DAMAGE IDENTIFICATION OF A BELT-CONVEYOR SUPPORT STRUCTURE USING LOCAL VIBRATION MODES: NUMERICAL STUDY

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ABSTRACT

Due to aging and corrosion, a large number of support structures of belt-conveyors in industrial plants have been deteriorating. In this work, a damage identification method based on two specific local vibration modes, called periodic and isolated local vibration modes, is numerically studied. First, the two local vibration modes are described and distinguished from other vibration modes. The characteristics of these two modes are studied using a numerical model of a belt-conveyor support structure. Then, the location to provide impact-type load to better observe these two local modes are introduced. The identification method utilizes the facts that support structures of belt conveyors are periodic in space and have many identical members repeated along the belt conveyor and that these members are considered to have some local modes vibrating at the frequencies close to each other. The sensitivity analyses show that the frequencies of these two local vibration modes almost depend only on the local boundary conditions of the corresponding member as well as the properties of the member itself. The results show that, due to damage, frequencies of periodic local vibration modes significantly change. Damage identification is formulated using the two local modes. Numerical study shows the damage identification capability even without the need of modal properties of the undamaged structure.

Keywords: Local vibration, Damage identification, Belt conveyor, Acceleration measurement.

1. INTRODUCTION

A large amount of support structures of belt conveyors in various industrial plants have been damaged due to corrosion. Although research on health monitoring of the conveyor belts or machinery parts has been reported (Mazurkiewicz 2008 and Harrison 1980), structural condition assessments of the support structure of belt conveyors have not been studied in details. Because

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damage on the support structure of belt conveyors may cause serious problems, establishment of effective structural assessment methods for the support structure is urgent. During last few decades, structural condition assessments based on modal properties changes of structures have been studied intensively (Doebling et al. 1996; Yoshioka et al. 2010; Dinh et al. 2012). However, most of previous studies assume a few number of damage elements as opposed large numbers of damages observed on belt conveyors. Moreover, before-and-after comparison, which is not practical, has been usually necessary.

In this paper, a new method based on Periodic Local Vibration Modes (PLVM) and Isolated Local Vibration Modes (ILVM) is introduced. This method is applicable to structures with a large number of damage elements in structures even when the baseline, or the structure in undamaged state, is unknown. At first, a finite element model of the support structure is prepared using Abaqus. Then PLVM and ILVM are defined. The sensitivity analyses of the frequencies of PLVM and ILVM to different parameters are then carried out. After that, beam theory is used to quantify the degree of damage. The technique is applied to a numerical model of the support structure, which confirms the damage identification capabilities.

2. FINITE ELEMENT MODEL OF THE SUPPORT STRUCTURE

One representative belt conveyor is modeled in ABAQUS (see Figure 1). The main frame of the belt conveyor consists of the main and secondary parts. The main parts include continuous longitudinal members while the secondary parts include braces, lateral members, and vertical members connected to the longitudinal members. The boundary conditions of the whole structure and the connections between main frame and columns are set as fix. 3-D linear beam element has been used for all members in the model.

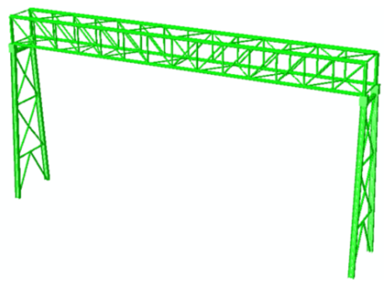


Figure 1: A support structure finite element model.

3. PERIODIC AND ISOLATED LOCAL VIBRATION MODES

For secondary members such as top and bottom braces, side braces, and vertical and lateral members, there are modes where only secondary members identical to each other strongly vibrate. These members have the same cross section, length, and local boundary conditions. The eigenvalue analysis shows all identical members strongly vibrate at the same frequencies. Because the members have nearly same intervals along longitudinal direction, this mode is named Periodic

Local Vibration Modes (PLVM). As an example, one of the PLVMs of the top and bottom braces is shown in Figure 2. In PLVM, the modal amplitudes of the vibrating identical members are much larger than those of the other members. Note that no PLVM is observed for the main members.

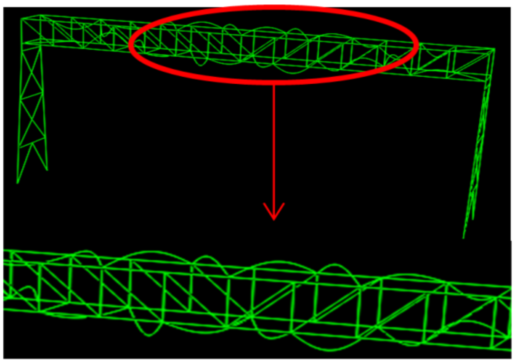


Figure 2: One PLVM of the top and bottom braces.

When one of the identical members is damaged, this member does not vibrate with the other members in the corresponding PLVM; instead, this damaged member alone vibrates. This mode is named the Isolated Local Vibration Modes (ILVM). After damage, the damaged member is no longer identical with the other members. As in Figure 3, the damaged member, shown in red, alone vibrates in the ILVM and does not vibrate in the PLVM. Note that other than PLVM and ILVM, there are many local and global modes.

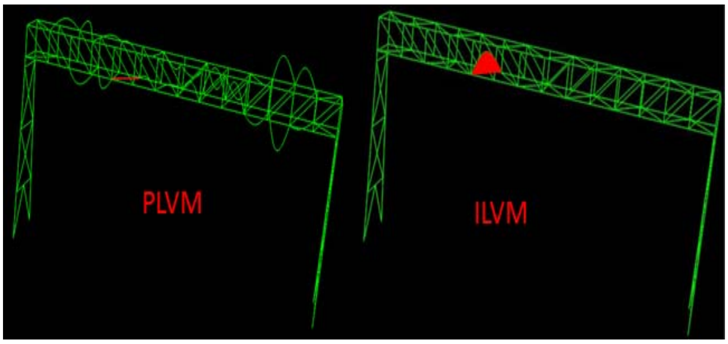
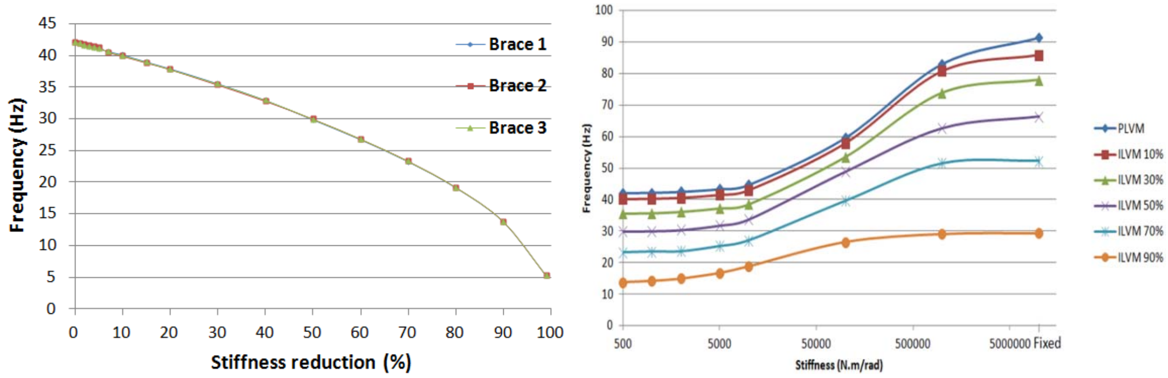


Figure 3: A PLVM and ILVM of the damaged structure.

4. FREQUENCY SENSITIVITY ANALYSIS

In order to reveal the feasibility of damage identification based on PLVM and ILVM, the sensitivity of PLVM and ILVM frequencies with respect to different parameters are investigated. The parameters to be examined are secondary member stiffness, their boundary conditions (i.e., connection condition) longitudinal member stiffness, and the boundary conditions of the main frame (i.e., column stiffness).

The sensitivity with respect to the stiffness changes of secondary members, the Young's moduli of three top or bottom braces are changed by different percentage. The frequencies of ILVM with respect to stiffness reduction of the members are plotted in Figure 4 (a). The sensitive is high. The differences among the three members are negligible.



(a) (b)

Figure 4: Frequency changes of ILVM with respect to (a) secondary member stiffness reduction and (b) rotational spring stiffness reduction

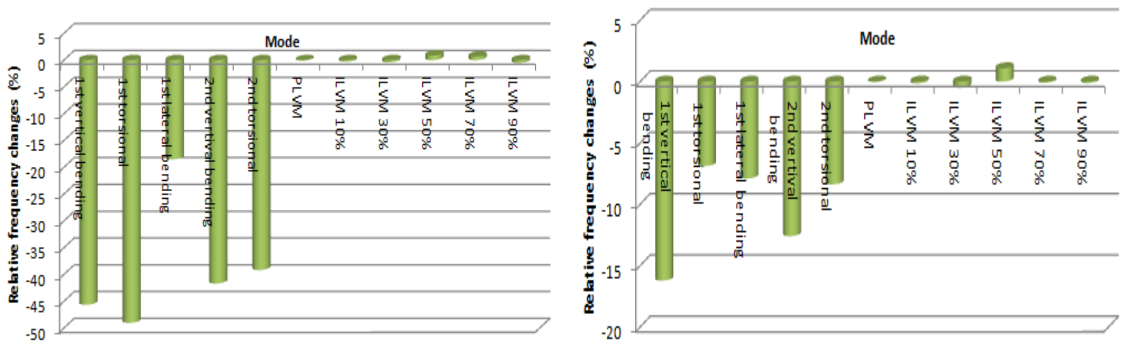


Figure 5: Frequency changes of global modes, PLVM, and ILVM for 80% stiffness reduction of (a) the longitudinal members and (b) the columns.

The frequency sensitivity with respect to the stiffness of rotational spring at both end of bottom brace is then studied. Figure 4 (b) shows the frequencies changes of PLVM and ILVM versus the stiffness changes of the rotational springs for the representative secondary member. The frequencies of PLVM and ILVM significantly change as the stiffness of the rotational springs changes from 500 Nm/rad (soft spring) to infinity (fixed local boundary condition).

The frequency sensitivity with respect to the main longitudinal member stiffness is then studied. The stiffness of all longitudinal members is reduced by 80%. The frequencies of PLVM and ILVM of a bottom brace are calculated. Figure 5 (a) shows the frequency changes of PLVM and ILVM. The frequency changes of global vibration modes are also shown in the figure. The frequency changes of PLVM and ILVM are less than 0.8% while those of some global modes are as large as 45%. The sensitivity to the main members is small.

As for the sensitivity to the boundary conditions of the main frame, the stiffness of all column members are reduced by 80%. The frequency changes of a bottom brace are calculated. Figure 5 (b) shows the frequency changes. Frequency changes of global vibration modes are also shown for comparison. The changes are always less than 1%. The sensitivity to the stiffness changes of the columns is small while the sensitivities of the global modes are high.

Thus, appropriate parameters in damage quantification are secondary member stiffness and their local internal connections. The effects of global boundary conditions (i.e., the column) and the main longitudinal members on the PLVM and ILVM frequencies are negligible.

5. THE QUANTIFICATION OF DAMAGE DEGREE

Consider a uniform simply-supported beam with two rotational springs with rotational stiffness k_{r1} and k_{r2}, shown in Figure 6. The end is hinged if k_{rx}=0 and clamped if $k_{rx} \rightarrow \infty$.

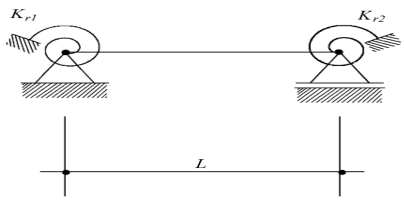


Figure 6: Simply-supported beam with two elastic rotational springs at the ends.

The exact *n*-th natural frequency ω_n of the elastic restrained beam can be shown as the square of a dimensionless coefficient λ_n multiplied by the fundamental frequency of the same hinged-end beam:

$$\omega_n = \lambda_n^2 \sqrt{\frac{EI}{\rho A L^4}} \tag{1}$$

In which *EI* is the modulus of flexural rigidity, ρA is mass per unit length and *L* is the span length. λ_n is the nth none-zero root of the following equation (Fung 2003; Naanasi 1994; Maurizi et al. 2003):

$$2R_1R_2\phi_1(\lambda)\lambda^2 + (R_1 + R_2)\phi_6(\lambda)\lambda - \phi_4(\lambda) = 0 \tag{2}$$

where

$$R_1 = \frac{EI}{K_{r1}L}, \quad R_2 = \frac{EI}{K_{r2}L}, \quad \phi_1(\lambda) = \sin(\lambda)\sinh(\lambda), \quad \phi_4(\lambda) = \cos(\lambda)\cosh(\lambda) - 1, \phi_6(\lambda) = \sin(\lambda)\cosh(\lambda) - \sinh(\lambda)\cos(\lambda) \tag{3}$$

As the frequencies of PLVM and ILVM depend mostly on the properties of secondary members and their local boundary conditions, the above equations are expected to be applicable to damage quantification. The first, second or higher frequencies of PLVM and ILVM are measured. Then using the above equations, the stiffness are estimated. In the next section, this method is examined for the numerical model.

6. DAMAGE IDENTIFICATION APPLICATION TO THE FINITE ELEMENT MODEL

In order to examine the applicability of the damage identification, 22 members of the support structure are randomly damaged. Damaged members include top and bottom braces, side braces, vertical members, lateral members, and longitudinal members as shown in Table 1 and Figure 7Figure 7: Damaged elements in each member type..

Table 1: Introduced damages and its identified values (stiffness reduction in percentage)

Member sets	Member 1		Member2		Member 3		Member 4		Member 5	
	damage	identified	damage	identified	damage	identified	damage	identified	damage	identified
Bottom and top braces	75	74.81	5	4.50	10	10.10	20	19.70	35	35.19
Side braces	90	89.86	5	5.15	65	64.38	25	25.39	25	25.39
Vertical members	85	85.11	5	5.27	55	55.32	15	15.86	30	31.74
Lateral members	5	4.28	15	14.06	40	39.69	-	-	-	-
Longitudinal members	50	-	10	-	20	-	80	-	-	-

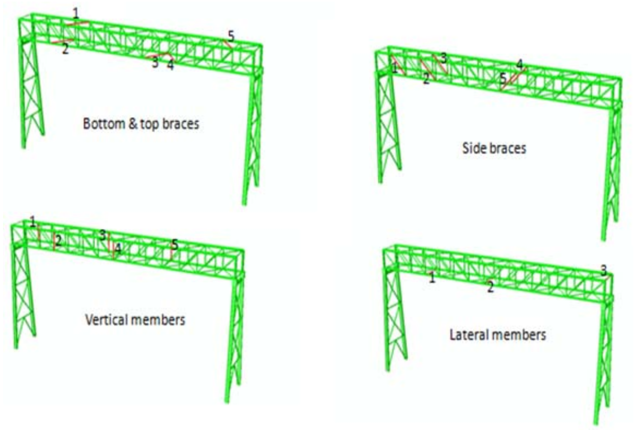


Figure 7: Damaged elements in each member type.

The velocity time histories of the support structure are generated through dynamic implicit analysis with sampling rate of 5 kHz when impact force is applied at the bottom of the two columns. Fourier amplitude spectrum is examined to pick up ILVM and PLVMs (see Figure 8). While the PLVMs are in the close frequency ranges, the damaged members have frequency peaks corresponding to ILVMs away from the PLVM frequency range. ILVM frequencies corresponding to all the damaged members and PLVM ranges of undamaged members are thus identified.

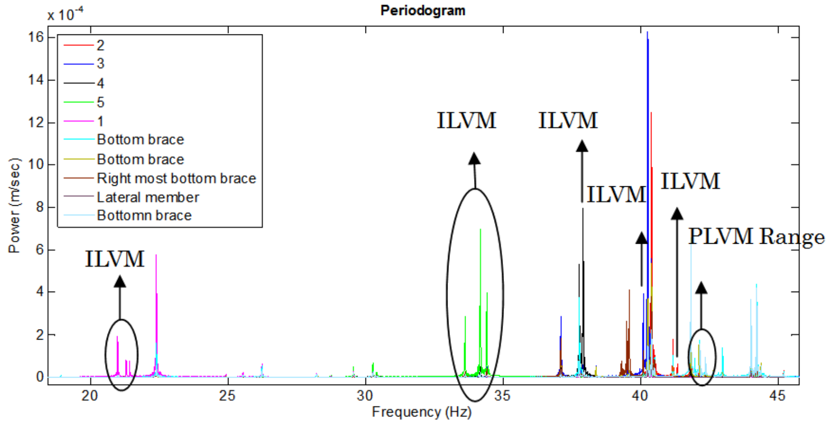


Figure 8: Fourier amplitude spectrum of bottom and top braces.

The reduction in *EI* is considered as damage and is identified. The material and cross section properties, *EI* and *ρA*, as well as the length *L* of undamaged secondary members are assumed known. On the other hand, the stiffness of rotational springs corresponding to the connections is estimated.

The undamaged members have PLVM. From equation (1), λ_n is

$$\lambda_n = \left(\omega_n \Big/ \sqrt{\frac{EI}{\rho A L^4}} \right)^{0.5} \tag{4}$$

The frequency of PLVM, ω_n, and undamaged member properties are known, giving λ_n. Assuming the stiffness of rotational springs at the ends of an undamaged secondary member have the same values, equation (2) is written as

$$2R^2\phi_1(\lambda)\lambda^2 + 2R\phi_6(\lambda)\lambda - \phi_4(\lambda) = 0 \tag{5}$$

where $R = EI/KL$ in which K is the stiffness of the rotational springs. Therefore, the only unknown parameter K is readily calculated.

For damaged members, the frequency of ILVM, ω_n, is known. Assume that the damage reduces secondary member stiffness but does not the rotational spring stiffness. The identified *K* value is used as the rotational spring stiffness. Now, the only unknown parameter in equation (5) is *EI*. Thus, the damage is quantified. The ratio of identified *EI* to that of the undamaged member indicates the damage percentage, which is summarized in Table 1.

The maximum error is 1.74% at vertical member 5. For the other members, the error is always less than 1%. Using PLVM and ILVM, even small and multiple damages of secondary members can be located and quantified without the need of modal information of undamaged structure. Note that higher PLVM and ILVM are utilized to quantify damage when damage is considered on the local connections.

7. CONCLUSION

A new damage identification technique based on two specific local vibration modes, called PLVM and ILVM, is proposed and examined on a numerical model of a belt conveyor support structure. The technique utilizes the facts that support structures have many identical secondary members and these members have specific local modes, called PLVM, vibrating at frequencies close to each other. If any of those identical secondary members are damaged, the damage member does not vibrate in PLVM. However, the member vibrates in another local mode called ILVM. The numerical study shows that the frequencies of PLVM significantly change due to damage. Damaged members are identified and the degree of damage can be quantified without the need of modal properties of the undamaged structure. Moreover, a large number of damage elements do not contaminate the results. Experiments on a laboratory scale-model and belt conveyor support structures in fields are expected to reveal practical applicability. For the structural condition assessment of belt conveyors, damage identification techniques for the main frame primary members are also needed.

8. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of this research by the Japan Society for the Promotion of Science(JSPS) under Grant-in-Aid for Young Scientists (A) 80451798. The authors gratefully acknowledge the valuable assistance of Dr. Ryoichi Kanno at Nippon Steel & Sumitomo Metal Corporation.

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