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Damage identification of belt conveyor support structure using periodic and isolated local vibration modes

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Abstract. Due to corrosion, a large number of belt conveyors support structure in industrial plants have deteriorated. Severe corrosion may result in collapse of the structures. Therefore, practical and effective structural assessment techniques are needed. In this paper, damage identification methods based on two specific local vibration modes, named periodic and isolated local vibration modes, are proposed. The identification methods utilize the facts that support structures have many identical members repeated along the belt conveyor and there exist some local modes within a small frequency range where vibrations of these identical members are much larger than those of the other members. When one of these identical members is damaged, this member no longer vibrates in those modes. Instead, the member vibrates alone in an isolated mode with a lower frequency. A damage identification method based on frequencies comparison of these vibration modes and another method based on amplitude comparison of the periodic local vibration mode are explained. These methods do not require the baseline measurement records of undamaged structure. The methods is capable of detecting multiple damages simultaneously. The applicability of the methods is experimentally validated with a laboratory model and a real belt-conveyor support structure.

Keywords: damage Identification; belt conveyor; local vibration mode; periodic structure; sensitivity analysis

1. Introduction

A large number of belt conveyor support structures in industrial plants have deteriorated due to corrosion. The corrosion may cause structural failure endangering the safety of the working conditions. The failure may also result in significant social and economic loss. In case of ironworks, the total length of belt conveyors, carrying iron-ore and other materials, often reaches tens of kilometers. Dust falls from the belt and adheres to the support structure. Kilograms of dust accumulates on support structure members. Accumulated dust, which is sometimes wet due to rain, causes severe corrosion. The corrosions occasionally result in the complete loss of cross section.

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Furthermore, the occurrence of multiple corrosion damages is not rare. Effective monitoring and assessment of such structures are needed.

For the condition assessment of structures, a significant amount of research efforts have been made in the field of structural health monitoring (SHM). Some research has been performed on the health monitoring of belts or machinery parts of belt conveyors (Harrison 1980, Mazurkiewicz 2008). However, structural condition assessment of the support structure has not been studied in details.

Condition assessment based on dynamic property changes has been studied by many researchers in the last three decades (Ewins 1985, Ojalvo and Pilon 1988, Mottershead and Friswell 1993, Salawu 1997, Law *et al.* 1998, Shi and Law 1998, Kim and Bartkowicz 2000, Shi *et al.* 2000, Ricci 2000, Park and Kim 2002, Ren and De Roeck 2002, Gao and Spencer 2008, Yang *et al.* 2009, Dinh *et al.* 2012). Comprehensive reviews of existing techniques are available (Doebling *et al.* 1996, Chang *et al.* 2003, Sohn *et al.* 2004, Carden and Fanning 2004, Farrar and Worden 2007). However, these techniques have not seen practical usage in belt conveyor support structure monitoring. The damage introduced and identified were limited to only a few elements while the corrosion damages on the support structures are not. Moreover, before-and-after comparison of structures, which is often impractical for the support structure assessment, has been assumed. In addition, the non-structural members of belt conveyor such as machinery parts and sidewalks affect the global vibration modal properties because the size of these members are not small as compared to the size of support structures.

In this paper, new damage identification methods for secondary members of belt conveyor support structures based on local vibration modes are proposed. Periodic Local Vibration Modes (PLVM) and Isolated Local Vibration Modes (ILVM) are utilized to overcome the difficulties in identifying a large number of damage elements in the absence of baseline measurement records of undamaged structures. Local vibration modes are difficult to observe because the modes usually appear in high frequency ranges and are small in amplitude. The differentiation of specific local modes among numerous local modes is also difficult. To enable observation and differentiation of local vibration modes efficiently, the Laser Doppler Vibrometer (LDV), capable of non-contact measurement of small vibration with a high resolution in a wide frequency range, is utilized. First, a finite element model of the support structure is constructed using commercial FE software, ABAQUS (Abaqus FEA 2015) and dynamic characteristics of the structure are investigated. Then the sensitivity analyses of the frequencies of PLVM and ILVM to several parameters are carried out. The applicability of these modes in damage identification is investigated. Finally, the proposed methods are experimentally validated in a laboratory model as well as in a real belt conveyor structure.

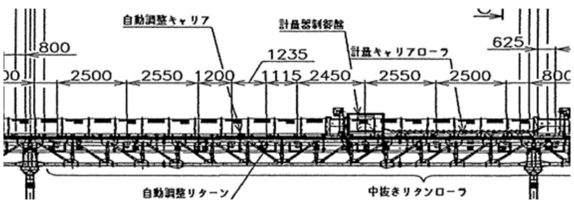
2. Finite element model of the beltconveyor support structure

A design drawing of a typical belt conveyor is shown in Fig. 1(a). One representative span of this support structure is modeled in ABAQUS (Fig. 1(b)). The support structure consists of the main frame and columns. The main frame consists of main and secondary members. The main members include continuous longitudinal members. The secondary members include braces, lateral members, and vertical members; these members are connected to the longitudinal members. The connections between the columns and the ground and those between the main frame and columns are modeled as fixed. Three-dimensional linear beam element are employed for all members.

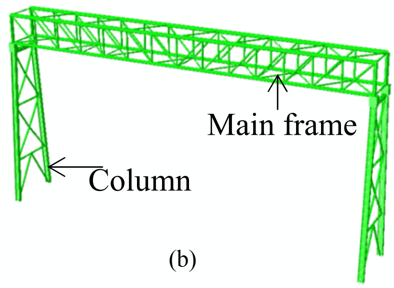
3. Local vibration modes of the main frame

The eigenvalue analysis shows that there are some modes within a small frequency range where all identical members strongly vibrate. Here, the identical members are defined as the secondary members of the same cross sections, lengths, and local boundary conditions. Because these members have nearly the same intervals along the longitudinal direction, the modes are named Periodic Local Vibration Modes (PLVM). As an example, one of the PLVM of the top and bottom braces is shown in Fig. 2. The mode shape amplitudes at the identical members are much larger than those at the other members; the amplitudes at connection points are small. On the other hand, no PLVM of the continuous main members exists. The damage identification methods discussed in this paper utilize PLVM and are not applicable to the main members.

If one of the identical members is damaged, this damaged member does not vibrate in the PLVM; instead, only this damaged member vibrates in another mode named Isolated Local Vibration Modes (ILVM). In fact, the damaged member is no longer identical with the other members and the dominant frequency shifts. Example PLVM and ILVM are shown in Fig. 3. The damaged member, shown in red, is under isolated vibration in the ILVM and does not vibrate in the PLVM. Other than PLVM and ILVM, there are many local modes, such as combination of local and global vibration modes, and other modes, where all or some of non-identical members vibrate.



(a)



(b)

Fig. 1 Modeled span of the belt conveyor; (a) Design drawing of main frame and (b) FE Model

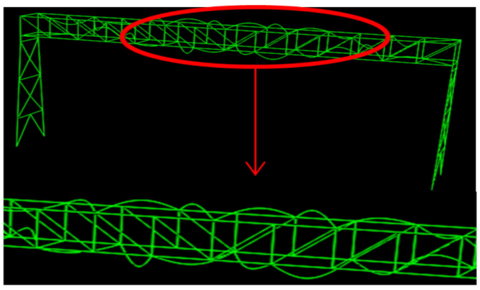


Fig. 2 One of the PLVM of the undamaged structure

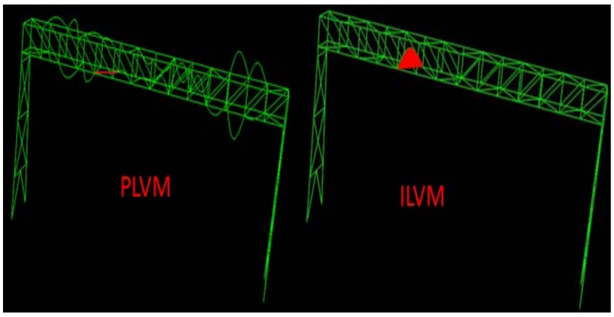


Fig. 3 PLVM and ILVM of the damaged structure

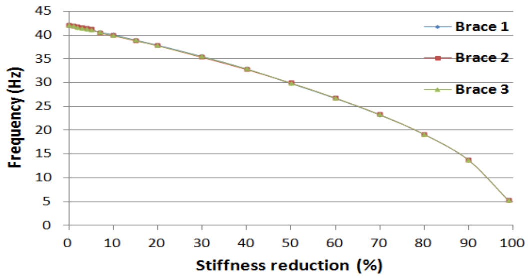


Fig. 4 Frequency changes of ILVM versus stiffness reduction

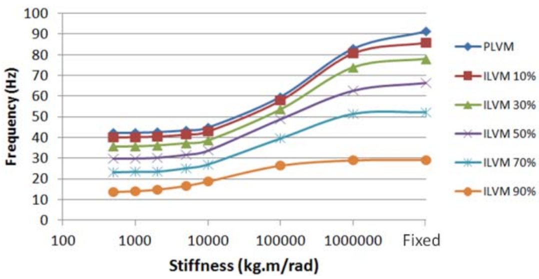


Fig. 5 Frequency changes of PLVM and ILVM versus stiffness change of the rotational springs

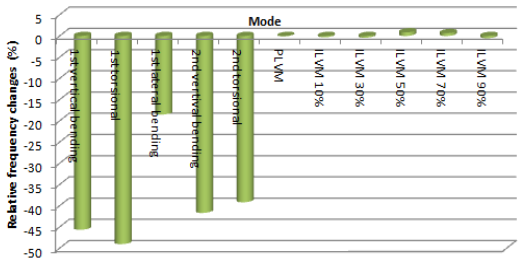


Fig. 6 Relative frequency change versus stiffness reduction of the longitudinal members

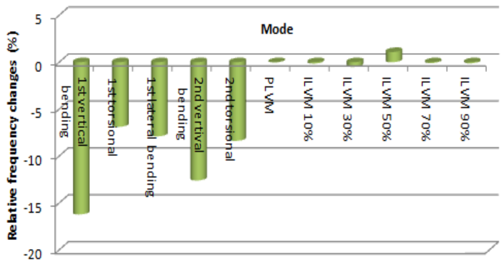


Fig. 7 Relative frequency change versus stiffness reduction of the two columns

4. Sensitivity of PLVM and ILVM to parameter changes

The sensitivity of PLVM and ILVM frequencies to various structural parameters is investigated herein. The parameters include the properties of the secondary member, local boundary conditions (i.e., stiffness of rotational springs at the connection points), the properties of the longitudinal members and the global boundary conditions of the main frame (i.e., properties of the columns).

To investigate the sensitivity of the ILVM frequency to the secondary member stiffness changes, the Young's moduli of three identical braces, i.e., brace 1, 2 and 3, at the bottom and top are changed. The sensitivity is large and almost the same for all identical members (Fig. 4).

The sensitivity to the rotational springs at the ends of secondary members is then investigated. The frequency of PLVM and ILVM significantly changes when the rotational spring stiffness at the ends of bottom brace members changes (see Fig. 5).

Next, the sensitivity to the stiffness of the main longitudinal members is examined. The stiffness of all longitudinal members is reduced by 80%. In addition, the frequency change of some global vibration modes are shown for comparison. The frequency change of PLVM and ILVM are always less than 0.8% (see Fig. 6).On the other hand, the frequencies of global vibration modes are much more sensitive than the frequencies of PLVM and ILVM.

As for the boundary conditions of the main frame, the stiffness of all members of the two columns is reduced by 80%. The frequency changes of PLVM and ILVM, as well as those of global modes, are shown in Fig. 7. The changes of PLVM and ILVM are always less than 1%.

Thus, the PLVM and ILVM frequencies are sensitive to the properties of the secondary members and their local connections. The effects of global boundary conditions and the properties of the main longitudinal members are negligible. These local modes are considered equivalent to the modes of the simply supported beam. The secondary member properties and their connections can therefore be updated based upon the frequencies of the local modes. Next, damage identification methods using PLVM and ILVM are discussed.

5. Damage identification by comparing the frequencies of local vibration modes

5.1 Damage identification principle

Consider a uniform simply supported beam with two rotational springs with stiffness, k_{r1} and

k_{r2}, as shown in Fig. 8. The hinge corresponds to the stiffness of $k_r=0$ and the clamped end corresponds to the stiffness of $k_r=\infty$.

The n^{th} natural frequency, ω_n, of the elastic beam can be represented as the square of a dimensionless coefficient, λ_n multiplied by the fundamental frequency of the hinged end beam

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

in which, EI is the flexural rigidity, ρA is mass per unit length and L is the span length. λ_n is the n^{th} non-zero root of the following equation (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

$$R_1 = \frac{EI}{k_{r_1}L},\ R_2 = \frac{EI}{k_{r_2}L}\ ,\ \phi_1(\lambda) = \sin(\lambda)\sinh(\lambda), \phi_4(\lambda) = \cos(\lambda)\cosh(\lambda) - 1,$$

$$\phi_6(\lambda) = \sin(\lambda)\cosh(\lambda) - \sin h(\lambda)\cos(\lambda) \tag{3}$$

The frequencies of PLVM and ILVM are used in the above equations to evaluate the stiffness parameters. From Eq. (1), λ_n is

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

The frequency of PLVM, ω_n, is measured and ρA, EI, and L are obtained from the design drawings. Thus, λ_n is calculated. When the connection designs at both ends of each secondary member are identical, the stiffness of rotational springs at the ends of each member has the same values. Eq. (2) is written as

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

where $R = \frac{EI}{k_r L}$ and $k_r = k_{r1} = k_{r2}$. The only unknown parameter, k_r, which is the rotational spring stiffness at the ends, is obtained numerically from this equation.

For damaged members, the frequency of ILVM, ω_n is known. The damage is assumed to occur only on the members. The stiffness of rotational springs at the ends is thus the same as that of undamaged members. Therefore, the only unknown parameter in Eq. (5), *EI,* is identified numerically.

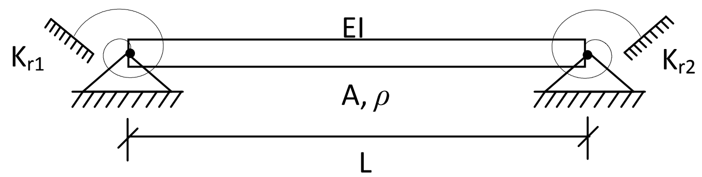


Fig. 8 A simply supported beam with two elastic rotational springs at the ends

In practice, observation of PLVM and ILVM is difficult unless these modes are strongly excited. Direct excitations effectively excite the corresponding PLVMs or ILVMs and help identification of the PLVM frequencies among many other modes. In experiments, a secondary member is directly hit by Hammer while its response is measured by the non-contact LDV. This process is repeated for all the secondary members by moving the Hammer and LDV. Note that the responses of nodal points and some secondary members of different design are also measured; by comparing the power spectrums of responses of identical design secondary members and others, PLVM, ILVM, and other modes are distinguished. The frequencies of the modes are identified by the peak-picking method.

5.2 Application to a numerical model

Damages introduced to the finite element model of a support structure are identified using the proposed method (see Fig. 9).There are four identical member sets in the main frame. In total, 18 members have been damaged with different severities. The percentage of stiffness reduction is shown in Table 1. These reductions of stiffness are considered as damages. Note that the introduced stiffness reductions are of realistic damage level. There are support structures of belt conveyors with severely corroded members. Even a complete loss of cross section is not rare.

The velocity time history of the main frame of the support structure are obtained through dynamic implicit analysis with a sampling frequency of 5000 Hz after both columns are hit near the bottom. Because no noise is introduced, the excitation even at the columns, instead of the excitation at each secondary member, resulted in sufficient observability of the local modes. The power spectrum of the bottom and top braces and one lateral member are shown in Fig. 10. There are five ILVM corresponding to the damaged members and one PLVM frequency range. In the PLVM range, the amplitude of the undamaged bottom and top braces are much larger than the other members. The other peaks correspond to global vibration modes or other modes in which all or some parts of the structure vibrate. The PLVM range is zoomed in and shown in Fig. 11(a). The PLVM frequency range is defined as the frequency range between the lowest PLVM frequency and the highest PLVM frequency. Note that the rightmost bottom brace and the lateral member are not of the identical design with the other bottom and top braces.

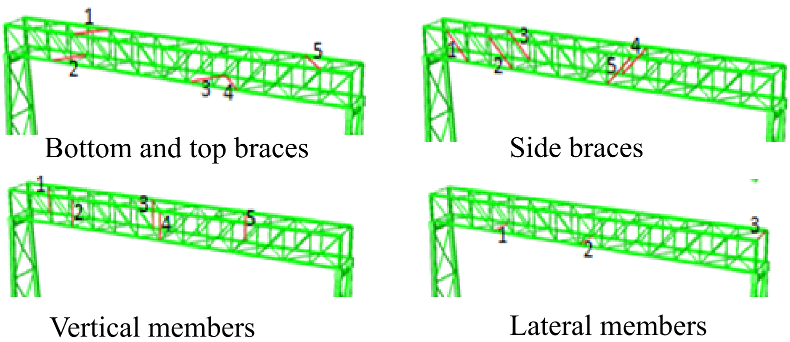


Fig. 9 Damaged members in different member sets

Table 1 Stiffness reductions introduced in the FE model and their estimation

Member sets	Member 1		Member 2		Member 3		Member 4		Member 5	
	*a	*b	a	b	a	b	a	b	a	b
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	-	-	-	-

*a = Stiffness reduction (%) introduced in the FE model; b = Estimated stiffness reduction (%)

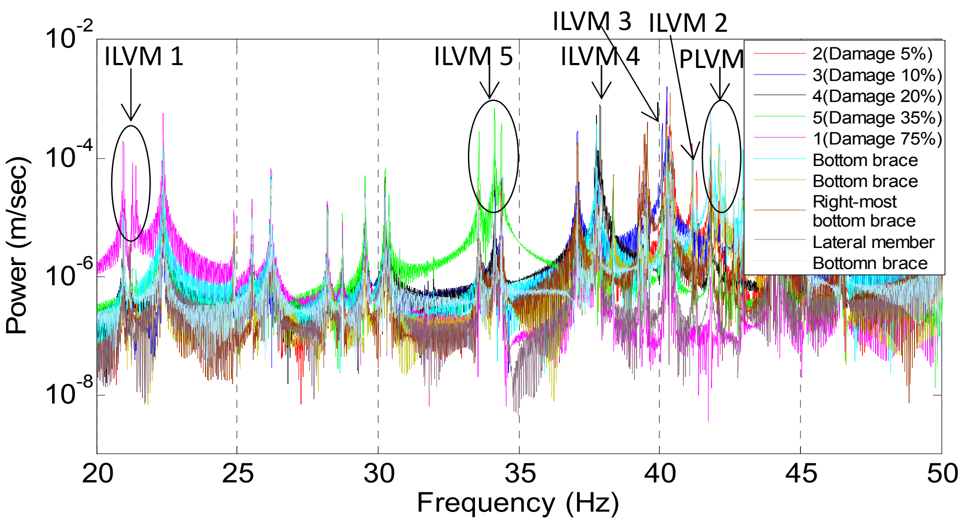


Fig. 10 Fourier spectrum indicating PLVM and ILVM frequency peaks of the bottom and top braces

The ILVM peak corresponding to member 5 is shown in Fig. 11(b). There are three peaks where the amplitude of member 5 is much larger than the other members. Only one of these three peaks is considered to be the ILVM of member 5; however, because the frequency of ILVM is at the vicinity of two other modes, there are, in total, three peaks. In case of existence of many peaks, the mean value of frequencies of these peaks is defined as the frequency of ILVM.

Likewise, based on PLVM and ILVM frequencies, damages of the other members are identified (see Table 1). The maximum error is 1.74% at vertical member 5. For the other damaged members, the error is less than 1%. The main cause of the damage quantification error is considered the coupling of closely spaced modes. As the signal to noise ratio can be improved by adjusting the impact force, the observation noise is not considered in this analysis.

If damage is considered both on the members and the local connections of the members, the higher PLVM and ILVM needs to be utilized to distinguish and quantify these damages. When Eq.

(2) or (5) are not directly applicable (e.g., three dimensional model), model updating can be performed; the boundary conditions are first identified from frequencies of undamaged members and then damage member stiffness is identified from those of damaged members.

6. Damage identification by comparing the amplitudes of local modes in the PLVM range

6.1 Damage identification principle

The damage quantification method introduced in previous section requires local mode frequency identification of each member, which is typically realized by directly hitting each member. However, direct hit of every member is oftentimes impractical. Damage identification without the need of direct hit of every member is introduced herein. The method can localize damages and evaluate their relative severity.

Consider the impact load, $P_0\delta(t)$, applied at location l

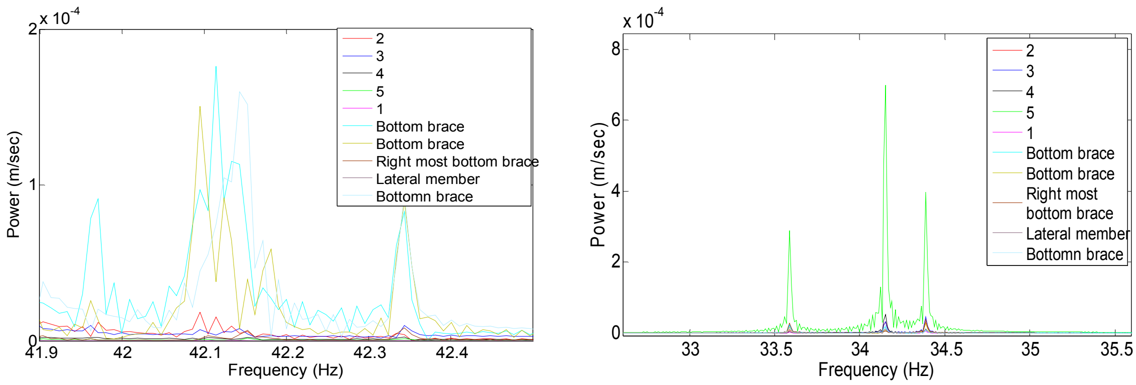
$$\{P(t)\} = P_0\delta(t)E_l \tag{6}$$

where E_l is a unit vector whose elements except for the location of impact are all zero. The impulse response in the modal coordinate, $q_i(t)$, is written as

$$q_i(t) = \frac{P_0\phi_{i,l}}{m_i\omega_i} sin\omega_i t \tag{7}$$

where $\phi_{i,l}$ is the i-th mode shape at the location l, m_i is the generalized mass and ω_i is the i-th natural frequency. The response in the PLVM frequency range at the location $m$in the physical coordinate, $x_m(t)$ is approximately obtained by summing all PLVM components as follows

$$x_m(t) = \sum_i \frac{P_0\phi_{i,m}\phi_{i,l}}{m_i\omega_i} sin\omega_i t \cong \sum_{i\in PLVM} \frac{P_0\phi_{i,m}\phi_{i,l}}{m_i\omega_i} sin\omega_i t \tag{8}$$



(a) (b)

Fig. 11 (a) Fourier spectrum of the PLVM frequency range of the bottom and top braces (b) Fourier spectrum of the ILVM of member 5

The maximum modal amplitude at the location m in its PLVM range, x_{ml}, is

$$x_{ml} = \max_i \frac{P_0 \Phi_{i,m} \Phi_{i,l}}{m_i \omega_i} \tag{9}$$

When the mode shape amplitude is large both at location l and m, as in PLVMs of undamaged members, the maximum modal amplitude is large. When the member at the location m is damaged, the PLVM mode shape is small at this point. Therefore, the maximum modal amplitude at the damaged member is small. Thus, the location of damage is indicated by the maximum modal amplitude. This maximum modal amplitude is approximately obtained as the peak values of frequency spectrum of $x_m(t)$ in the PLVM range. The differences come from closely spaced modes.

In practice, the location of damage is identified by comparing the spectrum peak values in the PLVM range when an impact load is applied at one undamaged member. One undamaged member is identified first. In case of the belt conveyor support structure, some undamaged members are easily identified by visual inspection. One of these undamaged member is hit by a Hammer equipped with a load cell while the response of an identical design secondary member is measured by LDV. This measurement is repeated for all of the identically designed secondary members while the Hammer hit location is unchanged. The response signals are normalized by the input force. Then the frequency spectrum amplitudes of all the identical design members are compared to identify the PLVM frequency range. In the identified range, the spectrum amplitudes are compared with each other to identify the damaged members and their severity.

6.2 Application to a numerical model

The proposed method is numerically examined using the same model (see Fig. 9). There are 24 identical bottom and top braces in the main frame and damage is introduced at five members. Brace 1is hit and the velocity time histories of all 24 identical bottom and top braces are obtained. The maximum Fourier amplitudes of the velocity responses in their PLVM range are shown in Fig. 12. The maximum amplitudes for damaged members, 2, 8,9,13, and 22, are much smaller than those of the other members. Moreover, severer damages results in smaller amplitudes. By comparing the value of maximum amplitude of Fourier spectrum in the PLVM range, the damage degree is estimated. The damaged members are ordered from the member with the smallest amplitude as 22, 13, 9, 8 and 2 in Table 2. This order is consistent with the damage degree (see Table 1).

The observation noise is not considered in this analysis either because the signal to noise ratio can be improved by adjusting the impact force. The coupling of closely spaced modes is considered the main source of the estimation error.

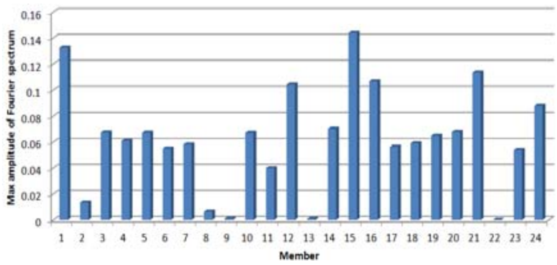


Fig. 12 Maximum Fourier spectrum amplitude of the 24 bottom and top braces in their PLVM range when brace No 1 is hit

Table 2 Maximum amplitude of damaged members in PLVM range

Member	Damage degree	Max amp. in PLVM
2	5%	0.01338
8	10%	0.006375
9	20%	0.001191
13	35%	0.000918
22	75%	0.000201

7. Local mode property changes of a laboratory truss structure

The proposed damage identification techniques are applied to a laboratory truss model and the identification performances are examined. The scale model is 5-bay truss frame shown in Fig. 13. The model is 2 m tall from its base plate and the dimension of each bay is 41×41×40 cm. The four vertical continuous main members are made of 1.5 cm steel solid rods. The model has diagonal and lateral secondary members made of aluminum pipes. Their external and internal diameters are 1.0 cm and 0.8 cm, respectively. The vertical member go through the connection element while the other members are connected to the elements via thinner threaded rods and nuts (see Fig. 13).

To simulate damage, several secondary members are replaced with rods with various diameters. Also some secondary members are partially cut. Locations of simulated damage members are shown in Fig. 14(a). The detail of damage members are provided in Table 3.

7.1 The frequencies of local vibration modes

In order to localize and quantify the damage using frequencies of PLVM and ILVM of the secondary members, each member is directly hit and its velocity time history is measured by Laser Doppler Vibrometer (LDV) (see Fig. 13). The sampling frequency is 10,000 Hz. In order to compare the local vibration modes with the vibration of a simply supported beam, the truss is also disassembled and each member is separately installed on the two connection elements which are fixed to the base plate (see Fig. 14(b)).

As for the undamaged diagonal and lateral members, there are PLVMs, in which only undamaged members vibrate. The power spectrum of some undamaged diagonal members are shown in Fig. 15. The PLVM ranges of diagonal members are 104-114Hz. All undamaged members, including those not shown, strongly vibrate in the PLVM range.

The ILVM frequencies of the damaged diagonal member, member 13, is shown in Fig. 16. The damage members do not vibrate in PLVM range. The ILVM frequency peak below the PLVM ranges is clearly observable. Then the model is disassembled so that each secondary member is measured separately. The frequency peak of the local vibration mode and that of the separate simple beam are close with each other (see Fig. 16). The 1st PLVM and ILVM of the secondary members and the 1stnatural frequencies of the corresponding simple beams are summarized in Table 3. The frequencies of the local modes are nearly the same as the natural frequencies of the corresponding simple beams.

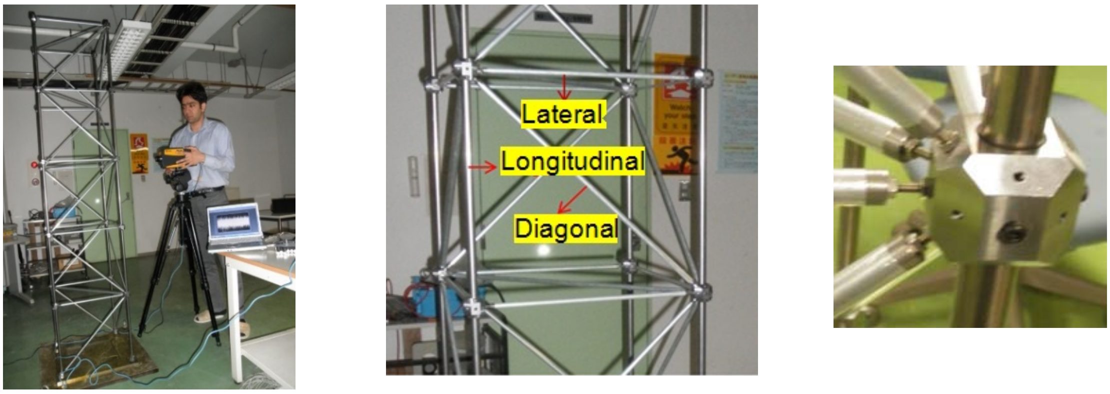
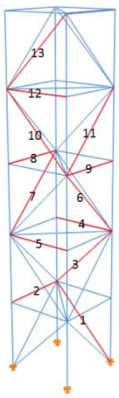


Fig. 13 Laboratory truss structure



(a)

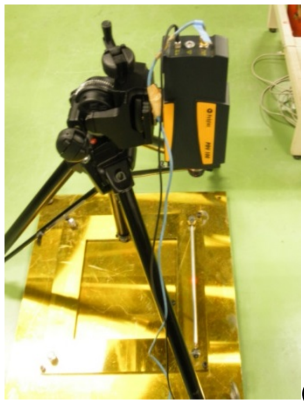

(b)

Fig. 14 (a) Location of the damaged members and (b)Measurement of each member with LDV

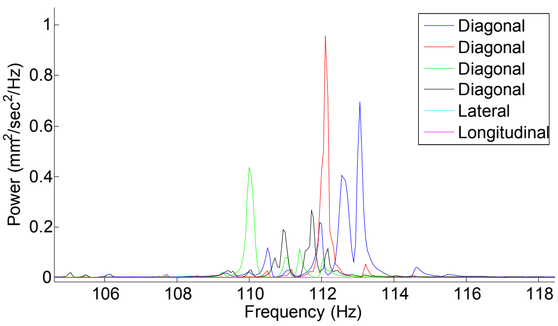


Fig. 15 PLVM range (undamaged diagonal members)

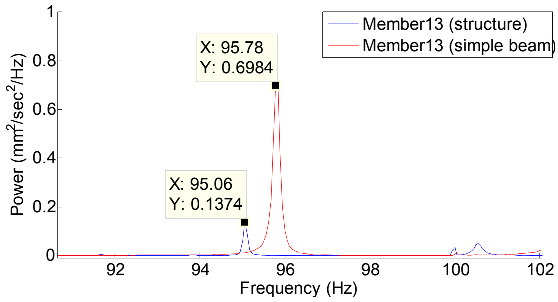


Fig. 16 Power spectrums of member 13 in the structure and the member fixed on the base plate

Table 3 Frequencies of ILVM and PLVM of secondary members and their corresponding simple beams

Member No.	Cross section	Type	Freq (Hz) Structure	Freq (Hz) Simple Beam	Member No.	Cross section	Type	Freq (Hz) Structure	Freq (Hz) Simple Beam
1	Φ13×1	ILVM	132.2	130.8	9	Φ10×1 (1/3 cut)	ILVM	201	198.6
2	Φ12×1	ILVM	230.82	233.6	10	Φ10×1 (1/2 cut)	ILVM	92.22	93.44
3	Φ11×1	ILVM	115.5	114.1	11	Φ9.5×1	ILVM	109.3	107.7
4	Φ10×1 (1/2 cut)	ILVM	186.2	188.1	12	Φ13×1	ILVM	245.2	247.6
5	Φ12×1	ILVM	228.4	233.6	13	Φ8×1	ILVM	95.06	95.83
6	Φ13×1	ILVM	127.4	126	Undamaged Diagonal elements	Φ10	PLVM	104~114	112.1
7	Φ10×1 (2/3 cut)	ILVM	89.61	90.06	Undamaged Lateral elements	Φ10	PLVM	204~213	207.6
8	Φ8×1	ILVM	167	167.1					

7.2 The amplitude of local modes in the PLVM range

The amplitudes of local modes in the PLVM frequency ranges are examined using the scale model. The damaged structure considered here is same as that in Fig. 14(a). The maximum power spectrum amplitudes of diagonal members in the PLVM frequency range (i.e., 104 to 114 Hz) are summarized in Fig. 17 when one of the undamaged diagonal members is hit. The damaged members generally have smaller amplitudes than intact members. The exception is member 11 (Φ9.5×1). Because the damage severity is small, its frequency of ILVM remains in the PLVM frequency range. The local mode amplitudes of member 11 in the PLVM frequency range is therefore large.

Fig. 18 shows the maximum power spectrum amplitude for lateral members in PLVM range when one of the undamaged lateral members is hit. The maximum amplitude of the damaged lateral members in PLVM range is smaller than intact lateral members. The exception is member 9. Because the damage severity is small, its frequency of ILVM is close to the PLVM range. Thus, damaged lateral members are identified by comparing amplitudes except for small damage. Note that the input force was not measured through this analysis due to limitation in experimental setup. Measurment of the input force and normalization of the output data are expected to result in better identification.

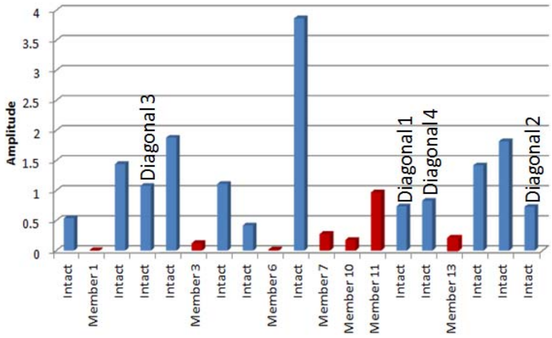


Fig. 17 Maximum power spectrum amplitude of the diagonal members in PLVM range

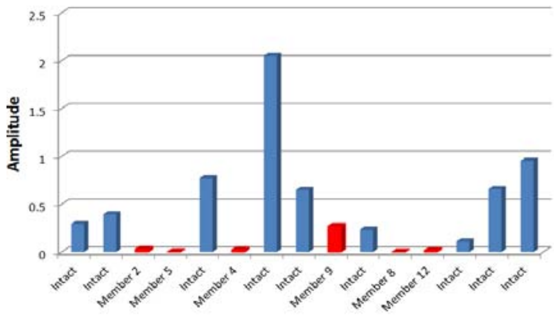


Fig. 18 Maximum power spectrum amplitude of the lateral members in PLVM range

8. Damage identification of a real belt conveyor

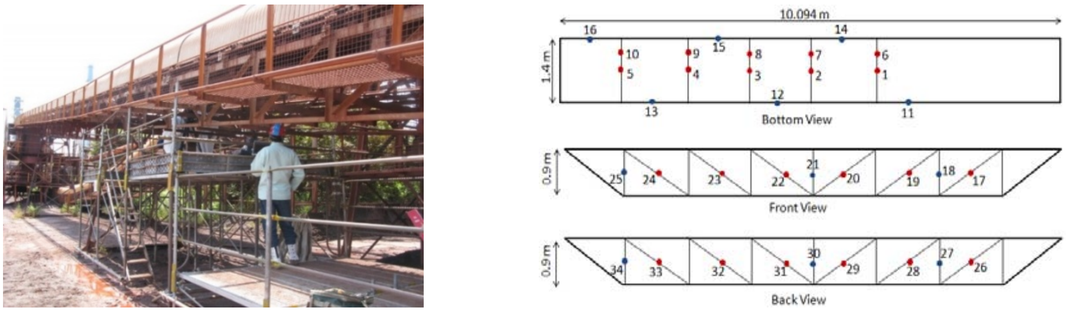
8.1 Damage identification by comparing the frequencies of local vibration modes

Damage identification is performed on a real belt conveyor shown in Figs. 19(a) and 19(b). This structure contains a support structure of the belt conveyor, walkways, machinery parts and some non-structural segments protecting the machinery parts. The length is 10 m. All members are of L50×50×6 made of SS400. Lateral members are 1.3 m long while side braces are 1.06 m long.

To identify PLVM and ILVM among various local vibration modes, the velocity time histories of points shown in Fig. 19(b) are obtained by LDV while each member is directly hit. The sampling frequency is 10,000 Hz. Note that the lateral members are measured along the vertical direction while longitudinal members, side braces and vertical members are measured along the horizontal direction.

The identification results of lateral members are discussed herein. The members 1 to 5 indicated by the sensor location number in Fig. 19(b) are assessed. The power spectrums of the lateral members together with other members are shown in Fig. 20. Each member is directly hit during the measurement. There is a range in which only members 3 and 4 strongly vibrate. This range corresponds to the 1^{st}PLVM of the undamaged lateral members. Moreover there are three peaks corresponding to the1stILVM of member 1, 2 and 5. These members are considered damaged. Also, the severity of the damage, in terms of the frequency change, is in the order of member 2, 1 and 5. This severity is consistent with visual inspection results. Member 2, shown in Fig. 21, clearly has the severest corrosion.

Note that higher order PLVM and ILVM are also observed (see Fig. 22). The measurement are performed at the quarter point of the lateral members (see Fig. 19(b)). The frequency ranges of PLVMs of lateral members and the ILVM frequencies of the damaged members are shown in Tables4 and 5, respectively.



(a) (b)

Fig. 19 (a) A real belt conveyor and (b)Measurement points of the belt conveyor

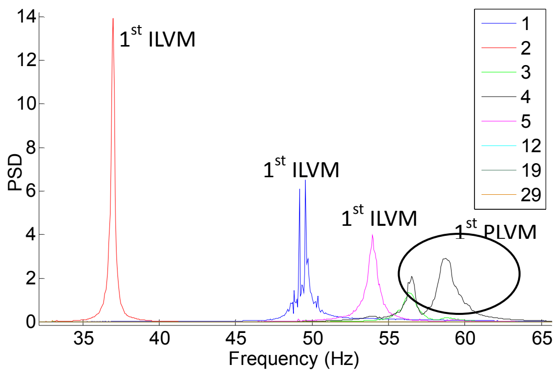


Fig. 20 Power spectrums of the lateral members together with some other members

Fig. 21 A corroded part of member 2

Then, the absolute severity of the damage is evaluated assuming the connections are undamaged as in section 5.1. First, the frequencies of PLVM for the two undamaged members are utilized to evaluate the stiffness of springs at the ends of the undamaged members. The rotational springs are identified by model updating. Table 6shows the estimated values of the springs at the ends of the lateral members. The natural frequencies and mode shapes of a beam with the same springs at two ends are shown in Fig. 23. The natural frequencies are close to those of PLVMs, which indicates the similarity of PLVM to vibration of an independent beam.

Then, the stiffness reduction, i.e., reduction of *EI*, of the damaged members is estimated. The estimated stiffness reduction values are summarized in Table 7. The natural frequencies of the simple beam with the identified stiffness reduction and the rotational spring at the ends are also shown in Table 7. The frequencies are close to the observed ILVM frequencies in Table 5. Note that the assumption of uniform damage is not necessarily satisfied. This assumption is considered a source of damage identification errors.

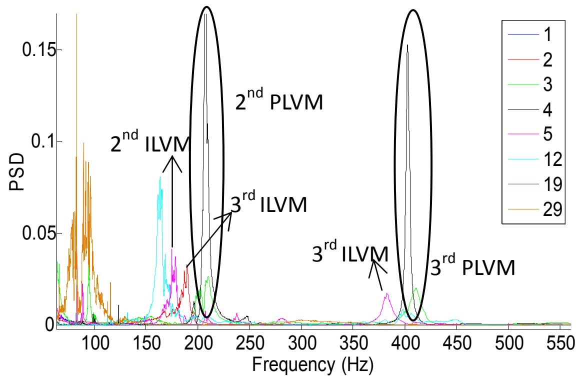


Fig. 22 Some higher PLVM and ILVM of the lateral members

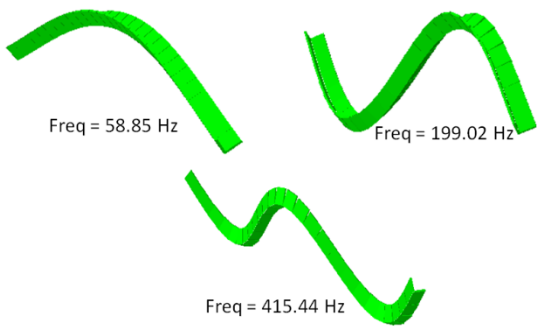


Fig. 23 Corresponding modes of the beam with the estimated spring values

Table 4PLVM frequency ranges of lateral members (Hz)

Member	**1st PLVM**	**2nd PLVM**	**3rd PLVM**	**Condition**
3 , 4	56.33 - 58.94	199.2 – 207.4	402.4 – 411.4	Undamaged

Table 5 ILVM frequencies of the damaged lateral members (Hz)

Member	1st ILVM	2nd ILVM	3rd ILVM	Condition
1	49.37	154.3	353.5	Damaged
2	37	116.1	188.3	Damaged
5	53.94	176.7	381.7	Damaged

Table 6 Estimated values of the stiffness of springs at the ends of the lateral members

Spring	Direction	Value of stiffness
Rotational	Transversal	$15000\ N.m/rad$
Rotational	Vertical	$15000\ N.m/rad$

Table 7 Stiffness reduction of damaged members and calculated natural frequencies

Member	Stiffness reduction (%)	1st Freq. (Hz)	2nd Freq.(Hz)	3rd Freq.(Hz)
1	42%	49.37	157.76	324.48
2	77%	37.12	108.98	209.67
5	23%	53.99	177.75	369.44

8.2 Damage identification by comparing the amplitudes of local modes in the PLVM range

The relative severity of the damage on the support structure is determined by comparing the maximum amplitude of frequency spectrum of identical design members in the PLVM range. This method does not require hitting each identical design members and thus, is more practical.

The velocity response of each member is measured by LDV while member 4, which was identified as undamaged in the previous section, is hit. A hammer equipped with a load cell (model PCB 086C03) is used to measure the input force.

The Fourier spectrums of normalized velocity responses of lateral members are shown in Fig. 24. The maximum amplitudes of Fourier spectrums of members 3 and 4 are much larger than the other members. The maximum amplitudes of Fourier spectrum of the lateral members are summarized in Fig. 25. The damaged members, 1, 2, and 5 have much smaller Fourier spectrum amplitudes. Moreover, the severer the damage is, the smaller the amplitude is. The damage identification capability is thus experimentally confirmed on the real belt conveyor support structure.

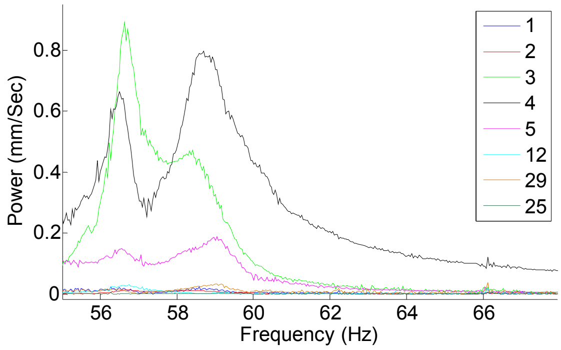


Fig. 24 Fourier spectrums in PLVM range of the lateral members

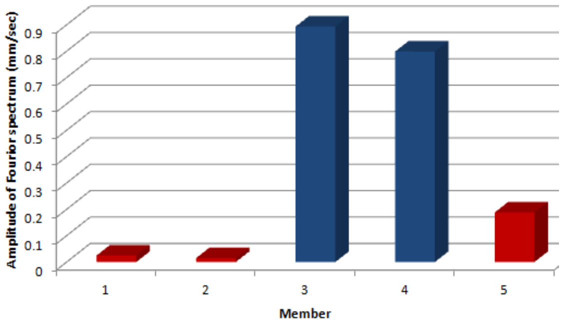


Fig. 25 Maximum amplitude of Fourier spectrum of the lateral members intheir PLVM range

9. Conclusions

Damage localization and quantification methods based on two specific local vibration modes, i.e., PLVM and ILVM, are proposed for the structural assessment of belt conveyor support structures and examined numerically and experimentally. Both methods can deal with a large number of damages on a single structure and do not require the baseline measurement records of undamaged structure. The first method utilizes the frequency change of the local vibration modes. The numerical and experimental studies show that the frequency of PLVM significantly change due to damage. The degree of damage is shown to be quantified accurately. The limitation in practice is that direct Hammer hit of each member is required to excite the local vibrations. The second method utilizes the amplitude comparison of PLVM. By hitting only one of undamaged members and measuring vibration of identical design members, damaged members are localized. Though the degree of damage cannot be quantified, the relative severity among identical design members are evaluated.

The applicability of these methods is limited to secondary members because the PLVM and ILVM exist only on these members. The extension of this approach to the main frame members is important from a perspective of belt conveyors structural assessment.

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