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Inclinometer-based method to monitor displacement of high-rise buildings

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Abstract. Horizontal displacement of high-rise building is an essential index for assessing the structural performance and safety. In this paper, a novel inclinometer-based method is proposed to address this issue and an algorithm based on three spline interpolation principle is presented to estimate the horizontal displacement of high-rise buildings. In this method, the whole structure is divided into different elements by different measured points. The story drift angle curve of each element is modeled as a three spline curve. The horizontal displacement can be estimated after integration of the story drift angle curve. A numerical example is designed to verify the proposed method and the result shows this method can effectively estimate the horizontal displacement with high accuracy. After that, this method is applied to a practical slender structure - Shanghai Tower. Nature frequencies identification and deformation monitoring are conducted from the signal of inclinometers. It is concluded that inclinometer-based technology can not only be used for spectrum analysis and modal identification, but also for monitoring deformation of the whole structure. This inclinometer-based technology provides a novel method for future structural health monitoring.

Keywords: structural health monitoring; inclinometer-based technique; three spline interpolation principle; story drift angle; horizontal displacement

1. Introduction

In the recent decade, large-scale structures such as high-rise buildings and long-span bridges have been developing at a faster rate than ever before. These structures pursue fantastic architecture style and they are becoming slender and more irregular. However, more and more engineers are concerned about the safe operation and maintenance of these structures during their service life (Li *et al*. 2017, Su *et al*. 2017, Zhang *et al*. 2016c). Many structures (Chowdhur *et al*. 2015, Abdelrazaq *et al*. 2012, Ni *et al*. 2009, Ni *et al*. 2017, Zhang *et al*. 2016a) have been equipped with various sensors during their construction and service stages to monitor the structural performance and alert its safety. The real-life data collected can be used for modal identification, model updating and damage detection (Lam *et al* 2015a, Lam *et al* 2015b, Zhang *et al* 2016b, Zhang *et al* 2017a, Ni and Zhang 2018).

For high-rise buildings, its serviceability against horizontal loads such as wind loads is a key

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issue. Horizontal displacement and acceleration are two important types of structural responses to be evaluated (Xie and Gu 2009, Quan *et al*. 2005), especially the horizontal displacement. If the horizontal displacement of a structure is too large, it would cause the structure to be unsafe. Therefore, a great deal of research has been conducted to investigate the technical feasibility of measuring and controlling the horizontal displacement of high-rise buildings (Yi *et al*. 2013, Breuer *et al*. 2002).

There are several techniques for monitoring structural displacement, including accelerometers, Global Positioning Systems (GPS), vision-based systems and inclinometers. Accelerometers are widely used instrument for measuring structural displacements (Moschas and Stiros 2011, Hong *et al.* 2008). When the signal of acceleration is recorded, the displacement can be calculated after doubled integration. Since the measured signal is usually contaminated by noise, it is difficult to obtain the accurate static and quasi-static displacements. In contrast, the GPS technology can measure directly both static and dynamic responses, and the accuracy of dynamic displacement measurement can reach at a sub-centimeter to millimeter level (Yi *et al*. 2013). However, high-accuracy and high sampling rate GPS-based tracking is usually much expensive. The vision-based technique has been successfully used to measure the displacement of a flexible steel column (Park *et al*. 2010) and two bridges (Feng *et al*. 2015). However, the problems such as off-line processing for sophisticated signal processing (Wahbeh *et al.* 2003) are still remained to be resolved.

Inclinometers generally provide a measurement of slope or tilt, which can be converted to a lateral displacement. There were widely used to monitor the landslide and debris flow in geotechnical area (Calcaterra *et al*. 2012, Pei *et al*. 2011). Pei et al developed a new type of FBG-based in-place inclinometers and applied it in one vertical borehole in a slope after the laboratory calibration (Pei *et al*. 2012). Simeoni described the inclinometers monitoring system installed at the landslide of Castelrotto northern Italy and suggested how in-place inclinometers were combined with periodical measurements to evaluate the current movement of a landslide and assess the reliability of data (Simeoni *et al.* 2007). Recent years some researchers tried to introduce inclinometers to monitor the high-rise buildings. Guo proposed a rectangle method, which was validated using experiment data from shaking table test of a super tall building (Guo 2011). Xiong et al. proposed a novel subregional least square method and applied it to a practical structure (Xiong *et al* 2016). The aforementioned methods are all curve fitting models based on the data from inclinometers, and they do not consider the continuous of curvature in different elements. In addition, if the fitting polynomial is high-order, the fitting model may exist Runge phenomenon, which may cause estimation errors. In this paper, a novel three spline interpolation model will be built for the story drift angle curve of objective structure and is used to estimate the horizontal displacement. This method is an interpolation method, which can exactly fit the measured data and improve the accuracy of fitting curve. A numerical model is designed to verify its accuracy and this method is eventually applied to a super tall building to investigate its horizontal displacement. This inclinometer-based technology provides a novel method for future structural health monitoring.

2. Three spline interpolation method for displacement monitoring by using inclinometers

2.1 Displacement function of an element

Inclinometers usually provide a measurement of slope or tilt. Slope is usually regarded as the first-order derivative of displacement, which can be converted to the horizontal displacement.

A brief derivation about displacement calculation from inclinometers is illustrated herein. Fig. 1(a) shows the deformation of structure under lateral loads. Supposed $p(z)$ is a function of lateral loads and O is the fixed end of structure. Taking an infinitesimal analysis, as can be seen in Fig. 1(b), if the deformation of a structure is small

$$d\phi \approx \tan\ (d\phi) \tag{1}$$

$$\frac{dx}{dz} = d\phi \tag{2}$$

where ϕ is the story drift angle; x is the horizontal displacement; z is the height of a building.

After integrating the height of a building from Eq. (2), the displacement of a structure can be calculated as

$$x = \int \phi dz + c \tag{3}$$

where c is an integral constant, which can be calculated by continuous conditions with two sequential elements.

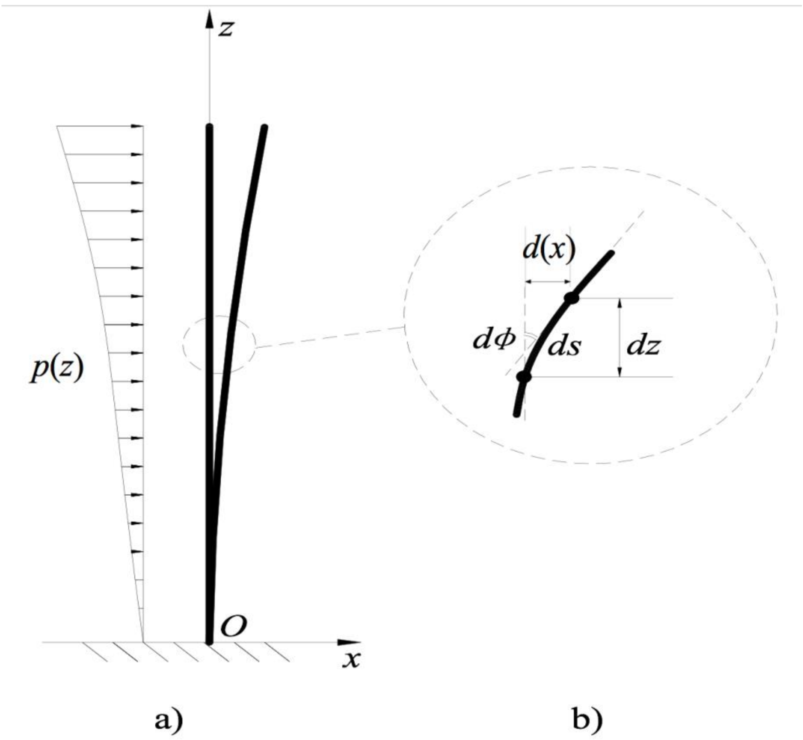


Fig. 1 Sketch of structure deformation under horizontal loads

Therefore, if the whole structural story drift angle is known, the displacement can be calculated with Eq. (3). As the story drift angle varies with building's height increasing, it is necessary to develop a model that can estimate story drift angle function with a few floors instrumented with inclinometers. In the following section a three spline interpolation method is developed to estimate the story drift angle function of the whole structure.

2.2 Algorithm of three spline interpolation

Based on the idea of finite element, a set of measured points are regarded as nodes. It means when there are *n* inclinometers installed on a structure, the structure can be discretized into *n* elements. For the *n* elements, a three spline interpolation method (TSIM) is introduced to fit these known data. The detailed procedure of TSIM is illustrated as follows:

a) Set three spline curve function for each element

Assuming a structure is in elastic state, the story drift angle function of each element is set as

$$S''(z_i) = M_{i-1}\frac{z_i - z}{\nabla z_i} + M_i\frac{z - z_{i-1}}{\nabla z_i}, \quad z \in [z_{i-1}, z_i] \tag{4}$$

where $S''(z_i)$ denotes the second-order derivation of story drift angle; z is a variable representing the height of building; z_i denotes the height of floor installed inclinometers; Subscript i denotes the ith element; $V_{z_i} = z_i - z_{i-1}$; M_i, M_{i-1} are coefficients remained to be solved.

For each element, it usually satisfies continuous conditions with two sequential elements. The continuous condition can be described as

$$\begin{cases} S(z_{i-1}) = \phi(z_{i-1}) \\ S(z_i) = \phi(z_i) \end{cases} \tag{5}$$

where $\emptyset(z_i)$ denotes the known story drift angle measured from inclinometers

After double integration of Eq. (4) and substituting Eq. (5) into Eq. (4), the story drift angle function can be expressed as:

$$\begin{aligned} S(z) = {} & M_{i-1}\frac{(z_i - z)^3}{6\nabla z_i} + M_i\frac{(z - z_{i-1})^3}{6\nabla z_i} + \\ & [\phi(z_{i-1}) - \frac{M_{i-1}\nabla z_i^2}{6}]\frac{z_i - z}{\nabla z_i} + [\phi(z_i) - \frac{M_i \nabla z_i^2}{6}]\frac{z - z_{i-1}}{\nabla z_i} \end{aligned} \tag{6}$$

b) Establish a set of equations

Since each element is continuous at interior points, the first-order derivation of story drift angle function $S'(z)$ can be given by taking the derivation of Eq. (6)

$$S'(z) = -M_{i-1}\frac{(z_i - z)^2}{2V_{z_i}} + M_i\frac{(z - z_{i-1})^2}{2V_{z_i}} + \frac{\phi(z_i) - \phi(z_{i-1})}{V_{z_i}} - \frac{M_i - M_{i-1}}{6}V_{z_i}, z \in [z_{i-1}, z_i] \tag{7}$$

If setting z=z_i, the left derivative $S'(z_{i-0})$ in Eq. (7) can be given by

$$S'(z_{i-0}) = \frac{Vz_i}{3}M_i + \frac{Vz_i}{6}M_{i-1} + \frac{\emptyset(z_i) - \emptyset(z_{i-1})}{V_{z_i}} \tag{8}$$

where $S'(z_{i-0})$ donates the left derivative of $S'(z_i)$.

Similarly, the right derivative of $S'(z_{i+0})$ can be given by

$$S'(z_{i+0}) = -\frac{Vz_i}{3}M_{i-1} - \frac{Vz_i}{6}M_i + \frac{\phi(z_i)-\phi(z_{i-1})}{V_{z_i}} \tag{9}$$

where $S'(z_{i+0})$ donates the right derivative of $S'(z_i)$.

As the first-order derivation of $S'(z_i)$ is continuous, both the left and right derivatives are equal, i.e.

$$S'(z_{i+0}) = S'(z_{i-0}) \tag{10}$$

Combining Eqs. (8)- (10), the equations of story drift angle curve can be expressed as

$$\lambda_i M_{i-1} + 2M_i + \mu_i M_{i+1} = 6\phi[z_{i-1}, z_i, z_{i+1}] \ , \quad (i = 1,2,\cdots,n-1) \tag{11}$$

where

$$\phi[z_{i-1}, z_i, z_{i+1}] = \frac{\phi(z_{i+1}) - \phi(z_i)}{\mathrm{V}z_{i+1}} - \frac{\phi(z_i) - \phi(z_{i-1})}{\mathrm{V}z_i} \tag{12}$$

$$\lambda_i = \frac{\mathrm{V}z_i}{\mathrm{V}z_i + \mathrm{V}z_{i+1}} \tag{13}$$

$$u_i = \frac{\mathrm{V}z_{i+1}}{\mathrm{V}z_i + \mathrm{V}z_{i+1}} \tag{14}$$

Actually Eq. (11) are underdetermined equations. The solutions to underdetermined equations are always not unique. Natural boundary conditions are added as extra constrain equations, which are defined as

$$\begin{cases} S''(z_{0+0}) = M_0 \\ S''(z_{n-0}) = M_n \end{cases} \tag{15}$$

c) Solve the equation coefficient M_i

When substituting Eq. (15) into Eq. (11), the system equations can be rewritten

$$\mathbf{A}x = \mathbf{B} \tag{16}$$

where

$$A = \begin{pmatrix} 2 & \mu_1 & & & \\ \lambda_2 & 2 & \mu_2 & & \\ & \lambda_3 & 2 & \ddots & \\ & & \ddots & \ddots & \mu_{n-2} \\ & & & \lambda_{n-1} & 2 \end{pmatrix}, \quad x = \begin{pmatrix} M_1 \\ M_2 \\ M_3 \\ \vdots \\ M_{n-1} \end{pmatrix}, \quad B = \begin{pmatrix} 6f[z_0, z_1, z_2] - \lambda_1 M_0 \\ 6f[z_1, z_2, z_3] \\ 6f[z_2, z_3, z_4] \\ \vdots \\ 6f[z_{n-2}, z_{n-1}, z_n] - \mu_{n-1} M_n \end{pmatrix} \tag{17}$$

It can be found that the coefficient matrix **A** in Eq. (16) is diagonally dominant strictly, which means that the coefficient matrix **A** is nonsingular. Therefore, Eq. (16) has unique solution vectors and the story drift angles function for each element can be obtained. Then the horizontal displacement of a structure can be calculated with Eq. (3). The procedure of TSIM is shown in Fig. 2.

Generally, TSIM can exactly match the measured points as the continuous condition is taken into account. This can effectively improve the accuracy of fitting curve. In addition, TSIM is a piecewise interpolation method, which can avoid the Runge phenomenon in the high-order interpolation polynomial. Based on the condition that the left and right derivations are equal, it also ensure continuity of the first and second derivations at the end of interpolation interval, which further keeps the story drift angles curve continuous.

3. Numerical verification

To evaluate the proposed method, a simulated high-rise building is designed. In this example, the wind response of a prototype structure is simulated using the commercial software ETABS. When the structure is applied to wind loads, the story drift angle curve and horizontal displacement curve can be simulated, which are regarded as true values later. The story drift angle of some floors instrumented with inclinometers are considered as measured data, in which the proposed TSIM framework is employed to calculate the story drift angle curve. The performance of the proposed framework and the effect of sensor placement are also evaluated and discussed.

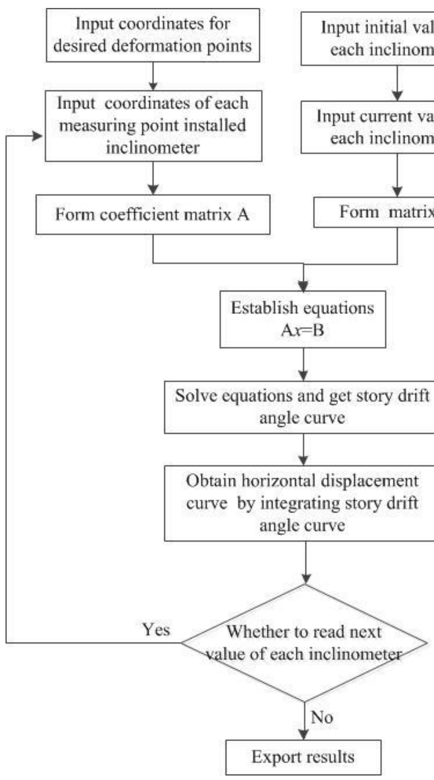


Fig. 2 Flowchart of three spline interpolation method

3.1 Finite element model

Shanghai Tower is a 632 meters super high-rise building with a total of 124 layers, as can be seen in Fig. 3. It adopts a mega-frame core-wall structural system, which comprises a core wall inner tube, an outer mega-frame, and a total of six levels of outriggers between the tube and the frame (Su *et al*. 2013). Along its height the structure is divided into nine zones by eight independent strengthened floors.

The three-dimensional finite element model (FEM) of this super tall building was built using (ETABS software), as shown in Fig. 4. A mega column is simplified as composite elements of shell and beam based on the principle of equivalent stiffness. The outrigger trusses adopt beam elements and floors adopt shell-thick elements. The components of beams and braces are simulated as line elements. The rigid-floor assumption is adopted. The entire model has 64321 node elements, 35731 frame elements and 25846 shell elements, including 36 section types and 21 materials' properties.

Fig. 3 View of Shanghai Tower

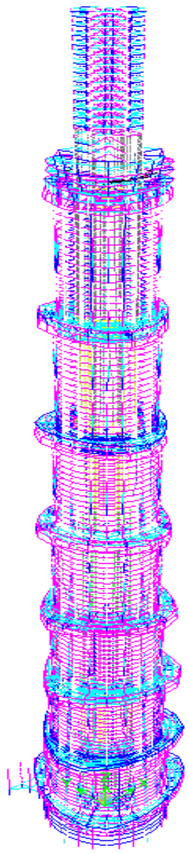


Fig. 4 FEM established by ETABS

3.2 Scheme of inclinometers sensor placement

According to the mechanic properties of strengthened layers, the following sensors placement scheme is adopted: 1) An inclinometer is for each strengthened layer. 2) Two inclinometers are installed between two strengthened layers. 3) In each floor inclinometers are set at the same place of core tube. The vertical arrangement of inclinometers is shown in Fig. 5. To make it more clear, different letters are given a statement: “F” donates floor, for example “F124” represents there is an inclinometer installed at the 124th floor; “b” represents the serial number of sensors installed on the floors. Red line represents strengthened floors.

3.3 Evaluate the accuracy of TSIM

The structural response of story drift angle and horizontal displacement can be simulated from FEM. Figs. 6 and 7 show the story drift angle curve and the horizontal displacement curve of the structure under wind load, respectively. It can be found that there are some cusps among story drift angle curves. Since there are eight strengthened floors in the structure, the structural stiffness along its vertical direction is irregular. From the mathematical viewpoint, if inclinometers are placed at strengthened floors, it can effectively reduce the difference between the true story drift angle curve and the estimated one.

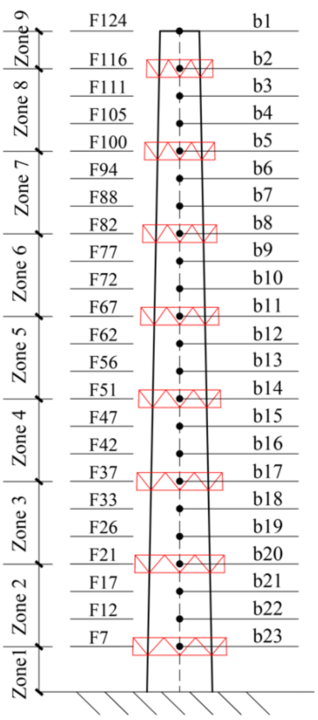
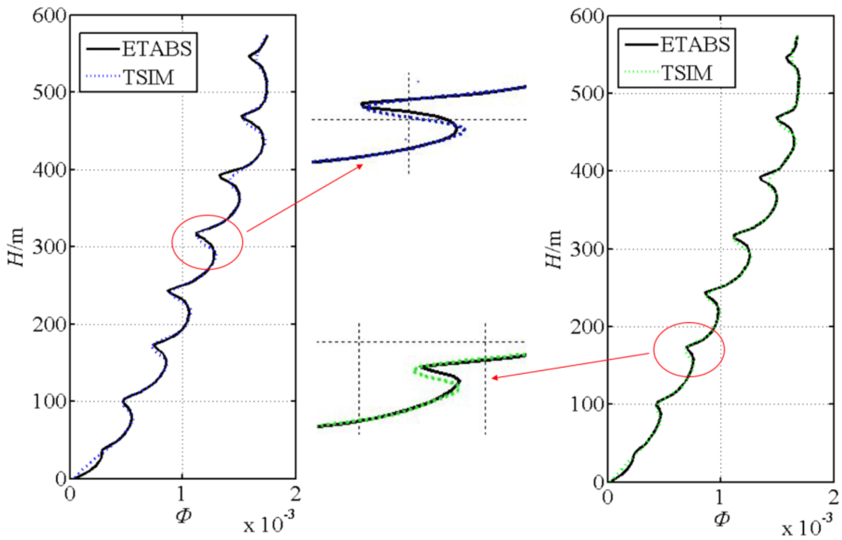
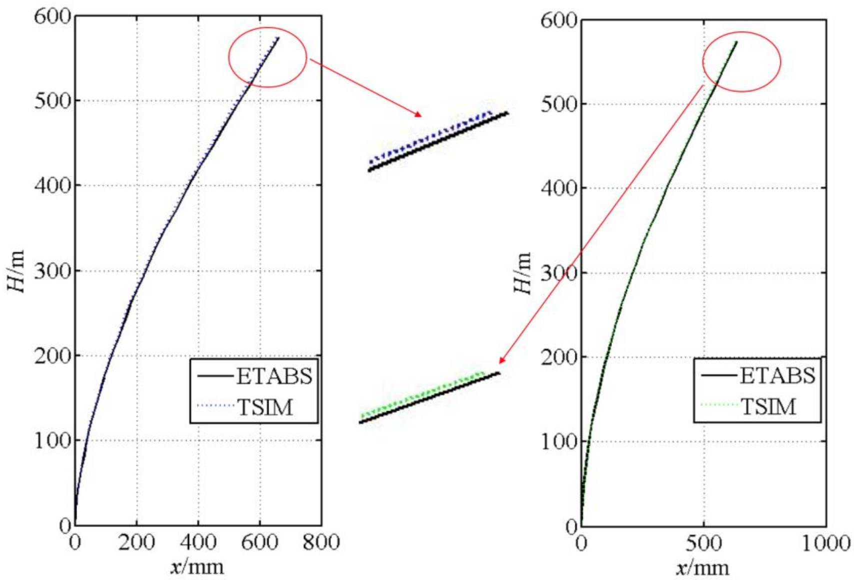


Fig. 5 Sketch of inclinometers placement



(a) X direction (b) Y direction

Fig. 6 Comparison of story drift angle curve from ETABS and TSIM



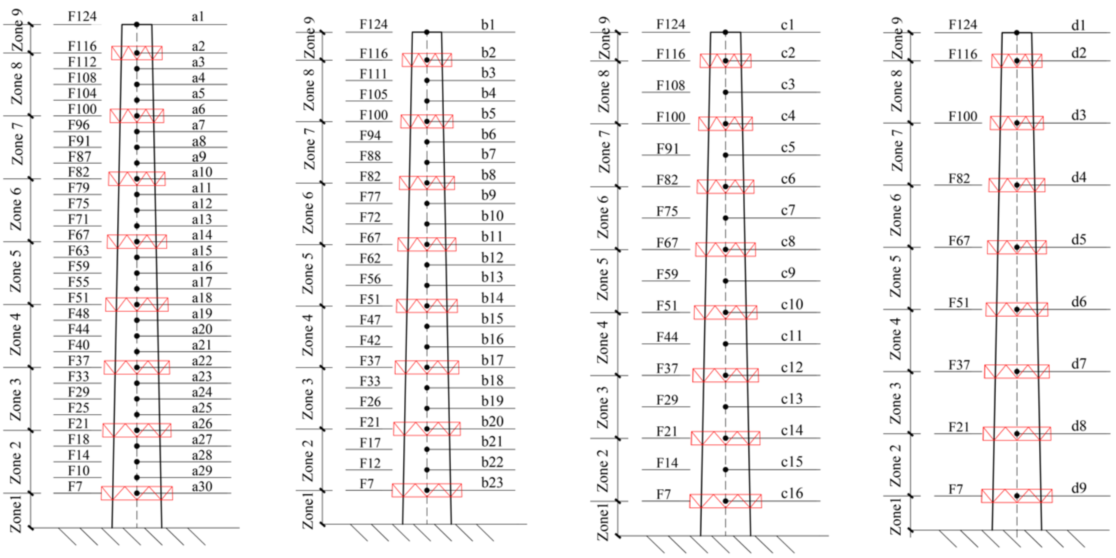
(a) X direction (b) Y direction

Fig. 7 Comparison of horizontal displacement curve from ETABS and TSIM

In this stage, the story drift angle of floors instrumented with inclinometers are regarded as measured data. The story drift angle curve and horizontal displacement curve can be estimated by the proposed method. They are also shown in Figs. 6 and 7, respectively denoted by dotted line. From these figures, it can be found the estimated curve can match the true curve well. To evaluate the accuracy of TSIM, the modal assurance criterion (MAC) (Pastor *et al*. 2012) is employed here. The MAC values of the story drift angle curve are 0.9991 and 0.9994 for X direction and Y direction, respectively. While the MAC values of the horizontal displacement curve are 0.9999 and 0.9999 for X direction and Y direction, respectively. It is seen that the MAC values are all closed to 1, indicating that the estimating values are almost the same with the true ones.

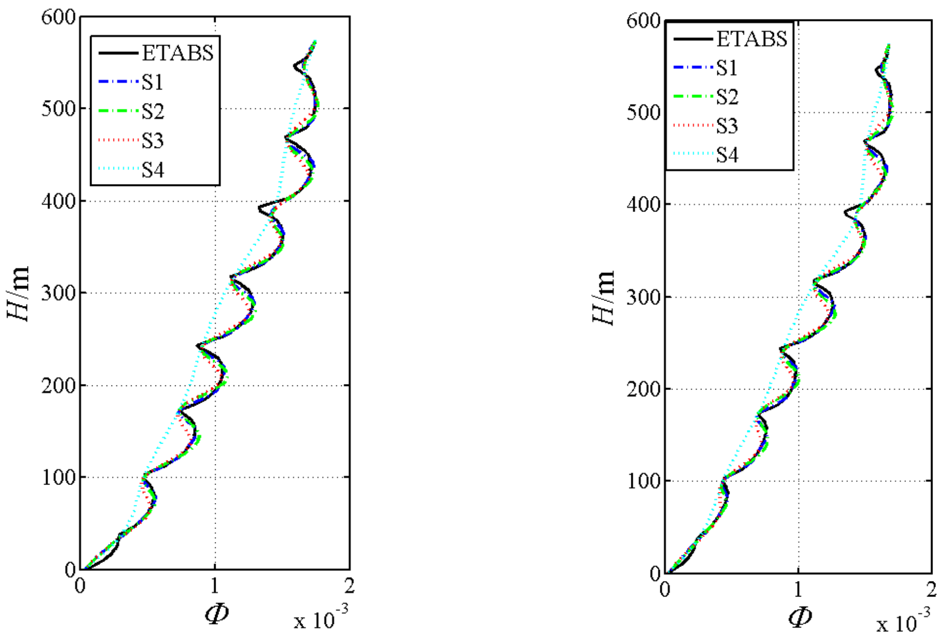
3.4 Effect of sensor placement

Sensor placement plays an important role in the structure health monitoring (Li 2016, Zhang *et al*. 2017b). Generally, the more locations of sensors placed on a structure, the more detailed information on the structure can be obtained. Practically, high cost of data acquisition systems, sensors and accessibility limitations constrain the wide distribution of a large number of sensors on a structure. Here, another three schemes were put forward to compare the accuracy influenced by the amount and placement of sensors, as shown in Fig. 8. For these four schemes, in each strengthened layer, one inclinometer was installed. Between two strengthened layers, three, two, one and zero inclinometers were set respectively. In other words, the difference of four schemes is the number of inclinometers between two strengthened layers.



(a) S1 (b) S2 (c) S3 (d) S4

Fig. 8 Different schemes of inclinometers placement



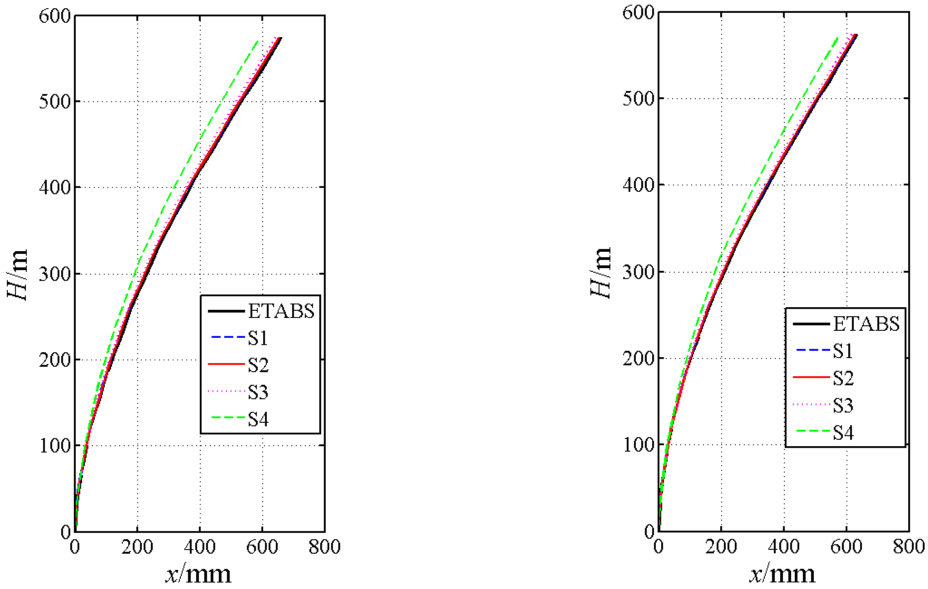
(a) X direction (b) Y direction

Fig. 9 Comparison of story drift angle curves with different schemes

Table 1 MAC values between the estimated curves and true curves

Schemes	Story drift angle curve		Horizontal displacement curve	
	MAC in the X direction	MAC in the Y direction	MAC in the X direction	MAC in the Y direction
S1	0.9995	0.9997	0.9999	0.9999
S2	0.9991	0.9994	0.9999	0.9999
S3	0.9988	0.9991	0.9998	0.9999
S4	0.9932	0.9951	0.9992	0.9994

Figs. 9 and 10 show the comparison of story drift angle curve and horizontal displacement curve from ETABS and TSIM, respectively. Table 1 summarized the MAC values of the story drift angle curve and horizontal displacement curve. It is seen that the MAC values of S1, S2 and S3 are very close, which is more accurate than S4. For S1, S2 and S3, although the value of MAC is almost the same, the number of inclinometers reduces from 30 to 16, a reduction of nearly half. Although the estimated curve is smooth continuous and satisfies boundary condition well, it can only demonstrate that the estimated curve is the most fitting curve to the practical one from mathematical view. Therefore, the sensors are usually put at the locations where the engineers are concerned about.



(a) X direction (b) Y direction

Fig. 10 Comparison of horizontal displacement curves with different schemes

4. Application of TSIM in a super tall building

4.1 Description of the structure health monitoring system in Shanghai Tower

A sophisticated SHM system, which consists of more than 400 sensors with 11 different types, was designed for monitoring the performance and safety of the Shanghai Tower (Su *et al*. 2013). Among various kinds of sensors, a series of inclinometers were installed to achieve reliable measurement of static and dynamic displacement. Based on the mechanical characteristics of structure and access to the data acquisition units, each of eight strengthen floors is installed with two inclinometers for each direction, and there are two floors installed with inclinometers between two strengthen floors. The detailed information for layout of inclinometers is illustrated in Fig. 11. There are two uniaxial inclinometers installed for each direction every floor. The sensitivity of the inclinometer is $\pm 0.03\ \mathrm{mm/m}$ and the sampling frequency was set to 100 Hz. As the structure may have torsional deformation under lateral load, inclinometers were installed at the same direction in the core tube. A typical plan layout of inclinometers is shown in Fig. 12. The data recorded from 12:00 to 12:20 on May 14, 2016 were used for analysis.

4.2 Estimated result of structural natural frequency

Natural frequency is an important modal parameter for condition assessment of a structure. It is commonly calculated by FEM or identified by ambient vibration test. However, the data from inclinometers can also be used to identify the parameters. The power density spectrum (PSD) of the signal recorded on the 124th floor is shown in Fig. 13.

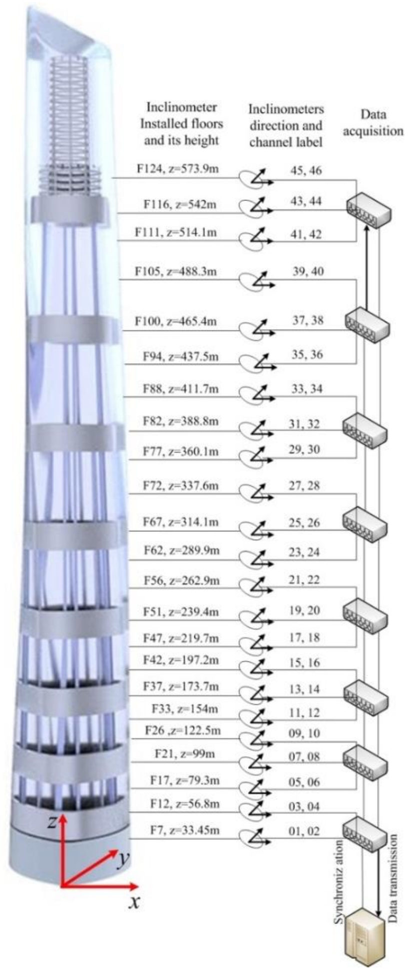


Fig. 11 Vertical layout information of inclinometers

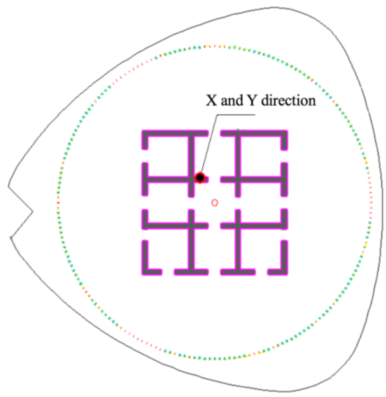
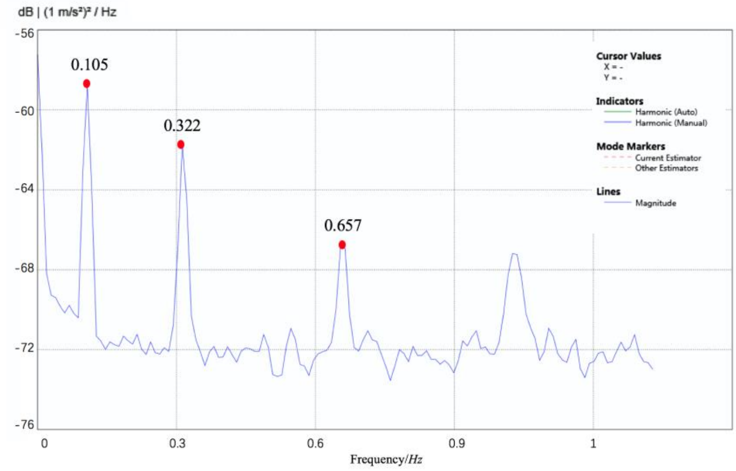
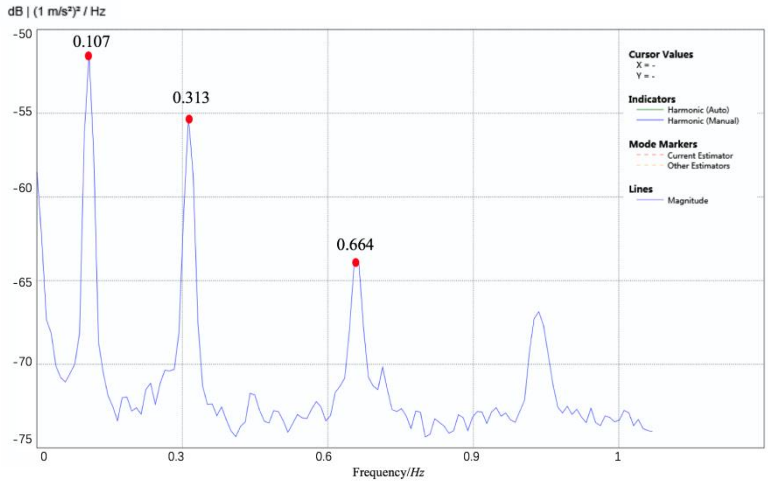


Fig. 12 Plan layout information of inclinometers in the 36th floor



(a) X direction



(b) Y direction

Fig. 13 Power spectral density of the data on the 124th floor

The identified natural frequencies using inclinometers data and velocity data (Zhang *et al.* 2018) are all shown in Table 2. It is seen that the natural frequencies identified using different data coincide well. The results suggest that inclinometer-based technology can also provide accurate estimation for inherent modal parameters of such a large structure.

4.3 Horizontal displacement

Based on the recorded data from inclinometers, TSIM is adopted to estimate the story drift angle curve and horizontal displacement curve. Fig. 14 and Fig. 15 show the maximum story drift angle curve and maximum horizontal displacement curve of the structure within 20 minutes in both X and Y directions respectively. It can be seen that the strengthened floors can effectively constrain the story drift angle, which can further reduce the structural horizontal displacement.

Table 2 Natural frequencies (Hz) identified by inclinometers and accelerometers

Mode	Frequency identified by inclinometer data		Frequency identified by accelerometer data		Relative difference (%)	
	X direction	Y direction	X direction	Y direction	X direction	Y direction
1	0.105	0.107	0.108	0.108	2.78	0.93
2	0.322	0.313	0.326	0.319	1.23	1.88
3	0.657	0.664	0.661	0.675	0.61	1.63

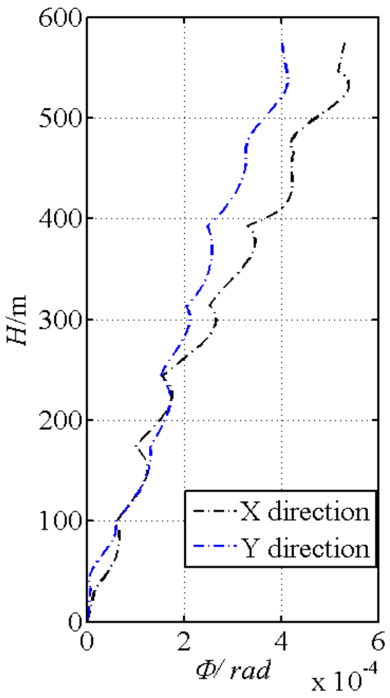


Fig. 14 the maximum story drift angle curve within 20 minutes

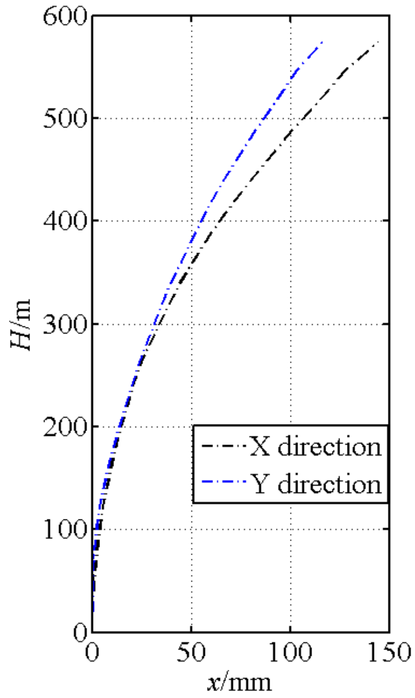


Fig. 15 the maximum horizontal displacement curve within 20 minutes

5. Conclusions

A novel inclinometer-based method is proposed to monitor the horizontal displacement of structure. Conclusions are given as follows:

- Based on the properties of inclinometers, an algorithm of three spline interpolation is presented to estimate the displacement. A numerical simulation is designed to verify its accuracy and the result shows three spline interpolation method has high accuracy.
- The proposed method is applied to monitor a practical structure. Nature frequencies and the deformation of the structure are estimated from the signal of inclinometers. It can be concluded that inclinometer-based technology can not only be used to identify the natural frequency of structures, but also for calculating its deformation.

- In this future work, by combining different types of sensors, such as GPS, a more reliable measurement can be conducted and the results can be verified with each other. The research using inclinometers provides a new method for future structural health monitoring.

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