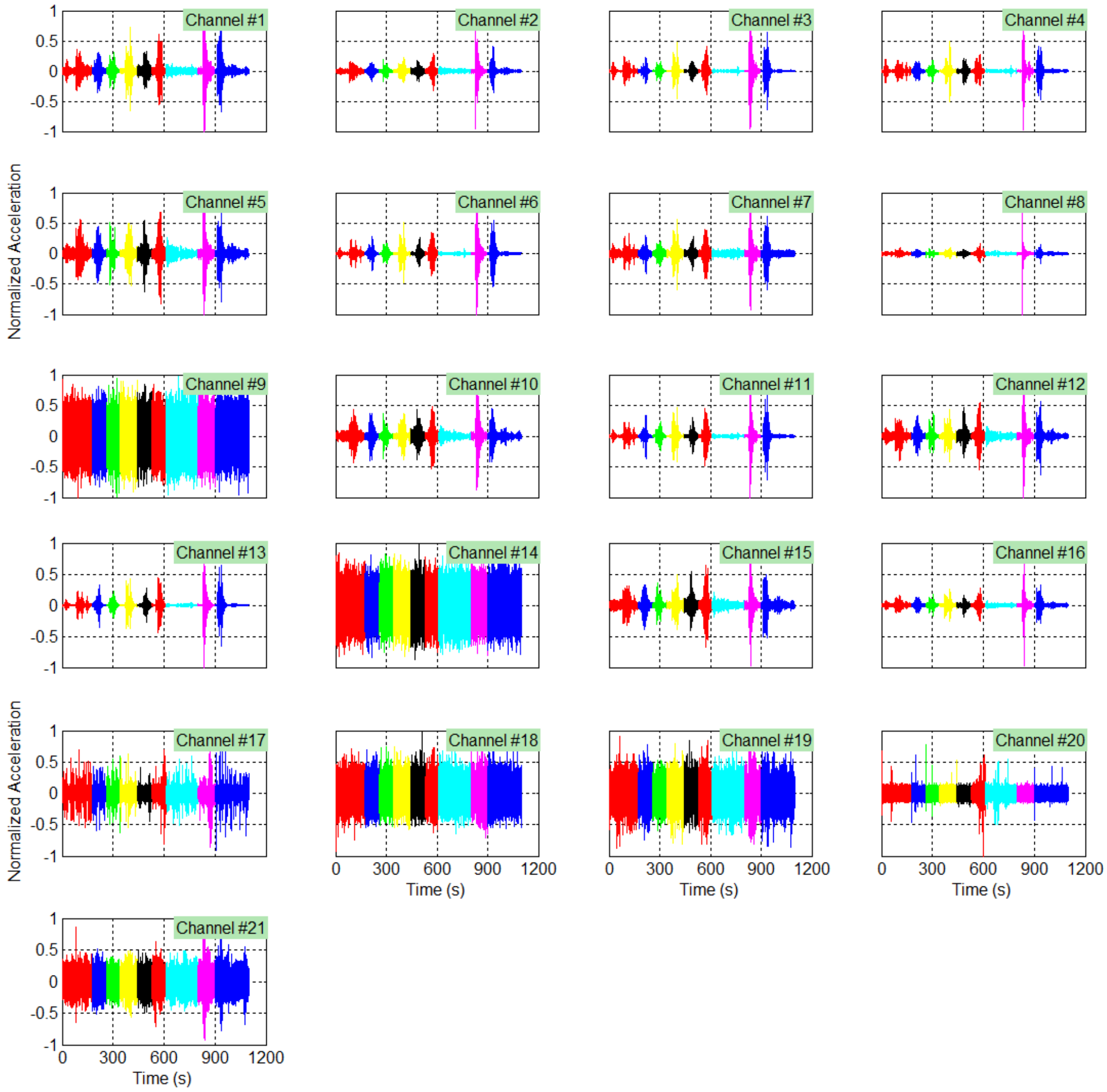
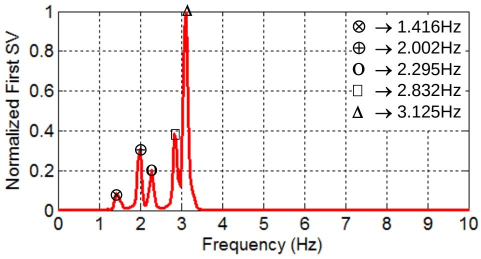


Figure 6. Normalized acceleration time-history response at sensors during the vehicle tests

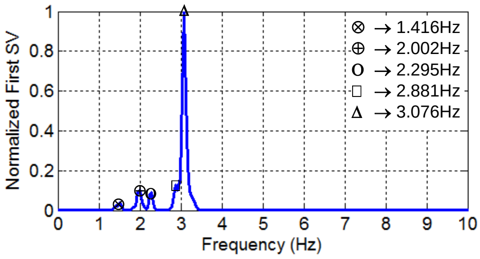
3.1 Bridge Modal Identification

The frequency domain decomposition (FDD) was applied to the acceleration datasets to identify bridge modal parameters. The FDD technique was introduced by Brincker et al. (2000) as an alternative to other frequency domain system identification techniques. The FDD technique has been widely used for system identification of bridges in recent years (Kim et al., 2003; Feng et al., 2004; Chen et al., 2006; Gomez et al., 2011; Gomez, 2011).

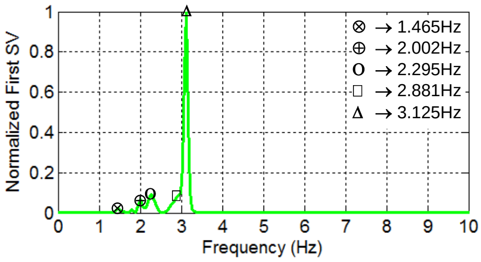
The power spectral density functions used by the FDD were estimated using Hanning windows with 60% overlap. In order to reduce background noise, a butter-worth infinite impulse response filter of order 8 was applied to the data with a pass-band defined by a lower frequency of 1 Hz and a higher frequency of 10 Hz. The FDD results are shown in Figure 7. The identification of the natural frequencies is presented for the nine groups of bridge responses separately. The natural frequencies are identified at approximately 1.465, 2.002, 2.295, 2.881, and 3.076 Hz. It can be seen that natural frequencies are consistent for each set of data.



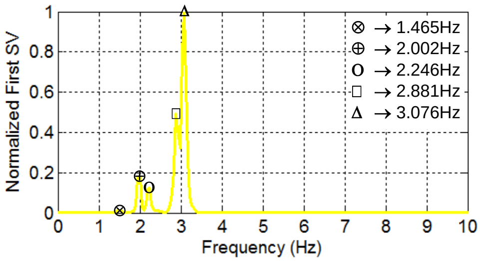
For 1st group data (first red color section in Fig. 6)



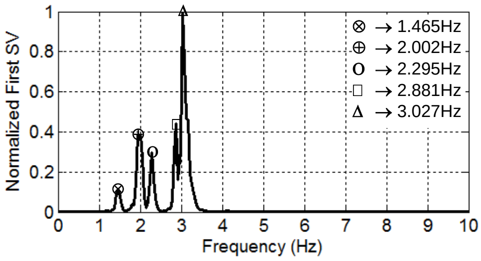
For 2nd group data (first blue color section in Fig. 6)



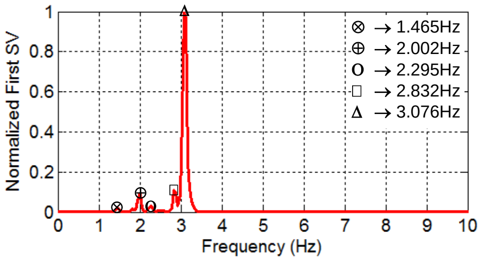
For 3rd group data (green color section in Fig. 6)



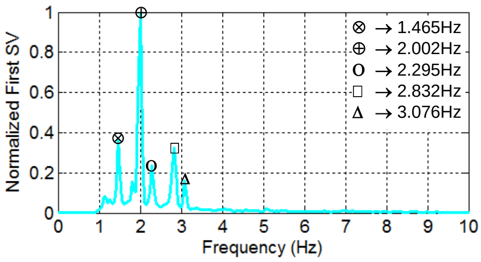
For 4th group data (yellow color section in Fig. 6)



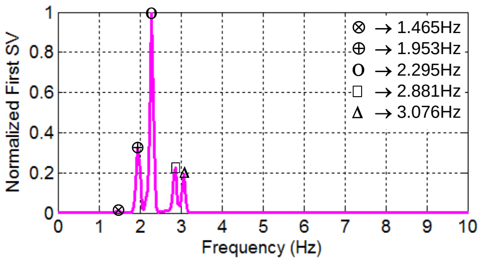
For 5th group data (black color section in Fig. 6)



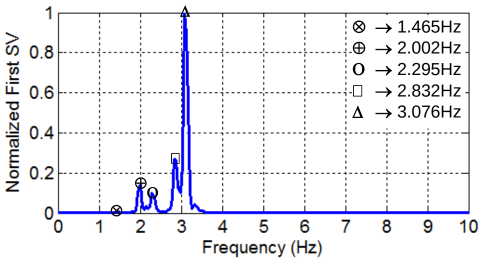
For 6th group data (second red color section in Fig 6)



For 7th group data (cyan color section in Fig. 6)



For 8th group data (magenta color section in Fig. 6)



For 9th group data (second blue color section in Fig. 6)

Figure 7. Normalized first SV obtained from FDD applied to data recorded during vehicle crossing tests

In addition to bridge natural frequencies, partial mode shapes (as the bridge is instrumented at discrete locations only) are plotted for the first three modes (see Figure 8). Although the first three modes exhibit some combination of vertical and horizontal motions, it is clear that the first mode (f_1 = 1.465 Hz) is a lateral rocking mode about the longitudinal axis of the bridge with the three bents in phase. This mode is clearly identified from the time history segment from 610 s to 800 s (cyan color). During this time segment no vehicle was on the bridge. It is noted this mode is not always identified (or it has a low peak amplitude in the frequency plots) because in most of the data sets the data contain the response of the bridge due to the truck load, which predominantly excites the vertical modes. This is clearly observed in the next two modes of vibration (f_2 = 2.002 Hz and f_3 = 2.295 Hz), which are a combination of vertical bending and torsion of the bridge deck.

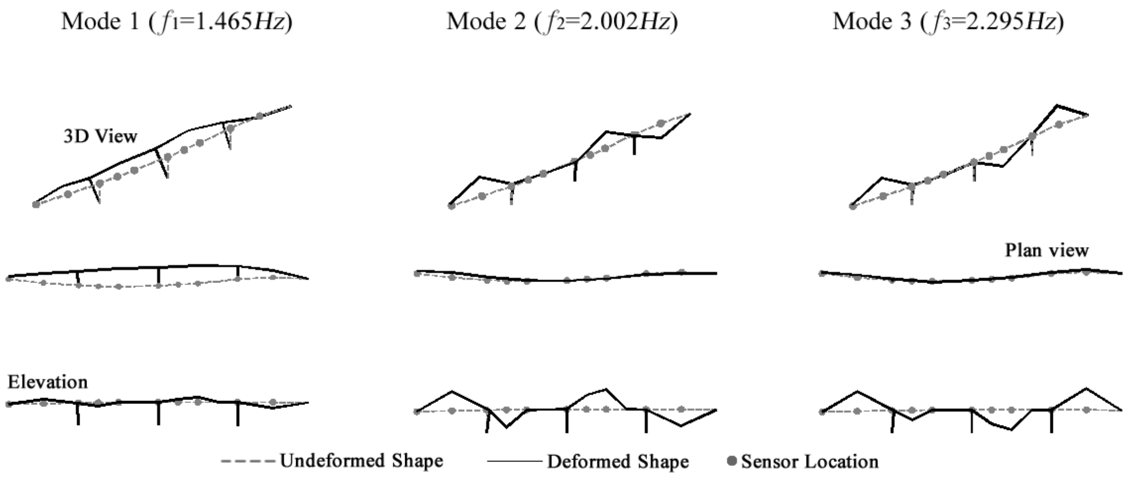


Figure 8. Identified partial mode shapes of the FRO bridge

From the results presented above, it can be sensibly argued the passing of the truck rendered difficult to identify the first bridge frequency. Conversely, the vehicle tests improved the identification of higher vibration modes. This is because the truck tends to excite the bridge vertical response, which is associated with higher modes of vibration, especially when a sudden stop of the vehicle occurs (magenta and blue last two segments, from 800 s to 1098 s in Fig. 6).

Another observation from the identification results is the natural frequencies are practically the same for different speeds of the truck as different segments in the time histories were recorded for different speeds as described earlier. Therefore, the modes of vibration were not influenced by truck speeds, which ranged from 8 to 80 km/h. Further studies are recommended to study the effect of truck speed on the modal identification by using higher vehicle velocities.

4 CONCLUSIONS

In this study, the findings of a series of vehicle crossing test on a concrete bridge are presented. Acceleration response datasets were recorded during the tests. The natural frequencies of the bridge were determined using the frequency domain decomposition (FDD) technique for all datasets. The identification results show that the first frequency is associated with lateral mobilization of the deck and bending of the columns whereas higher modes are associated with the vertical and torsional mobilization of the deck.

It was observed that the passing of the truck renders difficult to identify the first bridge frequency. This is because the first bridge frequency is associated with bending of the columns and lateral mobilization of the deck. Conversely, the vehicle tests improved the identification of higher vibration modes because these are associated with vertical bridge response. This is more apparent for the crossing vehicle tests where a sudden stop was applied inducing a bigger vertical force on the bridge. In this case, the magnitude of the vertical response of the bridge is drastically increased (about 200%).

Since no change in the identification results was observed due to an increase in truck speed, it is concluded the amplification of the magnitude of the bridge response due to an increased vertical load (heavier vehicles or a sudden stop), exceeds any velocity effect.

It is the authors' opinion that carefully conducted vehicle-crossing tests provide detailed information about the bridge structure dynamics in the vertical direction. However, to identify lower modes, no vehicle on the bridge is preferred. Moreover, much higher truck velocities than those attained in this study (a maximum of approximately 80 km/h) are recommended in order to study any effects on bridge response.

5 ACKNOWLEDGMENTS

This research was supported by the Scientific and Technical Research Council of Turkey (TUBITAK) under the *2219-Foreign Postdoctoral Research Scholarship Program*. The authors also wish to thank the support of the California Department of Transportation.

6 REFERENCES

Billing, JR. 1984. Dynamic loading and testing of bridges in Ontario. *Canadian Journal of Civil Engineering*, 11(4), 833-843.

Brady, SP, O'Brien, EJ and ZnidariC, A. 2006. Effect of vehicle velocity on the dynamic amplification of a vehicle crossing a simply supported bridge. *J. Bridge Eng.*, 11(2), 241-249.

Brincker, R, Zhang, L and Andersen, P. 2000. Modal identification from ambient response using frequency domain decomposition. *Proc., 18th Int. Modal Analysis Conf., Society for Experimental Mechanics*, San Antonio, TX, U.S.A, 625-630.

Cantieni, R. 1983. Dynamic load tests on highway bridges in Switzerland. Rep. No. 211, *Eidgenossische Material-prufungs-und Versuchsantalt (EMPA)*, Dubendorf, Switzerland.

Chen, Y, Feng, MQ and Tan, CA. 2006. Modeling of traffic excitation for system identification of bridge structures, *Comput. Aided Civ. Infrastruct. Eng.*, 21(1), 57-66.

Feng, MQ, Kim, DK, Yi, J-H and Chen, Y. 2004. Baseline models for bridge performance monitoring, *Journal of Engineering Mechanics*, 130(5), 562-569.

Gomez, HC, Fanning, PJ, Feng, MQ and Lee, S. 2011. Testing and long-term monitoring of a curved concrete box girder bridge, *Engineering Structures*, 33(10), 2861-2869.

Gomez, HC. 2011. System identification of highway bridges using long-term vibration monitoring data, *Ph.D. Dissertation*, University of California, Irvine, Irvine, USA.

Huang, D. 2008. Dynamic loading of curved steel box girder bridges due to moving vehicles. *Structural Engineering International*, 18(4), 365-372.

Kim, CY, Jung, DS, Kim, NS, Kwon, DS and Feng, MQ. 2003. Effect of vehicle weight on natural frequencies of bridges measured from traffic-induced vibration, *Earthquake Engineering and Engineering Vibration*, 2(1), 109-115.

Kim, S, Sokolik, A. and Nowak, A. 1996. Measurement of truck load on bridges in Detroit, Michigan, area. Transportation Research Record: *Journal of the Transportation Research Board*, 1541(-1), 58-63.

Senthilvasan, J, Thambiratnam, DP and Brameld, GH. 2002. Dynamic response of a curved bridge under moving truck load. *Eng. Struct.*, 24(10), 1283-1293.