Structural Engineering and Mechanics, Vol. 21, No. 3 (2005) 369-374
DOI: http://dx.doi.org/10.12989/sem.2005.21.3.369

Moving force identification from bridge dynamic responses

Ling Yu†

Blasting and Vibration Department, Changjiang River Scientific Research Institute, Wuhan, Hubei, 430010, P. R. China
Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, P. R. China

Tommy H.T. Chan‡

Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, P. R. China

(Received December 30, 2004, Accepted July 26 2005)

Abstract. A big progress has been made for moving force identification from bridge dynamic responses in recent years. Current knowledge and the potentials on moving force identification methods are reviewed in this paper under main headings below: background of moving force identification, experimental verification in laboratory and its application in field.

Key words: moving force identification; vehicle-bridge interaction; dynamic response; review.

1. Introduction

In recent years, some great effort has been made for moving force identification from bridge dynamic responses. A series of identification methods have been put forward, which can compute dynamic wheel loads with an acceptable accuracy, further these methods have been enhanced and merged into a moving force identification system (MFIS) (Yu 2002). The MFIS has been proved to be a successful identification system and the identification methods involved in the MFIS could be accepted as practical methods with higher identification accuracy to some extent (Yu 2002, Yu and Chan 2003, 2004). However, there still exist some limitations if these methods could actually be implemented and operated in practice (Chan *et al.* 2000). This paper tries to provide a review on current knowledge and the potentials of moving force identification methods, as well as finding a right way to steer the direction of further work.

† Professor, Senior Engineer
‡ Associate Professor, Corresponding author, E-mail: cetommy@polyu.edu.hk

2. Background of moving force identification

In practice, a bridge-vehicle system is a very complicated system. The interaction between the bridge and the vehicle is a complex phenomenon governed by a large number of different parameters. The use of simplified models is more effective to establish a clear connection between the governing parameters and the bridge response than a complex model. Normally, the bridge decks are modelled as beams or plates, the vehicles as a moving force, a moving mass (Lin and Trethewey 1990) or a moving oscillator (Pesterev and Bergman 1997, Yang *et al.* 2000). Usually, a quarter-truck model, a half-truck model, and a whole truck model (Todd *et al.* 1989), or 3D, 2D and single sprung mass (1D) system (Chatterjee *et al.* 1994) are adopted.

A series of identification methods are proposed and emerged into the MFIS system, which include IMI developed by O'Connor and Chan (1988), IMII by Chan *et al.* (1999), TDM by Law *et al.* (1997) and FTDM by Law *et al.* (1999) respectively. Most of the identification methods are eventually converted into a linear algebraic equation set, such as $Ax = b$. In principle, the *pseudo-inverse* (*PI*) *solution* is often adopted, but the *SVD solution* is recommended if the coefficient matrix A is rank deficient, or close to rank deficient.

3. Experimental verification in laboratory

A series of experiments have been carried out in laboratory to evaluate the moving force identification methods developed. After considering the practical parameters of real bridge-vehicle systems, a two-axle vehicle model and a multi-axle vehicle model have been developed based on the AASHTO (1996) loading codes using a simply supported beam, a continuous supported beam or a plate bridge models (Yu 2002).

3.1 Evaluation of identification methods

Table 1 gives a comparison on the relative percentage error (RPE) between the measured and rebuilt responses when four identification methods are adopted. It shows that all the RPE data are lower than 10% except at the first station ($L/8$) and 7th station ($7L/8$) for IMII method where L is the span length. This illustrates that all the four methods involved in the moving force identification

Table 1 Comparison of identified results by various methods

Method	RPE (%)						
	$L/8$	$2L/8$	$3L/8$	$4L/8$	$5L/8$	$6L/8$	$7L/8$
IMI	9.37	9.51	9.73	9.62	9.55	9.14	8.36
IMII	12.2	6.00	6.98	4.40	6.05	5.75	13.2
TDM	5.42	3.08	1.80	2.58	1.95	3.44	4.83
	<u>5.43</u>	<u>3.09</u>	<u>1.80</u>	<u>2.56</u>	<u>1.94</u>	<u>3.43</u>	<u>4.83</u>
FTDM	5.74	2.80	2.15	2.08	2.14	2.41	4.74
	<u>4.53</u>	<u>2.52</u>	<u>1.87</u>	<u>1.95</u>	<u>1.82</u>	<u>2.24</u>	<u>3.17</u>

Notes: The underlined values are from SVD solution, other from PI solution, same meanings below.

system are correct and effective. Further, both TDM and FTDM results are clearly better than the IMI and IMII results, and the SVD results are better than ones from the PI solution, especially for FTDM, which shows SVD technique can improve the identification accuracy.

3.2 Effects of parameters on identification accuracy

3.2.1 Bridge-vehicle parameters

Mode number of a bridge should be enough in the identification calculation. The IMI is independent of the mode number and not reported here. The IMII needs at least the first three modes or more to correctly identify the two moving forces. The minimal necessary mode number required is 4 for both TDM and FTDM (Chan *et al.* 2000). Generally, the mode number should be more than or at least equal to one more than axle numbers of the vehicle which axle load histories are to be identified.

Vehicle speed plays an important role for the dynamic behavior of a bridge subjected to dynamic loads across the bridge. The RPE values first decrease and then increase with increase of vehicle speed for IMI. But both IMII and TDM are almost independent of vehicle speeds. A faster speed is of benefit to both TDM and FTDM, but FTDM fails in the lower speed cases if adopting the PI solution (Chan *et al.* 2001b). However, adopting the SVD solution can make the FTDM from original ineffective to effective (Yu and Chan 2003).

For the axle spacing to span ratio (ASSR), results of illustrative studies show errors larger than 10% are obtained for IMI at and below ASSR of 0.12. For IMII, the errors also increase with a smaller ASSR. However, it is shown that acceptable results can be obtained for values as small as 0.05. For TDM and FTDM, the results show that there is no adverse effect by reducing the ASSR (Chan *et al.* 2001b).

Heavy vehicles mainly include the articulated and the nonarticulated frames. The results show that the identified multi-axle vehicle loads are reasonable and acceptable for both the articulated and nonarticulated vehicles. The moving force identification system can correctly identify the multi-axle vehicle loads even if the middle axle of the nonarticulated vehicles is hanging in the air (Yu and Chan 2004).

Three different types of suspension systems, i.e., rigid connection, sprung connection, and pre-compressed sprung connection between vehicle frame and axle respectively, are incorporated in the vehicle models. Results show that the suspension systems make an obvious impact on both dynamic characteristics of vehicles and identification accuracy. It is evidently beneficial to the improvement of identification accuracy when the nonarticulated vehicles are suspended and equipped with more suspension systems (Yu and Chan 2004).

3.2.2 Measurement parameters

The effects of sampling frequency using IMI or IMII are not too obvious within 333 Hz, but beyond that, the effects become more significant, even make both the methods of IMI and IMII fail at 1000 Hz. The TDM is suitable for the higher sampling frequency. The effect of sampling frequency on FTDM increases with the sampling frequency, and FTDM fails if the PI solution is used and the sampling frequency equal to or higher than 333 Hz (Chan *et al.* 2001b). However, the use of the SVD not only makes the identification method effective but also results in good identified results with higher accuracy, whereas direct calculation of the PI solution causes the identification method to fail. Moreover, both TDM and FTDM have higher identification accuracy than both IMI and IMII.

The effects of measurement stations on both TDM and FTDM are directly reported here. The TDM requires at least three measurement stations to obtain two correct moving forces. The FTDM should have at least one more, i.e., 4, but, it is sensitive to the locations of measuring station, which should be selected carefully when the PI solution is adopted (Chan *et al.* 2000). Once the SVD is used for FTDM, the identified results are acceptable and give a very high accuracy, for example, the RPE values reach to less than 2.53% at the middle five stations. It is predicted that the identification method is independent of the measurement stations if the SVD method is adopted (Yu and Chan 2003). In general, the identification accuracy is better if more measuring stations are adopted for both TDM and FTDM, but it will take longer computational time.

Measurement errors are usual found in experiments. Possibly, speeds are the most difficult to be correctly measured as the speeds of vehicles vary significantly with traffic conditions and individual drivers. Moreover, speed errors affect indirectly the calculation of axle spacing. If more than one kind of measurement error occurs, a study on the effect of combination measurement errors shows that both TDM and FTDM are the best and worst methods respectively (Chan *et al.* 2001a, b).

3.2.3 Algorithm parameters

The executing CPU time is important for the practical application of each identification method in field. Both IMI and IMII take only a few minutes in the force identification calculation for any study cases set using PII 266 M Hz CPU, 64 RAM PC. They are therefore suitable for real time analysis from this point of view. However, both TDM and FTDM consist of three periods, they take much longer time than IMI or IMII although TDM takes a shorter time to perform identification than FTDM (Chan *et al.* 2000). Although the SVD technique can obviously improve the identification accuracy, especially for FTDM, it increases executive CPU time by 60% when compared to that for the PI solution (Yu and Chan 2003). This is too expensive and not beneficial to the real-time analysis in situ. The situation could be improved when computers with faster CPU are introduced.

Tolerance parameter ε is not only a given tolerance parameter but also a criterion related to rejecting or accepting of zero singular values. This criterion may depend on the accuracy of the expected results and, in practice, may be difficult to establish. Results show that a smaller tolerance parameter ε is beneficial to moving force identification, however, if ε is too small the computation cost (CPU) is higher because it needs more iteration times for convergence. To take account of all the above aspects at the same time, the value ε set to be 1.0e-6 for study cases is appropriate (Yu and Chan 2003).

Bound parameter λ is another important algorithm parameter, which was introduced to provide bounds to the solution in the Tikhonov regularization (Tikhonov and Arsenin 1977). Although the regularization only provides bound to the ill-conditioned solution without any smoothing effect on the measurement noise, and the results obtained are greatly improved over those without regularization, the difficulty of applying the Tikhonov regularization lies in the method to find the optimal regularization parameter λ. Moreover, the TDM is found better than the FTDM in solving for the ill-posed problem. Both simulation and laboratory test results indicate that the total weight of a vehicle can be estimated indirectly using moving force identification methods with some accuracy at least with FTDM (Law *et al.* 2001).

Table 2 Summary of equivalent static forces identified with considering prestressing

Test case	Axle 1		Axle 2		Total	
	Equivalent static force (kN)	Difference (%)	Equivalent static force (kN)	Difference (%)	Gross weight (kN)	Difference (%)
2	65.22	1.97	91.22	4.95	156.44	3.69
3	62.48	−2.31	89.69	3.19	152.17	0.85

4. Application in field

Based on IMI method, the effects of prestressing has been taken into account before the field tests (Chan and Yung 2000), which were carried out to verify the proposed method on an existing prestressed concrete bridge of Ma Tau Wai Flyover, Hunghom, Kowloon, Hong Kong, P. R. China (Chan *et al.* 2000). A two-axle heavy vehicle of about 150 kN was hired for the calibration test of the field measurements. The dynamic bending moments of the test bridge deck induced by either a hired control vehicle or in-service 77 vehicles were acquired at seven locations respectively. Dynamic axle forces were identified by means of TDM. The equivalent static axle loads of the two cases shows that the gross weights identified are acceptable with percentage differences of 3.69% and 0.85%, respectively, as listed in Table 2. For the cases of 77 in-service vehicles, the accuracy of identified dynamic axle loads was studied using only the RPE data between the measured and rebuilt responses because no information was available for the axle loads of the in-service vehicles. All the above identified results show that the axle forces can be identified with acceptable accuracy for both the hired control vehicle and in-service vehicles. Therefore the proposed method is valid for identifying dynamic axle forces. Gross weights can be obtained by summing up the equivalent axle load of each axle.

5. Conclusions

This paper provides a review on recent advances on moving force identification from bridge dynamic responses. The background of four identification methods is introduced. Numerical simulations, illustrative examples and comparative studies on the effects of parameters have been carried out and critically investigated. Bridge-vehicle system models have been fabricated in the laboratory to validate the correctness and robustness of the proposed methods. Field tests have also conducted to assess the applicability of the methods involved in the MFIS in practice. The results show that all four identification methods involved in the MFIS can effectively identify moving axle loads on bridges and can be accepted as practical methods with higher identification accuracy. However, there are still many challenges and obstacles to be overcome before these methods could be implemented in practice, further studies on the moving force identification are necessary and recommended.

Acknowledgements

The project is supported by National Natural Science Foundation of China (50378009), The Hong Kong Polytechnic University Postdoctoral Fellowship Research Grants (G-YX25) and the Research Grants of Changjiang River Scientific Research Institute.

References

AASHTO, (1996), *Standard Specification for Highway Bridges*, American Association of State Highway and Transportation, Washington, D.C. USA.

Chan, T.H.T. and Yung, T.H. (2000), "A theoretical study of force identification using prestressed concrete bridge", *Eng. Struct.,* **23**, 1529-1537.

Chan, T.H.T., Law, S.S. and Yung, T.H. (2000), "Moving force identification using an existing prestressed concrete bridge", *Eng. Struct.*, **22**, 1261-1270.

Chan, T.H.T., Yu, L. and Law, S.S. (2000), "Comparative studies on moving force identification from bridge strains in laboratory", *J. Sound Vib.,* **235**(1), 87-104.

Chan, T.H.T., Law, S.S., Yung, T.H. and Yuan, X.R. (1999), "An interpretive method for moving force identification", *J. Sound Vib.*, **219**(3), 503-524.

Chan, T.H.T., Yu, L., Law, S.S. and Yung, T.H. (2001a), "Moving force identification studies I: Theory", *J. Sound Vib.*, **247**(1), 59-76.

Chan T.H.T., Yu, L., Law, S.S. and Yung, T.H. (2001b), "Moving force identification studies II: Comparative studies", *J. Sound Vib.*, **247**(1), 77-95.

Chatterjee, P.K., Datta, T.K. and Surana, C.S. (1994), "Vibration of suspension bridges under vehicular movement", *J. Struct. Eng.*, ASCE, **120**(3), 681-703.

Law, S.S., Chan, T.H.T. and Zeng, Q.H. (1997), "Moving force identification: A time domain method", *J. Sound Vib.*, **201**(1), 1-22.

Law, S.S., Chan, T.H.T. and Zeng, Q.H. (1999), "Moving force identification: A frequency and time domains analysis", *J. of Dynamic System, Measurement and Control*, ASME, **12**(3), 394-401.

Law, S.S., Chan, T.H.T., Zhu, X.Q. and Zeng, Q.H. (2001), "Regularization in moving force identification", *J. Eng. Mech.*, ASCE, **127**(2), 136-148.

Lin, Y.H. and Trethewey, M.W. (1990), "Finite element analysis of elastic beams subjected to moving dynamic loads", *J. Sound Vib.*, **136**(2), 323-342.

O'Connor, C. and Chan, T.H.T. (1988), "Dynamic loads from bridge strains", *J. Struct. Eng.*, ASCE, **114**, 1703-1723.

Pesterev, A.V. and Bergman, L.A. (1997), "Response of elastic continuous carrying moving linear oscillator", *J. Eng. Mech.*, ASCE, **123**(8), 878-884.

Tikhonov, A.N. and Arsenin, V.Y. (1977), *Solution of Ill-posed Problems*, Wiley, New York.

Todd, K.B. and Kulakowski, B.T. (1989), "Simple computer models for predicting ride quality and loading for heavy trucks", in *Transportation Research Record*, 1215, TRB, National Research Council, Washington, D.C.

Yang, B., Tan, C.A. and Bergman, L.A. (2000), "Direct numerical procedure for solution of moving oscillator problems", *J. Eng. Mech.,* ASCE, **126**(5), 462-469.

Yu, L. (2002), "Accounting for bridge dynamic loads using moving force identification system (MFIS)", Ph.D. Thesis, The Hong Kong Polytechnic University, Hong Kong.

Yu, L. and Chan, T.H.T. (2002), "Moving force identification from bending moment responses of bridge", *Struct. Eng. Mech.*, **14**(2), 151-170.

Yu, L. and Chan, T.H.T. (2003), "Moving force identification based on the frequency-time domain method", *J. Sound Vib.,* **261**(2), 329-349.

Yu, L. and Chan, T.H.T. (2004), "Identification of multi-axle vehicle loads on bridges", *J. of Vibration and Acoustics*, ASME, **126**(1), 17-26.