International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 10 (2015) pp. 26913-26918
© Research India Publications
http://www.ripublication.com

Inertia Effect Of A Moving Mass On Beam Structure For Damage Identification

Young-Jun Ahn, Seung-Guk Lee, Dong-Ho Cho, Hee-Chang Eun

*Department of Architectural Engineering, Kangwon National University,
Chuncheon 200-701, Gangwon-Do, Korea.
E-mail: v2zone@ naver.com, angangyo@naver.com, woolima79@hanmail.net,
heechang@kangwon.ac.kr*

Min-Su Lee

*NARA Structural Engineers. Co., Ltd.,
Chuncheon 200-114, Gangwon-Do, Korea E-mail: narasec@chol.com*

Abstract

The dynamic characteristics of the beam subject to a moving mass are affected by inertia force unlike a moving force. This work considers damage detection of the beam structure evaluating the flexural performance, and the applicability of such basic concept is illustrated in a numerical experiment. The experiment investigates the feasibility of damage detection by the measurement of the inertia force and the output responses without any baseline data. The measurement data are transformed to the proper orthogonal modes (POMs) in the time domain. It is shown that the proposed method can be practically utilized by reducing the effect of the external noise.

Keywords: damage detection, moving mass, inertia effect, flexural performance

1 Introduction

The existence of damage in a structure leads to changes in its mechanical responses or characteristics. Rigidity and strength of structural members are deteriorated by damage and the resulting deterioration will change various measurable data. The advantages of damage detection in time domain include that direct sensor data can be used with no complex feature extraction and the data dimensionality remains low [1], [2]. Frequency domain methods rely on analytical models but time domain methods are independent of modal parameters and analytical models.

The derived dynamic responses of the beam structure subject to a moving mass have been applied to its damage detection. Bilello and Bergman [3] provided an analytical tool for the analysis of a damaged beam under a moving mass. Bellino et al. [4] presented a time-varying identification method to detect a crack in a beam with a moving mass. Considering that natural frequencies of real structures are affected by environmental conditions such as the mass and the velocity of the train, Bellino et al. [5] established the relationship between the natural frequencies and the load characteristics. They proposed a damage identification method to detect the presence of damage in a railway bridge crossed by a train using the principal component analysis. Pala and Reis [6] studied the effects of inertial, centripetal, and Coriolis forces on the dynamic response of a simply supported beam with a single crack under moving mass load. Cavadas et al. [7] presented a damage detection approach for using moving-load responses as time series based on two data-driven methods of moving principal component analysis and robust regression analysis. Treetrong [8] presented a method of fault analysis for induction motors to distort the sinusoidal response of the motor RPM and the main frequency. Ma et al. [9] diagnosed the fault of the rolling bearing using the energy density distribution of signal. Ahn et al. [10] performed an experiment on damage detection of beam structure using a moving mass.

A numerical experiment in this work illustrates the validity of the basic concept of the proposed method on the damage detection of the beam subject to a moving mass including inertia effect. The experimental work examines the feasibility of damage detection of a beam structure based on only measurement data from strain gages and accelerometers without any baseline data. The measurement data are transformed to POM in the time domain to reduce the noise effect. It was observed that the proposed method is sensitive to the external noise and can be utilized in practical work by reducing the external noise.

2 Dynamic formulation and a numerical experiment

The moving mass problem assumes that the stiffness of the moving system is infinite and neglects the possibility that the mass may separate from the beam. Based on energy methods, the equation of motion for an Euler-Bernoulli beam of length L travelled by a mass M with velocity $v(t)$ is expressed by.

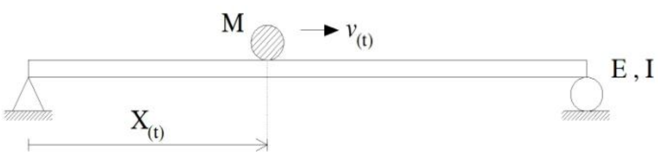


Fig. 1. A beam structure subject to a moving mass

$$EI\frac{\partial^4 y}{\partial x^4}(x,t)+m\frac{\partial^2 y}{\partial t^2}(x,t)=-M\left[g+v^2\frac{\partial^2 y}{\partial x^2}+2v\frac{\partial^2 y}{\partial x\partial t}+\frac{\partial^2 y}{\partial t^2}\right]\delta(x-\hat{x}(t)) \qquad (1)$$

where $y(x,t)$ is the vertical deflection of the beam; m and I are the mass per a unit length and the area moment of inertia, respectively; $\hat{x}(t)=vt$ is the instantaneous position of the mass along the beam; $\delta(x)$ is the Dirac delta function and g is the acceleration of gravity. It is shown in Eq. (1) that the dynamic responses of the beam are affected by the velocity of the moving mass and the ratio of the moving mass to that of the supporting structure.

The applicability of the damage detection method at beam structure considering subject to a moving mass is investigated by a numerical experiment. The test beam in Fig. 2 is utilized as the analytical model. A beam with a length of 1.2 m was modeled using 12 beam elements. The beam has an elastic modulus of $2.0\times10^5\,\mathrm{MPa}$ and a unit mass of $7{,}860\ \mathrm{kg/m^3}$. The beam's gross cross section is $100\,\mathrm{mm}\times10\,\mathrm{mm}$ and its damage section is established as the reduction of 30% flexural rigidity at element 4. The damping matrix is assumed as a Rayleigh damping to be expressed by the stiffness matrix and a proportional constant of 0.0001. The mass of $2.3\mathrm{kg}$ is assumed to travel with a velocity $337.8\mathrm{mm/sec.}$.

The dynamic responses at all nodes are numerically simulated at each time instant in Fig. 3(a) and are contaminated by external noise. In this study, the noise is simulated

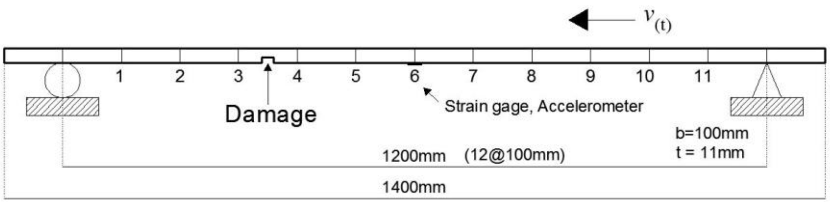
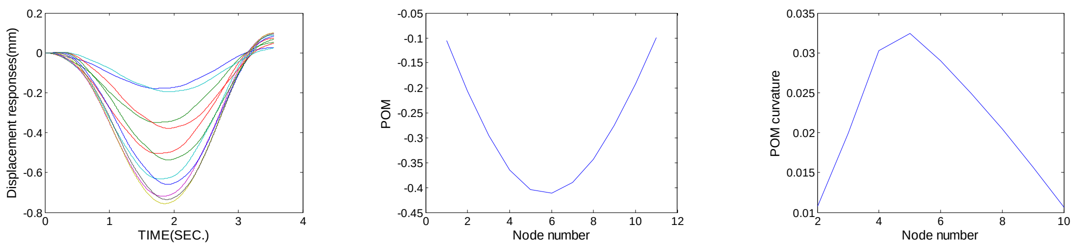


Fig. 2. A simply supported beam structure subject to a moving mass



(a) (b) (c)

Fig. 3. Numerical results: (a) numerically simulated displacement responses (b) POM corresponding to the first POV, (c) slope of the POM

by adding a series of random numbers to the calculated displacement responses. The displacements u_j for describing the practical responses at node *j* can be calculated from the simulated noise-free displacements, u_j^0 , by the following equation:

$$u_j = u_j^0 \left(1 + \alpha \sigma_j\right) \tag{2}$$

where α denotes the relative magnitude of the error and σ_j is a random number variant in the range $[-1, \ 1]$. This study assumed the noise factor as $\alpha = 3\%$.

The 300 displacement response data sets between 1.2569 sec. and 1.4197 sec. are extracted to transform to the POM. Figures 3(a) and 3(b) display the POM corresponding to the first proper orthogonal value (POV). It is observed that the POM curvature is abruptly changed between two nodes 4 and 5. From this numerical experiment, the validity of the damage detection method based on the flexural responses of beam structure due to the moving mass is verified.

3 Experimental work

A steel beam in Fig. 2 is 1200mm in length, and its gross cross-section is $100\text{mm} \times 11\text{mm}$. The damage is located at 350mm between nodes 3 and 4 from the left end, and its cross-section is $100\text{mm} \times 8\text{mm}$. Experimental data in the time domain are collected from two different types of measurement sensors of strain gage and accelerometer fixed at node 6. The acceleration of the inertia force by the moving mass of 2.5kg is measured by an accelerometer fixed on the mass. When the moving mass arrives at each node form, the left end support, the input data and output data are simultaneously collected in the time domain. However, because the data at the arrival instant cannot be accurately read, several response data near the node are collected and are transformed to the POM. The damage is traced by the ratio of the response output data with respect to the input data.

A battery-operated toy car functions as the moving mass by using a sum of the self-weight of the car and the weight of steel magnets. This study utilized the average velocity expressed by the distance covered with respect to the time taken. The experimental work was repeated several times under the same circumstance to detect the damage. Consistent results were not obtained due to the external noise while making experiments. This study considered one of the experimental datasets. Figure 4 represents the input data and the corresponding response data of accelerometer and strain gage along the beam. It is shown that the external noise is included in the measurement data and the input data include a large portion of external noise due to the battery vibration.

The POD (proper orthogonal decomposition) extracts feature by revealing relevant, but unexpected, structure hidden in the data. The POD is used to derive a reduced-order model for non-linear initial value problems. Figure 5 displays the POM ratio expressed by the output POM, with respect to the input POM in the time domain. When the moving mass approaches the damage region, the response should be abruptly increased because of the local stiffness deterioration along the beam. It indicates that the damage is located in the region that represents the abrupt change in the POM ratio. It was observed that the damage cannot be detected in all cases and the proposed method is sensitive to the external noise. However, it is understood that the method can be practically utilized by reducing the effect of the external noise without any baseline data

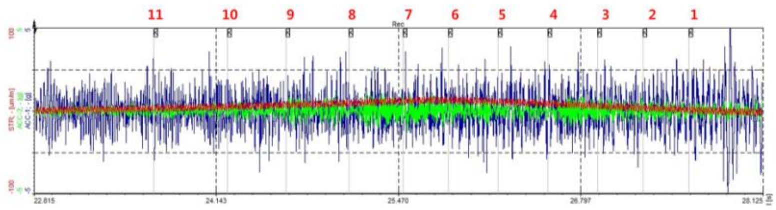
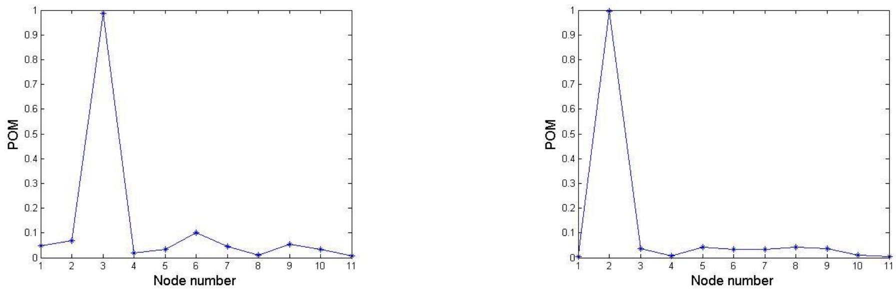


Fig. 4. Input and output data curves



(a) (b)

Fig. 5. POM ratio using input and output data: (a) accelerometer measurement, (b) strain gage measurement

4 Conclusions

The validity of the damage detection method is verified based on the flexural responses of beam structure due to the moving mass. Based on this concept, this experimental work investigated the feasibility of damage detection based on the POM ratio using the inertial input data of moving mass and the output data by accelerometer and strain gage. The POM ratio is expressed by the output POM with respect to the input POM in the time domain. The measured data are sensitive to the external noise and the input data include a large portion of external noise due to the battery vibration. It is observed that the damage cannot be detected in all cases, but the method can be practically utilized by reducing the effect of the external noise.

Acknowledgment
This work (Grants No. C0217650) was supported by Business for Cooperative R&D between Industry, Academy, and Research Institute funded Korea Small and Medium Business Administration in 2014.

References

[1] J. Kullaa, “Sequential structural health monitoring and damage detection”, 6th European Workshop on Structural Health Monitoring (2012).
[2] J. Kullaa, “Distinguishing between sensor fault, structural damage, and enviromental or operational effects in structural health monitoring”, Mechanical Systems and Signal Processing 25(8) , 2976-2989(2011).
[3] A. Bellino, L. Garibaldi, S. Marchesiello, “Time-varying output-only identification of a cracked beam”, Key Engineering Materials 413-414, 643-650 (2009).
[4] A. Bellino, L. Garibaldi, A. Fasana, S. Marchesiello, “Damage detection in time-varying systems by means of the PCA method”, Proceedings of ISMA, pp. 783--794 (2010).
[5] C. Bilello, L.A. Bergman, “Vibration of damaged beams under a moving mass: theory and experimental validation”, Journal of Sound and Vibration 274, 567-582 (2004).
[6] Y. Pala, M. Reis, “Dynamic response of a cracked beam under a moving mass load”, Journal of Engineering Mechanics ASCE 139(9), 1229-1238 (2013).
[7] F. Cavadas, L.F.C. Smith, J. Figueiras, “Damage detection using data-driven methods applied to moving-load responses”, Mechanical Systems and Signal Processing 39 (1,2), 409-425 (2013).
[8] J. Treetrong, “Fault detection of electric motors based on frequency and time-frequency analysis using extended DFT”, International Journal of Control and Automation 4(1), 49-58 (2011).
[9] J. Ma, J. Wu, X. Yuan, “The fault diagnosis of the rolling bearing based on the LMD and time-frequency analysis”, International Journal of Control and Automation 6(4), 357-375 (2013).
[10] Y.J. Ahn, S.G. Lee, D.H. Cho, H.C. Eun, M.S. Lee, “Damage detection by a moving mass on beam structure”, Proceedings of International Workshop on Architecture and Civil Engineering 2015 April , Jeju Island, Korea(2015).