Cable force estimation of a long-span cable-stayed bridge with microwave interferometric radar

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Abstract
Since cables are the critical structural components for ensuring the overall structural integrity and safety of cable-stayed bridges, the portable and rapid cable force measurement has a very important practical significance in the bridge health monitoring. In this paper, a method of simultaneous and continuous estimation of the forces of multiple cables using a self-developed microwave interferometric radar was proposed. In the proposed approach, first, the time-varying modal frequencies are identified by the Hilbert transform algorithm from the displacements of multiple cables, which are monitored by the self-developed radar, and then, the time-varying cable forces are obtained by the vibration method. In addition, for the problem of multiple cables located in the same range bin when distance test or the test angle is nonideal, a single-channel blind source separation algorithm based on vibrational mode decomposition (VMD) and time-frequency analysis was proposed to separate the cable signals. Furthermore, a method based on the spectrum correlation coefficients was proposed to determine the number of decomposition layers in VMD. The “Nanjing Eye” cable-stayed footbridge was used to conduct field measurement to validate the proposed method. Field measurement results show a good agreement with reference measurements, which demonstrate that the proposed method can perform well in an actual project for portable and rapid cable force estimation.

1 | INTRODUCTION
With a large spanning capacity and beautiful shape, the cable-stayed bridge has occupied a dominant position in the construction of the long-span bridges. Since cables are one of the most critical structural components for ensuring the overall structural integrity and safety of cable-stayed bridges, accurate estimation of the cable force is of great importance for both the internal force distribution and the structural safety of the overall bridge structure (Ni, Zhang, & Chen, 2019; Ni, Zhang, & Noori, 2019; Sun, Nagayama, Nishio, & Fujino, 2018; Svensson, 2013; Yoon, Shin, & Spencer, 2018). In particular, the portable and rapid cable force measurement plays an extremely vital role in the evaluation of initial damage and the formulation of recovery plans for ensuring the security of the bridge. Currently, many scholars have conducted a fair amount of work on the method for the estimation of cable force (Cho et al., 2013; H. Li, Zhang, & Jin, 2014; Wu, Chen, Jhou, & Lai, 2018). The vibration method, which is a method for indirectly estimating the cable force by monitoring some relevant parameters of the cable, is widely used for the estimation of cable force because it is simple, fast, economical, and reliable (Fu, Ji, Wang, & Wang, 2017; Zarbaf et al., 2018).
Researches on the cable force measurement using the vibration method can be broadly divided into two aspects: the calculation theory and the monitoring technology. The calculation theory of cable force measurement is gradually developed from the initial simple static analysis to the dynamic analysis, from the initial linear theory analysis to the complex nonlinear analysis, and the simple tension string theory is gradually developed to consider the relevant parameters, such as the flexure stiffness, sag, and boundary constraints (Giaccu & Caracoglia, 2012; Ma, 2017; Yan, Chen, Yu, & Jiang, 2019). The monitoring technology is mainly divided into the contact-type method and the noncontact-type method. The former requires physical installation of the sensor on the cable surface to collect the vibration signals of the cable, such as strain (Y. Kim, Sung, Kim, & Kim, 2011; H. Li, Ou, & Zhou, 2009), accelerometers (Moschas & Stiros, 2015; Yang, Li, Nagarajaiah, Li, & Zhou, 2016), ferromagnetic magnetoelectricity (Wang & Yim, 2010), and so on. The above-mentioned contact-type methods are effective and reliable; however, the installation is generally uneasy, time-consuming, and might subject the test crew to hazardous conditions if the bridge is in service. Furthermore, the big drawback is that only cables that are considered important in part or that are placed on the side have been measured. Therefore, the noncontact-type methods have been developed and applied for the measurement of cable vibrations, such as laser Doppler technology, global positioning system (GPS), vision-based method, and microwave remote sensing. Laser Doppler technology has relatively high precision, but it needs to arrange as many sensors as the cables, resulting in low cost performance and difficult application (Nassif, Gindy, & Davis, 2005). Similarly, due to signal error and sampling rate limitations, GPS methods are not universally applicable to estimate the dynamics of stay cables during traffic (Kaloop, 2012). As one of the typical noncontact methods, the vision-based method, which extracts dynamic characteristics of an object from video images through the template matching techniques, has received increasing attention for monitoring the dynamic characteristics of stay cables (Tian, Zhang, Jiang, Zhang, & Duan, 2020). For example, S. Kim, Jeon, Cheung, Kim, and Park (2017) developed a vision-based monitoring system that uses image-processing technology to estimate the cable force during traffic and installed a remotely controlled pan/tilt drive to estimate the force on multiple cables using a single system. Furthermore, based on the robust subpixel orientation code matching algorithm, Feng, Scarangello, Feng, and Ye (2017) used a vision sensor system instead of an accelerometer to monitor the cable force. However, it is worth emphasizing that although the image can effectively monitor the cable force, its accuracy is limited by outdoor field environmental conditions such as illumination variation and background disturbance.

Recent progress in radar techniques and systems have favored the development of a microwave interferometric radar, potentially suitable for the noncontact vibration monitoring of civil engineering structures, such as bridges, high-rise buildings, dams, towers, and so on (Beben, 2011; Liu et al., 2015; Luzi, Crosetto, & Cuevas-Gonzalez, 2014; Zhang et al., 2018). It can estimate the very small displacement (approximately 0.01 mm) along the line of sight (LOS) of the radar in principle along with some advantages such as high precision, possibility of use in almost all weather conditions, and simultaneous measurement of multiple targets. However, to our knowledge, only a few attempts have been made to apply microwave interferometric radar for the estimation of cable force. Furthermore, the researches mainly focus on cables that are considered important in part of the bridge structure (Gentile, 2009, 2010; Salamak, Owerko, & Łaziński, 2016). In actual operational conditions, the radar in the survey of an array of cables is inclined upward. Hence, the only targets encountered along the path of the electromagnetic waves are the cables. It is worth emphasizing that the radar has only one-dimensional (1D) imaging capabilities, that is, different targets can be individually detected only if they are separated in a range. However, if multiple cables are placed at the same range from the radar under a nonideal test condition, they cannot be individually detected, that is, there is a phenomenon where the signals of the range bin are aliased. Therefore, it means that inconvenience is carried to the field test operation, and another drawback is that it is impossible to take advantage of the multitarget simultaneous measurement by the radar.

The problem is how to independently obtain the signals of multiple cables from the observed signal of the range bin. In recent years, many studies on feature extraction, system identification, and blind source separation have been published (Amezquita-Sanchez & Adeli, 2015; Amezquita-Sanchez, Park, & Adeli, 2017; Z. Li, Park, & Adeli, 2017; Perez-Ramirez et al., 2016; Zibulevsky & Pearlmutter, 2001). Furthermore, the emerging blind signal processing, that is, since the source signal and the transmission channel parameters are unknown, the independent components of the source signal are recovered only by the observed signals in noisy environment, is very much suitable for the processing of multitarget signals (Hazra, Sadhu, Roffel, & Narasimhan, 2012; Yao, Yi, Qu, & Li, 2018a, 2018b). In this paper, a method for single-channel blind source separation based on vibrational mode decomposition (VMD) and time-frequency analysis (TFA) was proposed. Furthermore, an improved method based on the spectrum correlation coefficients was proposed to determine the number of decomposition layers in VMD.

The remainder of this paper is organized as follows. In Section 2, first the framework of the proposed method and the self-developed microwave interferometric radar were introduced. Then the single-channel blind source separation algorithm based on VMD and TFA for the range bin signal aliasing problem was introduced. In Section 3, “Nanjing Eye” cable-stayed footbridge was used to verify the accuracy and applicability of the proposed method. Finally, conclusions are drawn.
2 METHODOLOGY

2.1 Framework

As shown in Figure 1, based on the principle of the radar, the radar monitors the displacements of multiple cables by transmitting the microwave to the air with a range resolution of 0.5 m and a launch angle of $10^\circ$, the test cables are distributed in different range bins among the 1D imaging capabilities. It mainly includes two cases, the cables (such as Cable 1) located in different range bins, or multiple cables (such as Cables 4-8) located in the same range bin. For the former, the cable number can be easily locked by comparative analysis. However, for the latter, because the signal that is measured in the same range bin is just a single signal, that is, $s(t) = C^T d_{\text{LOS}}(t)$, where $s(t) \in \mathbb{R}^l$ is the observed single signal; $d_{\text{LOS}}(t) = \{ d_{\text{LOS},1}(t), d_{\text{LOS},2}(t), \ldots, d_{\text{LOS},l}(t) \} \in \mathbb{R}^l$ are the signals of the cables, $l$ is the number of the cables located in the same range bin, and $l = 4$ in Figure 1; $C \in \mathbb{R}^l$ is a coefficient vector, which is unknown. Hence, it is difficult to distinguish the information of different cables directly from the time-frequency domain of the observed signal $s(t)$, which means that it is a signal aliasing phenomenon.

### FIGURE 1
Overview of the range bins of the self-developed microwave interferometric radar and the framework of the proposed method
In order to solve the above problem, a blind source separation algorithm combining VMD and TFA is proposed. The framework of simultaneous estimation of the time-varying cable forces with the self-developed radar is shown in Figure 1. The research can be mainly divided into two parts: the first part includes simultaneously monitoring the displacements of multiple cables using the self-developed microwave interferometric radar. Based on the microwave technology and the interferometry technique, by transmitting and receiving microwaves and performing mixing processing, the beat frequency signal of the radar can be obtained using analog-to-digital (A/D) sampling, in which the displacement information of multiple cables is included. The second part, which is the core of the proposed method, uses a signal blind source separation algorithm based on VMD and TFA. First, VMD is used to decompose the observed single of the range bin, and $K$ intrinsic modal functions (IMFs) are obtained with a method based on the spectrum correlation coefficients. Second, the singular value decomposition (SVD) and Bayesian information criterion (BIC) are used to estimate the number of vibration sources from a virtual multidimensional observation signal combined with the observed signal, $K$ IMFs, and their remainder. Furthermore, according to the number of vibration sources, the IMF components that have a larger relationship with the observed signal are chosen to recombine a new multidimensional observation signal with the source signal and their remainder, and the TFA algorithm is used to realize the blind source separation to obtain the signals of multiple cables. Finally, the time-varying forces of multiple cables are identified by combining the Hilbert transform (HT) algorithm and the vibration method. The specific work is as follows.

### 2.2 The self-developed microwave interferometric radar

As shown in Figure 2a, a linear frequency-modulated continuous-wave radar was developed to measure the displacements of bridge in the authors’ previous work, which is different from the typical commercial and industrially engineered radar system developed by the Italian company IDS (Ingegneria Dei Sistemi, Pisa, Italy), in collaboration with various partners (Gentile & Bernardini, 2010). The weight of the radar unit is 10 kg and it sits on a tripod with a rotating platform. The sensing unit is equipped with a tilting device for three-dimensional rotation. Furthermore, an auxiliary processor unit equipped with a laser rangefinder, a laser pointer, and an electronic compass are mounted on the left side of the sensing unit to help the operators easily find the test targets, making the applications of the radar system more convenient and faster. The sensing unit is controlled via the USB port of the control computer and the power supply unit through a network cable interface and a power cable. Also, the control computer is installed with software for radar system management, which can set the radar parameters, store acquisition signals, process data, and view measurement target information in real time. Besides, it can be operated continuously for 8 hours by supplying power through a 24-V power supply unit. According to the antenna integration technology, the transmitting antenna and the receiving antenna are integrated with 16 single-shot antennas, respectively. Hence, the beam width of each antenna array is $10° \times 10°$. To ensure sufficient transmission and isolation, the transmitting and receiving antennas are directly provided with absorbing materials for isolation, which is a challenging requirement that calls for specific design solutions.

Figure 2b shows a block diagram of the self-developed microwave interferometric radar system, which consists of a transmitter, a receiver, a digital signal processor, an auxiliary processor unit, and a personal computer (PC). In the transmitter, a voltage-controlled oscillator generates a 100-MHz continuous wave to the frequency modulation continuous waveform generator, which is amplified and transmitted by the transmitting (Tx) antenna. The receiving (Rx) antenna captures the reflected wave which is filtered prior to being combined with the original transmitted signal via a quadrature mixer. Then Rx amplifies and down converts the signal from the carrier frequency to the in-phase/quadrature (I/Q) baseband signals. In digital signal processor, the I/Q signals are fed into the A/D converter ports, and sampled signals are processed in the field programmable gate array. Finally, the distances and displacements of the targets are calculated and stored in the PC. The I/Q baseband signals can be expressed as

$$
B_I(t) = \cos \left( \theta(t) + \varphi(t) + \theta_{\text{noise}}(t) \right)
$$

$$
B_Q(t) = \sin \left( \theta(t) + \varphi(t) + \theta_{\text{noise}}(t) \right)
$$

where $\theta$ denotes a constant phase shift due to the transmission path and target surface; $\varphi$ denotes the phase information corresponding to the target’s displacement $s(t)$; $\theta_{\text{noise}}$ denotes the total residual phase noise of the radar. By arctangent demodulation to the above I/Q signals, the accurate phase information $\varphi$ can be obtained. Finally, the relationship between the target’s displacement $s(t)$ and the phase difference $\Delta \varphi$ can be described using the following equation:

$$
s(t) = \frac{c}{4\pi f_{\text{center}}} \Delta \varphi(t)
$$

where $c$ and $f_{\text{center}}$ are the speed of light and the band center frequency of the radar, respectively.

As demonstrated in Figure 2c, a concrete continuous box girder bridge, which had the monitoring system with long-gauge fiber Bragg grating (FBG) sensors, was used for the field test. In this case, the self-developed microwave interferometric radar was placed below the bridge deck (at a distance of 6.5 m from the axis of the pier). Corner reflectors are the test targets that were installed on the center axis of the bridge deck near the long-gauge FBG sensors. The results of the measured displacement are shown in Figure 2d. Compared with the
displacement calculated using the traditional long-gauge strain, the measured displacement time history curve of the self-developed radar is in good agreement. Furthermore, the displacement sensitivity is much better than the long-gauge strain, which verifies the effectiveness of the self-developed radar in bridge microvibration monitoring application.

Based on the HT algorithm, the time-varying frequency of each cable can be obtained from the displacement time history response of the test multiple cables (Bertha & GolINVAL, 2014). According to the relationship between the cable force and its natural frequency, the cable force of each cable can be obtained by using the cable force calculation formula that ignores the cable sag and the bending stiffness, that is, 

\[ F = 4\rho L^2 f_1^2 \]

where \( F \) is the cable force, \( f_1 \) is the first-order natural frequency of the cable, and \( \rho L \) are the mass density and length of the cable, respectively.

2.3 Blind source separation algorithm based on VMD and TFA

2.3.1 Brief description of VMD

VMD is a method for solving variational problems based on the three concepts of classical Wiener filtering, HT, and frequency mixing (Dragomiretskiy & Zosso, 2014). The general idea of this method is to use an iterative solution to solve the optimal solution of the constrained variational model to obtain the IMF of each finite bandwidth. For the observed signal \( s(t) \), VMD can be described as a constraint \( \sum_{k=1}^{K} u_k(t) = s(t) \), seeking for \( K \) IMFs such that the sum of the estimated bandwidths of each modality is minimized, where \( u_k(t) \) is the \( k \)th IMF, and its corresponding center frequency is \( \omega_k \). The specific steps of the VMD algorithm are described in Dragomiretskiy and Zosso (2014).

In the VMD method, the number of decomposed layers \( K \) should be determined in advance. In this paper, a method based on the spectrum correlation coefficients between the decomposition IMF components \( u_k(t) \) and the observed signal \( s(t) \) was proposed, which is defined as

\[
\rho_{(u_k,s)} = \frac{\sum_{i=0}^{M} |U_k(i)| \cdot |S(i)|}{\sqrt{\sum_{i=0}^{M} |U_k(i)|^2 \cdot \sum_{i=0}^{M} |S(i)|^2}}
\]  

(3)

where \( |U_k(i)| \) and \( |S(i)| \) are the Fourier transform’s norm of the decomposition of the IMF component \( u_k(t) \) and the observed signal \( s(t) \), respectively, and \( M \) is the sequence length of the frequency domain discrete values.

The specific steps of the above method are as follows: first, by initializing \( K = 1 \) and repeating \( K = K + 1 \) to update, the
spectral correlation coefficients \( \rho(u_{1}, z), \rho(u_{2}, z), \ldots, \rho(u_{K+1}, z) \) are obtained. The minimum value of the spectral correlation coefficients can be defined as \( \rho(u_{k}, z)_{\min} \), that is, \( \rho(u_{k}, z)_{\min} = \min \{ \rho(u_{1}, z), \rho(u_{2}, z), \ldots, \rho(u_{K+1}, z) \} \), in this article. If \( \rho(u_{k}, z)_{\min} \) is obviously small, it can be judged that the IMF component \( u_{K+1}(t) \) is an illusive component, which means that the number of decomposition layers \( K \) needs to be reduced. Therefore, a threshold of 0.1 is set. If \( \rho(u_{k}, z)_{\min} < 0.1 \), the repeat end and the number of the decomposition layers \( K \) are defined. Then, combining the observed signal \( s(t) \) with the \( K \), IMF components \( \{u_{1}(t), \ldots, u_{K}(t)\} \) and their remainder \( r(t) \) form a virtual multidimensional observation signal, that is, \( s_{\text{imf}}(t) = \{s(t), u_{1}(t), \ldots, u_{K}(t), r(t)\}^{T} \in \mathbb{R}^{m} \), where \( m = K + 2 \). This method breaks the limitation of the traditional blind source separation method, where the number of sensors must be greater than or equal to the vibration frequency of the signal using TFA. In addition, it can match the number of the signal source with BIC (Minka, 2000; Yi, Lv, Xiao, You, & Dang, 2017). Furthermore, assuming that the estimated number of source signals is \( l \), a new multidimensional observation signal combined with the source signal \( s(t) \), the \( l - 1 \) IMF components \( \{u_{1}(t), \ldots, u_{l-1}(t)\} \), and their remainder was obtained, that is, \( X(t) \in \mathbb{R}^{l+1} \). Therefore, the blind source separation of the new multidimensional observation signal can be performed by the TFA algorithm.

### 2.3.2 Blind source separation algorithm based on TFA

TFA is an important tool for analyzing nonstationary signals. This paper makes full use of the advantages of TFA and blind source separation to separate the range bin signals of the radar (Morovati & Kazemi, 2016). The blind source separation of signals based on TFA is mainly as follows: first, whitening the virtual multi-channel signal \( X(t) \). The relationship between the virtual multi-channel signal \( X(t) \) and the source signal \( d_{\text{LOS}}(t) \) can be expressed as \( X(t) = Ad_{\text{LOS}}(t) + n(t) \), where \( A \in \mathbb{R}^{(l+1)\times l} \) and \( n(t) \in \mathbb{R}^{l+1} \) are the mixing matrix and additive white noise, respectively. The autocorrelation matrix of the virtual multi-channel signal \( X(t) \) can be defined as

\[
R_{XX} = E [X(t)X(t)^{*}] \tag{4}
\]

where superscript * indicates a complex conjugate. Eigenvalue decomposition is performed on \( R_{XX} \) to obtain its eigenvalues \( \Lambda = \text{diag}\{\lambda_{1} \geq \lambda_{2} \geq \cdots \geq \lambda_{l}\} \) and corresponding eigenvectors \( H = [h_{1}, h_{2}, \ldots, h_{l}] \). Besides, based on the remaining minimum eigenvalue, the estimated variance of the noise variance \( \sigma^{2} \) and the whitening matrix \( W \) is defined as

\[
\sigma^{2} = \sum_{i=1}^{l+1} \lambda_{i}
\]

\[
W = \left[ (\lambda_{1} - \sigma^{2})^{-0.5}h_{1}(\lambda_{2} - \sigma^{2})^{-0.5}h_{2} \cdots (\lambda_{l} - \sigma^{2})^{-0.5}h_{l} \right]^{T}
\]

where the superscript \( T \) indicates a complex conjugate transposition. By noise compensation and whitening, the virtual multichannel signal \( X(t) \) can be expressed using the following formula

\[
Z(t) = WX(t) = WAd_{\text{LOS}}(t) = Ud_{\text{LOS}}(t) \tag{6}
\]

where \( Z(t) \) is the signal after noise compensation and whitening, and \( U \) is a unitary matrix. Then the problem of estimating the arbitrary matrix \( W \) can be turned into the problem of estimating the unitary matrix \( U \). We use the smoothed pseudo-Wigner–Ville distribution function to time-frequency transform the left and right ends of the above equation. The relationship between the obtained source signal and the time-frequency distribution matrix of the whitened observation signal can be expressed as follows:

\[
D_{ZZ}(t, \omega) = WAD_{dd}(t, \omega)W^{T}A^{T} = UD_{dd}(t, \omega)U^{T} \tag{7}
\]

where \( D_{zz}(t, \omega) \) and \( D_{dd}(t, \omega) \) are the time frequency distribution of \( Z(t) \) and \( d_{\text{LOS}}(t) \), respectively. Then, the convolution mixture problem turns into an instantaneous mixture model and \( D_{ZZ}(t, \omega) \) can be joint diagonalized with unitary matrix at some frequency points. We mark the diagonal elements of \( D_{dd}(t, \omega) \) as self-terms and the nondiagonal elements of \( D_{dd}(t, \omega) \) as cross terms. The nondiagonal elements are marked as cross terms, representing the time-frequency distribution between the two source signals. According to a certain rule, \( L \) self-item points are selected, and the time-frequency distribution matrix at the position of the self-term is jointly diagonalized to estimate the unitary matrix \( U \). According to the above estimated whitening matrix \( W \) and unitary matrix \( U \), the estimated signal of the source signal can be obtained as

\[
d_{\text{LOS}}(t) = U^{H}WX(t) \tag{8}
\]

Therefore, based on the separated signal, it can obtain the frequency of the signal using TFA. In addition, it can match the size of the corresponding cables by comparing the signal’s frequency. The flowchart of this proposed method is shown in Figure 3. First, VMD is performed on each range bin signal measured by the self-developed microwave interferometric radar, and the number of decomposition layers \( K \) is determined using the spectrum correlation coefficients
method. Then, using the cable force formula initially discriminated the range bin in which signal aliasing occurs. Afterward, combining the original signal with the $K$ IMF components and their remainder forms a virtual multidimensional observation signal. Furthermore, the autocorrelation matrix of the above virtual multidimensional observation signal is subjected to SVD, and BIC is used to estimate the number of signal sources. According to the principle of maximum correlation coefficient, $(l-1)$ IMFs are selected together with the single-channel observation signal and their corresponding remainder to form a new observation matrix $X(t)$. Then blind source separation of the new observed signal matrix is based on TFA. The separated signals are screened and compared to obtain the source signals $d_{LOS}(t)$. Finally, based on the HT algorithm, the time-varying frequency of each cable can be obtained, so that the cable forces of the test multiple cables can be simultaneously estimated with the vibration method.

3 | EXPERIMENT VERIFICATION

3.1 | Nanjing Eye footbridge description and experiment layout

As the landmark of Nanjing Youth Olympic Games, “Nanjing Eye” cable-stayed footbridge was utilized to verify the accuracy and applicability of this proposed method. As depicted in Figure 4b, the investigated bridge is a double cable steel tower cable-stayed bridge, crossing the Yangtze River connecting Hexi and Jiangxinzhou. Its total length is 440 m with main span of 240 m and two side spans of 100 m. More specially, the tower is an elliptical tower that is inclined 35° to the shore. The “Nanjing Eye” cable-stayed footbridge is hung with 18 cables in a single plane. The stay-cables have a tensile strength of 1,860 MPa and a modulus of elasticity greater than $1.95 \times 105$ MPa. Among the 18 cables, eight cables (Z1–Z8 marked in Figure 4) on the unilateral side toward Hexi are
selected for the field test. The detailed specifications of the stay-cables are shown in Table 1. The bridge was in service during the test and was forced by walking load. As illustrated in Figure 4, the experimental layout scheme mainly includes the following two cases.

Case 1 (Figure 4a): In order to guarantee the stability of the radar central position, the radar was placed on the bridge deck of the contact area between the pylon and the bridge deck. Due to the design of the bridge being shrunk in the shape of the bridge, the cables in the bridge were not in the same plane. Thereby, in order to ensure that each cable is located in a different range bin, the pitch angle of $30^\circ$ was selected before the experiment. However, it should be noted that a number of tests had been tested before this experiment to ensure the test effect, which means that the method is generally difficult, time-consuming, and might subject the test crew to hazardous conditions if the bridge is in service.

Case 2 (Figure 4b): In order to avoid the above problems, and to take advantage of the unique features of the radar regarding long-distance, high-precision, and multidimensional simultaneous measurement, we randomly selected the 200-m wide pedestrian walkway at the bottom of the bridge to observe the vibration signal of the stay-cable group at a pitch angle of $20^\circ$. The advantage of this scheme was that the antenna radiation range was large when the radar was measured remotely. In particular, the program provided other advantages including a wide frequency range of response and quick setup time. The sampling frequency of the above two cases was 66 Hz.

**TABLE 1** Specifications of the test multiple cables

| Cable number | Length (m) | Mass (kg) | Cable tension (kN) | Cable number | Length (m) | Mass (kg) | Cable tension (kN) |
|--------------|------------|-----------|-------------------|--------------|------------|-----------|-------------------|
| Z1           | 44.312     | 1375.5    | 1734.1            | Z5           | 113.901    | 3952.5    | 2045.0            |
| Z2           | 61.848     | 1896.3    | 1774.3            | Z6           | 131.165    | 4540.9    | 2083.6            |
| Z3           | 79.073     | 2407.9    | 1807.5            | Z7           | 148.66     | 5634.7    | 2179.3            |
| Z4           | 96.449     | 2923.9    | 1901.5            | Z8           | 166.158    | 6289.1    | 2329.9            |

**FIGURE 4** View of “Nanjing Eye” cable-stayed footbridge and the measurement setup: (a) Case 1: The radar setup on the deck of the investigated bridge; (b) Case 2: The radar setup at the side of the investigated bridge

**FIGURE 5** The results from the studied multiple cables under the experimental condition of Case 1: (a) the in-phase signal; (b) the quadrature signal; (c) the phase difference signal of different range bins
3.2 | Experimental results

3.2.1 | Case 1

By transmitting and receiving the electromagnetic signals and performing the mixing processing, Figure 5a–b show the I/Q baseband signals when the radar monitors the tested multiple cables under the experimental condition of Case 1, respectively. By performing arctangent demodulation on I/Q data, Figure 5c shows the target echo phase map of each range bin. Furthermore, by performing FFT transformation on the target echo phase difference data of any time, the distance between the test multiple cables and the radar can be obtained, as shown in Figure 6a. Combined with the laser rangefinder of the radar auxiliary unit and the target echo energy peak point, the distance of each cable along the LOS direction of the radar can be determined, that is, the cables Z1–Z8 are mainly placed in range bin9.5, range bin17.5, range bin23.5, range bin32.5, range bin37, range bin43, range bin56, and range...
FIGURE 7 The results from the test multiple cables under the experimental condition of Case 2: (a) the in-phase signal; (b) the quadrature signal; (c) the phase difference signal of different range bins.

FIGURE 8 Power profile, the red circles denote the position of the test multiple cables in Range bin 65. Thus, it should be noted that the range bins (i.e., range bin 9 and range bin 17), which are near the peak point of each echo energy, represented by a red circle also give the cable’s information.

Then, based on the phase interferometry method (Equation 2), the displacement time history of each cable can be obtained by processing the difference frequency signal of the selected range bin, as illustrated in Figure 6b. Figure 6c illustrates their power spectrums and it can be found that the frequency information of the selected range bins is relatively simple, which basically conforms to the frequency domain characteristics of the cable.

Therefore, based on the HT algorithm, the time-varying frequency of each cable can be obtained from the displacement time histories of the selected range bins. Based on the vibration method, the time-varying cable force of each cable can be estimated, and the results are given in Section 3.2.2.

| Layer | The spectrum correlation coefficients $\rho_{\{u_k, s_l\}}$ |
|-------|------------------------------------------------|
| $K$   | $\rho_{\{u_1, s_1\}}$ | $\rho_{\{IMF_{1}, s_1\}}$ | $\rho_{\{IMF_{1}, s_2\}}$ | $\rho_{\{IMF_{1}, s_3\}}$ | $\rho_{\{IMF_{1}, s_4\}}$ | $\rho_{\{IMF_{1}, s_5\}}$ | $\rho_{\{IMF_{1}, s_6\}}$ | $\rho_{\{IMF_{1}, s_7\}}$ |
| 2     | 0.7395 | 0.4473 | – | – | – | – | – | – |
| 3     | 0.6620 | 0.7142 | 0.3943 | – | – | – | – | – |
| 4     | 0.6611 | 0.7125 | 0.3801 | 0.2762 | – | – | – | – |
| 5     | 0.6610 | 0.7121 | 0.3799 | 0.2760 | 0.1776 | – | – | – |
| 6     | 0.5914 | 0.6921 | 0.3099 | 0.2123 | 0.1716 | 0.1328 | – | – |
| 7     | 0.5604 | 0.6421 | 0.2799 | 0.1923 | 0.1526 | 0.1238 | 0.0762 | – |
Similarly, as demonstrated in Figure 7a–b, the baseband I/Q signals can be obtained when the self-developed microwave interferometric radar monitors the test multiple cables under the experimental condition of Case 2. Figure 7c illustrates the phase difference information of each range bin (range bin190–235) within the radar sight field. Furthermore, by transforming the target echo phase difference data at any time in the

**Case 2**

Case 2 experimental condition by the FFT transformation, the distance between the tested multiple cables and the radar is obtained. As summarized in Figure 8, it is realized that the target echo energy peak points are concentrated, which means that it is difficult to directly discriminate the cable information from the echo energy peak points under the Case 2 experimental condition.

In this experimental condition, the echo energy peak points, namely, range bin193.5, range bin199.5, range bin201, and
FIGURE 13 Identification results by VMD of multiple cables under the experimental condition of Case 1 and Case 2: (a) the first-order frequency; (b) the errors of the identified and reference first-order frequency

range bin 203.5, were selected for analysis. Based on the phase interferometry technology (Equation 2), the displacement time history information can be obtained by using the phase difference signal. Furthermore, Figure 9 shows their power spectrum, which indicated that the frequency domain information of the selected range bins is more complicated. Therefore, it means that selecting the frequency of each cable directly from the range bin based on the cable force calculation formula is very difficult. The reason is that as the distance of the radar is farther, the amplitude of the range bin in space is larger, which causes signal aliasing of different cables located in the same range bin. In order to solve the problem of signal aliasing, the above signal blind source separation algorithm was used, and the range bin 199.5 was selected as an example for analysis.

First, the number of decomposition layers is defined as six using the spectrum correlation coefficients, which are shown in Table 2. Furthermore, the IMF components of each order and their residual items are obtained as shown in Figure 10.

Then, the single-channel observation signal is combined with each modal component and their remainder to form a virtual multidimensional observation signal to realize the signal ascending dimension, so as to meet the requirements of blind source separation for the positive determination of the observation matrix. The autocorrelation matrix of the above virtual multidimensional observation signal is subjected to SVD, and BIC is used to obtain the number of signal sources of 4. According to the maximum principle of phase relationship, the first three IMFs are combined with the single-channel observation signal and its decomposition residuals to form a new observation matrix, and then TFA is performed.

Figure 11 shows the separated source signals from the new observed signal based on TFA. It can be found that the amplitude of each estimated source signal in the time domain is different from the original observed signal. However, it is convenient to accurately identify the cable signals by distributing the respective cable components included in

FIGURE 14 Identified time-varying cable forces of multiple cables under the experimental condition of Case 1 and Case 2 using the vibration method.
the observation signal in different channels in the frequency domain. It is worth mentioning that VMD can decompose a series of IMF of a signal around their corresponding estimated center frequencies. Therefore, each IMF appears orthogonal to each other in theory. However, in actual engineering applications, if the correlation between the two IMFs is very high, there may be some aliasing between the above two IMFs after decomposition, such as source signal 3 and source signal 4.

By separating the measured signals of the selected range bins in turn based on VMD and TFA, a total of 14 independent source signals are obtained. Figure 12 shows the frequencies of the above 14 source signals are plotted and sorted according to the size of the first-order natural frequency. The blue circles and the other circles indicate the first-order frequencies and the higher frequencies of the above 14 source signals, respectively. It can be found that even if the identified second-order frequency of Cable Z5 is inconsistent, but it can be easily found that there are only eight independent signals in the estimated source signals, which were obtained from the measured signals by TFA.

Based on the relationship between cable length and the first-order frequency, Figure 13 shows the identified first-order frequencies of the measured multiple cables under the experimental condition of Case 1 and Case 2 and clearly shows an excellent match between the identified and reference value of the first-order frequencies, where the maximum relative error is 4.085%. Afterwards, the HT algorithm is employed to solve the signal of each cable, and the time-varying cable tension forces of multiple cables can be estimated using the vibration method, as illustrated in Figure 14.

As shown in the figure, the variations of the estimated force of Cable Z5 with time are significant in Case 2. The reason may be that the uncertainty of the test environment and the decomposition IMF components of Cable Z5 obtained by VMD still have some aliasing with other signals. However, the identified cable tension forces of other cables (Z1-Z4, Z6-Z8) are relatively stable, and the mean relative error is less than 2%, which can be acceptable in real engineering application. Therefore, a conclusion can be made that the self-developed microwave interferometric radar and the proposed signal blind source separation method may be a reliable technique for simultaneous cable tension forces estimation of multiple cables of long-span cable-stayed bridge.

4 | CONCLUSION

This paper has described a method for simultaneous cable forces estimation of multiple cables of long-span cable-stayed bridge with microwave interferometric radar. The specific conclusions are drawn as follows:

1. Simultaneously measuring the dynamic response of multiple cables of an array using the developed microwave interferometric radar. In order to fully use the unique advantage of the radar such as long-distance, non-contact, real-time continuous measurement, a blind source separation algorithm that combines VMD and TFA was first introduced in this paper to separate the radar range bin signals that contain multiple cables’ information. Furthermore, an improved method based on spectrum correlation coefficients was proposed to determine the number of decomposition layers in VMD.

2. Experimental results from “Nanjing Eye” cable-stayed footbridge have revealed that the proposed method is relatively fast, economical, and reliable, which means that it can perform well as a reliable method for portable and rapid cable force estimation.

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