A Study on the Synchronous Testing Technology of Cable Group Forces Based on Wavelet Transform

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Abstract. This paper studies the synchronous testing technology of cable group forces based on wavelet transform using microwave radar measured data. A wavelet transforms method-based cable force identification method was established, which includes: (1) applying continuous complex Morlet wavelet transform to the vibration signal of the cable; (2) extracting the maximum value of the wavelet coefficient modulus from the wavelet ridge to identify the instantaneous frequency of the cable; and (3) improving wavelet threshold function for noise reduction. A cable force identification was conducted, where accelerometer and microwave radar were used to simultaneously collect the vibration response signals of the test cable when the cable force underwent linear changes. The signals were denoised and analyzed in the time-frequency domain, which enabled us to compute the cable forces by analyzing the identified frequencies.

The results indicated that the improved wavelet threshold function has a good denoise effect. It can extract clear wavelet ridges even with a low signal-to-noise ratio, enabling the identification of the cable force variation patterns of the test cables. The identified cable force from the accelerometer signal and radar signals closely matches the measured cable force, with a maximum deviation of only 1.6%. Leveraging the microwave radar's multi-target tracking capability, synchronous cable forces testing for a cable group on a cable-stayed bridge was achieved. The time history of cable forces of multiple cables was obtained during the test periods.

Keywords: Bridge engineering; Cable group; Synchronous cable force testing; Vibration frequency; Microwave radar; Wavelet transform.

1 Introduction

Cables (or hangers) are the primary load-bearing components in cable-stayed bridge structures. When tensioning one cable, the forces in neighboring cables simultaneously change. To understand the variation of cable force and correlation among neighboring cables, synchronous force testing of cable groups is necessary. Additionally, being able to test the cable force of multiple cables at once can significantly improve work effi-

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ciency. The vibration frequency method is a widely used technique for cable force testing. It typically involves the installation of accelerometer for vibration signal acquisition, where the number of sensors determines the quantity of cable that can be synchronously tested [1]. Although the development of wireless information transmission technology has eliminated the need for complex wiring, the sensor installation remains labor-intensive. Moreover, it is only able to collect data near the bridge deck's cable ends. It makes the extraction of frequency characteristics difficult due to the interference of cable damping facilities. Therefore, there is an urgent need to develop and apply more advanced synchronous cable testing techniques.

The development of science and technology makes non-contact vibration tests becoming possible [2]. The image-based method captures a series of instantaneous images of objects under vibration and after digital processing, extracts vibration information [3-4]. Radar-based methods involve real-time displacement measurements of objects through the reflection of radio waves to obtain vibration information [5-6]. Both the image-based and radar-based methods allow testing at the most significant and vibration-rich midsections of the cables. Furthermore, both methods can achieve synchronous measurements of multiple targets. Compared to the image-based method, the radar-based method is less affected by weather conditions (visibility), making it more suitable for cable vibration testing [7]. Regarding vibration signal analysis, traditional cable force dynamo-meters used Fourier transformation for spectral analysis. While it can accurately locate constant frequency, it lacks the capability to perform time-frequency analysis, and as a result, it cannot accurately identify changes in field tests, the collected signals are often subject to noise interference, resulting in distorted cable force identification results. Given the aforementioned circumstances, this study uses microwave radar as the measurement tool and explores the synchronous cable force testing technology based on wavelet transform. This research provides reference for the related cable force testing.

2 Test and Identification Methods

2.1 Synchronized test method for radar-based cable force measurement

Based on the distance between the observed object's surface and the measuring radar, the position of the wave crest is determined in the radar image, allowing the extraction of the corresponding phase value $\phi(t_s)$.Taking a specific time point in the measurement process as the reference phase ϕ_0, infinitesimal variation in the displacement of the measurement point can be deduced through time-differential interference phase [8]:

$$\Delta d = \frac{\lambda[\phi(t_s) - \phi_0]}{4\pi} \tag{1}$$

where, Δd is the displacement change of the measured object, λ is the wavelength of the electromagnetic wave, t_s is the time when the object's deformation is measured.

Usually, there is a fixed spacing between each cable. When there are multiple cables in the radar line of sight, the radar echoes clearly show the scattered reflections from these cables [9]. The synchronous testing of the cable group is achieved by: (1) identifying peaks of signal reflection intensity in the scattering diagram; and (2) determining the signal for each cable through the distance between the cable being measured and the radar, as illustrated in Figure 1.

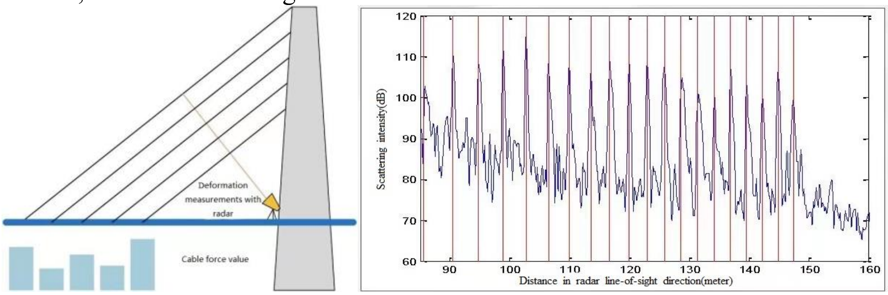


Fig. 1. Synchronized test method for radar-based cable force measurement

2.2 Frequency recognition based on wavelet transform.

Extraction of wavelet ridges.

By performing continuous wavelet transform on the signal for time-frequency analysis, and extracting the wavelet ridges corresponding to different structural modal components, we can identify the instantaneous frequency of the structure. The vibration response signals $s(t)$ the analytical form can be expressed as:

$$s(t) = A(t)e^{-i\phi(t)} \tag{2}$$

where, $A(t)$ is the amplitude, and $\phi(t)$ is the corresponding phase. Using tunable complex Morlet wavelets, we have [9]:

$$\psi(t) = (\pi F_b)^{-\frac{1}{2}} \cdot e^{-t^2 \cdot (F_b)^{-1}} \cdot e^{i2\pi F_c t} \tag{3}$$

where, F_b is the bandwidth parameter, and F_c is the central frequency. Based on the theory of smooth phase [10-11], the complex Morlet wavelet transform of $s(t)$ can be approximated by the first term of its asymptotic expansion:

$$W_s(a,b) = A(b) \cdot e^{i\phi(b)}\psi^*[a\phi'(b)] + o(|A'| \cdot |A|^{-1}, |\Phi\Phi''[\Phi']^{-1}|^2) \tag{4}$$

where, a and b are the scale and translation parameters, respectively; ψ^* is the conjugate of the wavelet basis Fourier transform, $o(\cdot)$ represents the higher order infinitesimal quantity, and $\phi(b)$ is the phase of the wavelet coefficients.

For the function ψ^*, at the central frequency $\omega = \omega_0$, the wavelet coefficients magnitude achieves a local maximum, that is:

$$a = a_r(b) = \omega_0 \phi'^{-1}(b) = 2\pi F_c \phi'^{-1}(b) \tag{5}$$

The line connecting these local maxima points are known as wavelet ridges. The frequency $f(t)$ can be calculated from the wavelet ridges as follows:

$$f(t) = f(b) = \phi'(b)(2\pi)^{-1} = F_c a_r^{-1}(b) \quad (6)$$

Denoise by wavelet thresholding.

In field test, the collected vibration signals are often contaminated with complex noise. When the signal-to-noise ratio is low, it becomes challenging to clearly extract the wavelet ridges. Therefore, this study employs a wavelet threshold denoising method to process the data to minimize noise interference.

First, the wavelet threshold is calculated, typically determined based on the signal-to-noise ratio of the original signal:

$$\delta = \sigma[2 \cdot log(n)]^{0.5} \quad (7)$$

where, n is the signal length, σ is the noise intensity, δ is the threshold which taken as the standard deviation of the wavelet decomposition coefficients from the original signal [12]. The key to wavelet threshold denoising is to define the threshold function. In this paper, we use an improved threshold function [13] that avoids some of the drawbacks of the traditional hard and soft threshold functions. The equation is expressed as:

$$\omega_\delta \begin{cases} sgn(\omega)|\omega| - \delta \cdot exp^{-2}[(|\omega| - \delta) \cdot N^{-1}], |\omega| \geq \delta \\ 0, |\omega| < \delta \end{cases} \quad (8)$$

where, ω_δ is the threshold-er wavelet coefficients; ω is the original wavelet coefficients and N is a positive constant. Since the value of the N can be adjusted, the type of threshold function can be flexibly changed, and the value of N can be determined according to the denoising effect by trial-and-error calculation. The process of wavelet thresholding denoising is shown in Figure 2.

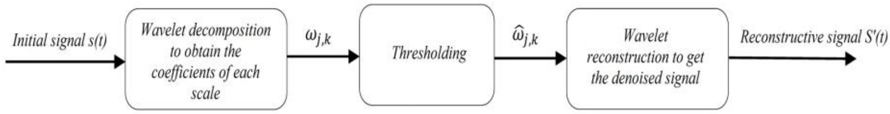


Fig. 2. Denoising process of wavelet thresholding

3 Cable force identification test

3.1 Test setup

A cable force identification test was designed to compare the effectiveness of using accelerometers and radar in the vibration test to verify the validity of the proposed method. The experiment used an 1860 grade 7Φ5 strand cable. Its geometrical and physical parameters are shown in Table 1. One end of the cable was anchored using a reaction frame, which was equipped with a penetrating pressure sensor. The other end applied tension using an electro-hydraulic actuator. The cable length is calculated as the distance between the two anchorage points. Vibration signal acquisition equipment included an accelerometer and a microwave radar. The layout of the test setup is shown in Figure 3, and the photos of the signal acquisition equipment are shown in Figure 4.

Table 1. Geometrical and physical parameters of the test cable

Cable Length /m	Nominal Diameter /mm	Elastic Modulus /MPa	Cross-sectional Area /mm^2	line density /(kg/m)
4.35	15.20	1.95×10^5	137.4	1.094

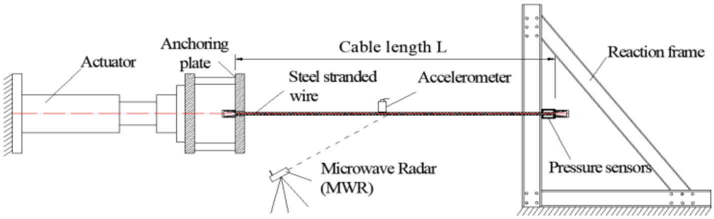


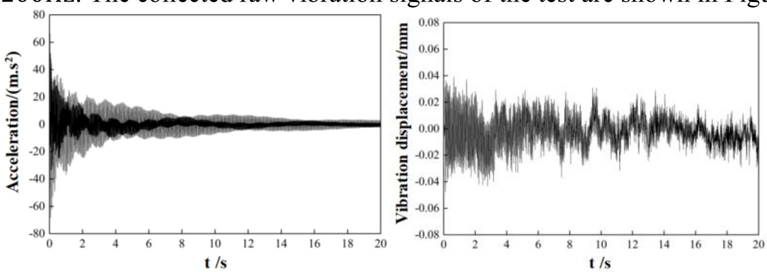
Fig. 3. Layout of the test setup

(a) Accelerometer (b)Microwave radar

Fig. 4. Vibration signal acquisition equipment

3.2 Loading and Data Acquisition

The test Started from a fixed initial tension a linearly increasing force was applied to the cable at a loading rate of 0.1 kN/s , with a loading duration of 20s. During the test, a rubber hammer was used to gently tape the cable for artificial excitation. Vibration signals from the cable were simultaneously collected by the accelerometer and microwave radar. Real-time cable forces were also recorded using pressure sensors. The accelerometer had a data acquisition frequency of 500Hz, and the microwave radar operated at 200Hz. The collected raw vibration signals of the test are shown in Figure 5.



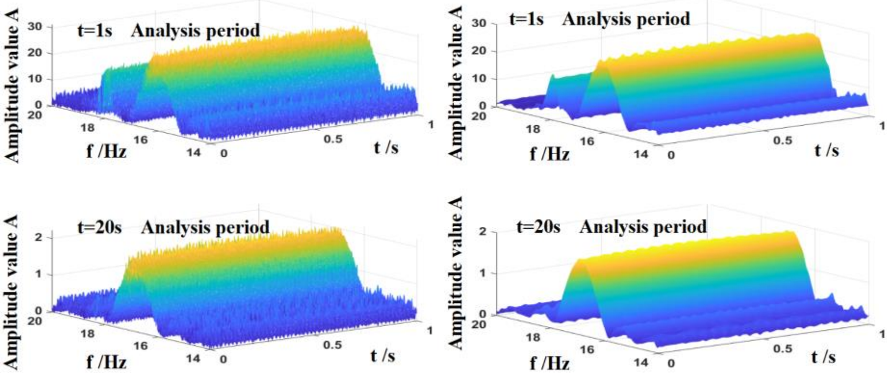
(a)Accelerometer (b)Microwave radar

Fig. 5. Cable vibration signals

3.3 Experimental results

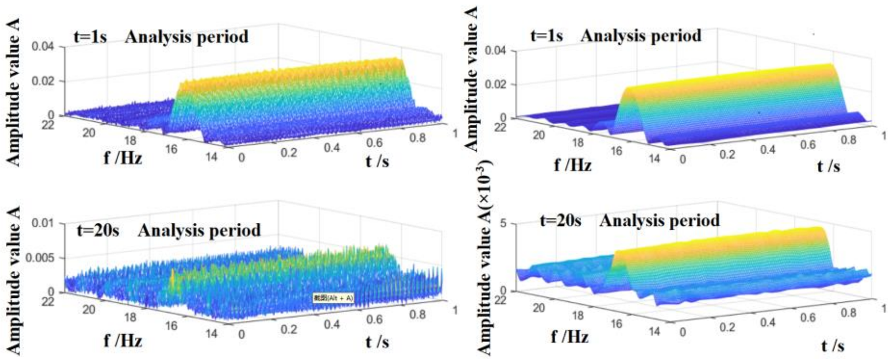
Effect of denoise removal.

The acquired vibration signals were denoised using Eq (8), where N was set to 100 and a duration of 1s was chosen in the analysis. The denoising effects at time t=1s and t=20s are shown in Figures 6 to 7. Clearly, the entire test was affected by noise before denoising. Compared to the accelerometer signal, the radar signal exhibited a lower signal-to-noise ratio, especially at the end of the test. The denoising effect of the improved threshold function was significant, resulting in clearer energy spectral maps that reflected the distribution of signal energy with respect to frequency.



(a)Before denoising (b)After denoising

Fig. 6. Wavelet energy spectrum of acceleration signal

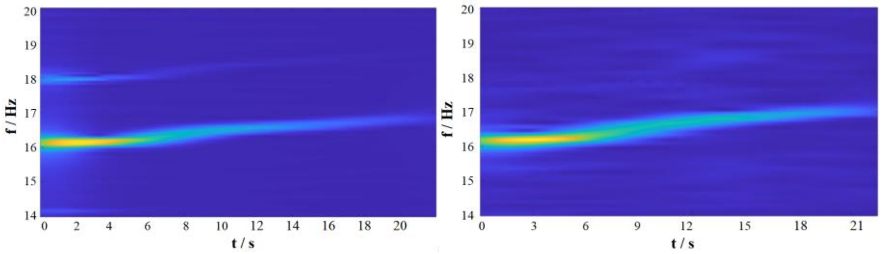


(a)Before denoising (b)After denoising

Fig. 7. Wavelet energy spectrum of radar signal

Cable force identification.

Wavelet ridges are extracted from the denoised vibration signals using Eqs. (2)-(6). Figure 8(a) presents the acceleration signal, showing two distinct wavelet ridges corresponding to the first two natural frequency of the cable. Despite the lower signal-to-noise ratio, the radar signal was still able to extract the fundamental frequency data of the cable, as shown in Figure 8(b).



(a)Accelerometer signal (b)Radar signal

Fig. 8. Extracted wavelet ridge results

The force of the cable was calculated based on the relationship between force and frequency. Taking the bending stiffness of cable into account, is the cable force can be calculated by [14]:

$$T = 4mL^2f_1^2 - \pi^2EIL^{-2} \tag{9}$$

where, T is the cable force, m is the linear density of the cable; L is the calculated length; EI is the flexural rigidity; f_1 is the fundamental frequency.

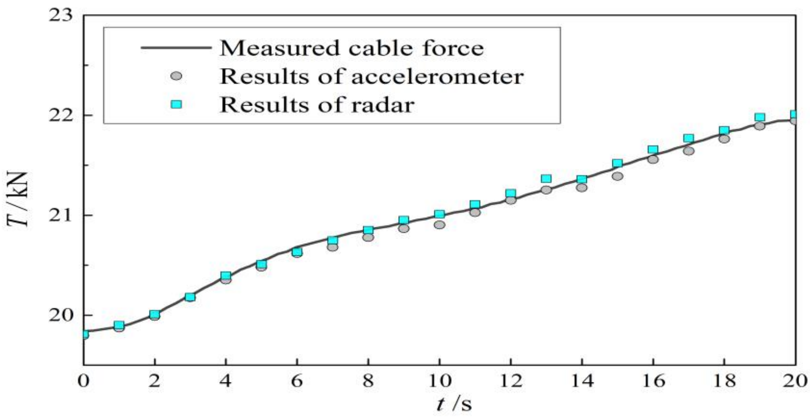


Fig. 9. Cable force identification results

Using Eq. (9), the cable forces were calculated and compared with the corresponding measured one using the pressure transducer, as shown in Figure 9. The results indicate that the identified forces are consistent with the measured force variations. The identification results from radar signals and accelerometer signals differ by less than 1%, with a maximum deviation from the measured force of only 1.6%. This demonstrates high identification accuracy. It suggests that using radar for force testing is feasible and validates the effectiveness of the force identification methodology presented in this paper.

4 Synchronous testing of cable group forces

4.1 Project overview

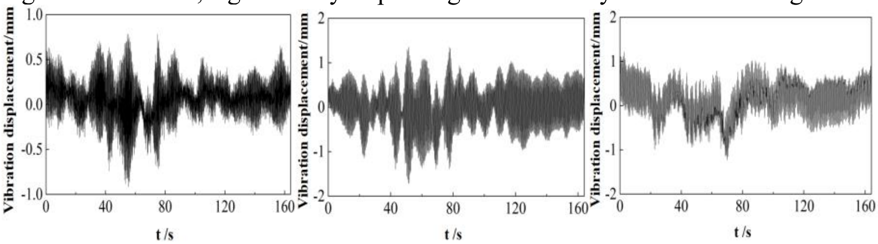
A cable-stayed bridge has a total of 13 pairs of 26 cable-stayed cables was used in the study. The cable spaced at 12m and arranged in parallel with a horizontal inclination of 25°. The cables were made of 1670 grade Φ7mm high-strength galvanized steel wire. They were equipped with corresponding cold casting pier head anchorage. The design parameters for cables S1 to S6 are shown in Table 2.

Table 2. Cable Design Parameters

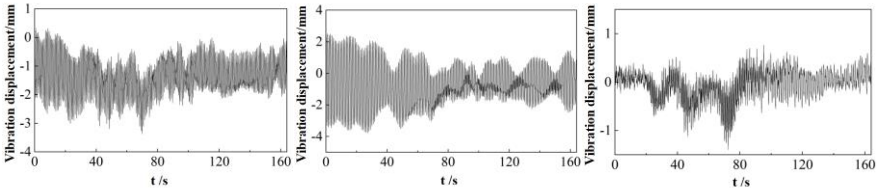
Cable number	Specification	Calculation of the cable length /m	line density /(kg/m)	cross-section area /(mm^2)	Designed cable force values /（KN）
S1	PES7-283	50.304	91.18	10891	6620
S2	PES7-283	68.925	91.18	10891	6390
S3	PES7-283	87.546	91.18	10891	6255
S4	PES7-223	106.157	71.85	8582	4672
S5	PES7-223	124.780	71.85	8582	4688
S6	PES7-223	143.403	71.85	8582	4721

4.2 Test results

Synchronous testing of cable group forces was conducted using the radar technology. The data acquisition frequency was set at 200 HZ. A 160s data segment was used in the analysis, Figure 10 presents the measured vibration displacement response signal of each cable. The frequency of the tested cables was extracted using the method mentioned earlier, and the cable force was calculated using Eq (9). The results are shown in Figure 11. Since the wavelet transform provides time-frequency analysis, it allows the identification of cable force variations over a short period, which is not possible with conventional Fourier transform method. With the help of the microwave radar's multi-target tracking capability, synchronous testing of cable group forces for the bridge was achieved, significantly improving the efficiency of tension testing.

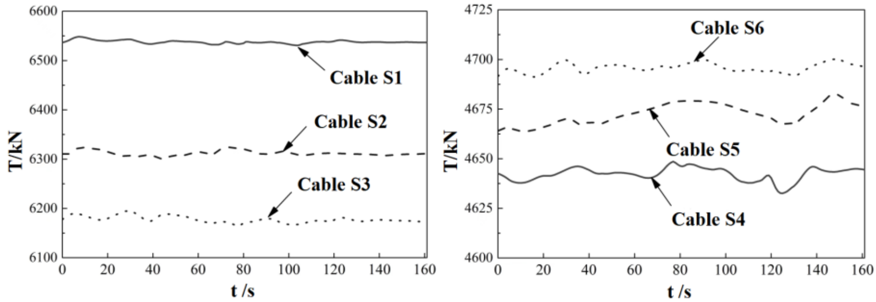


(a) Cable S1 (b) Cable S2 (c) Cable S3



(d) Cable S4 (e) Cable S5 (f) Cable S6

Fig. 10. Vibration displacement response of the tension cable group time course



(a) Cable S1~S3 (b) Cable S4~S6

Fig. 11. Synchronized test results of cable group cable force

5 Conclusions

This study explores the synchronous testing of cable group forces based on wavelet transform using microwave radar. The following conclusions are drawn.

(1) A wavelet transform-based cable force identification method was established. First, the complex Morlet wavelet transform was applied to cable vibration signal. Then, the wavelet ridges were extracted from the maximum values of wavelet coefficient modulus to identify the frequencies of bridge cables. To reduce noise interference, an improved threshold function was used for wavelet threshold denoising.

(2) Laboratory test results showed that the radar signal had a lower signal-to-noise ratio compared to signal collected by the accelerometer. It was more affected by noise. The effect of wavelet threshold denoising was significant, allowing the extraction of clear wavelet ridges and the identification of the frequency of the test cable. Cable forces were calculated based on the force and frequency relationship. The identified cable force matched well with the measured one. The difference between the results obtained from the radar signal and the accelerometer signal is less than 1%, with a maximum deviation from the measured force of only 1.6%, indicating high identification accuracy.

(3) Synchronous testing of cable group forces for a cable-stayed bridge was achieved by using the microwave radar's multi-target tracking capability and the time-frequency analysis of wavelet transform. The method not only significantly improve the efficiency of the cable force testing, but also enabled the identification of cable force variations

over a short period. This is highly desired for the construction, replacement, and health monitoring of bridge cables. It also provides a reference for the development of new cable force dynamic measurement systems and instruments.

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