A method of measuring the cable tension force with the application of smart phones

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Abstract

Smart Phones are portable and extensible, besides they can provide MEMS micro-accelerometer with good support. This article introduces a method of measuring the tension force of the cable-stayed bridge with the application of a Smart Phone. According to the FFT (Fast Fourier Transform) algorithm, the time domain is converted to the frequency domain while we program on the Android platform and the effective peak-picking algorithm is designed to determine the natural frequencies of the cables. An analysis of simulated signals demonstrates that the designed programs can accurately identify the natural frequencies with or without the disturbance and it can also compute the fundamental frequency based on the identified natural frequencies. With the fundamental frequency it goes on to calculate the tension force. A comparison of the result by adopting the method introduced in this article and the one collected from the JMM-268 tension force dynamic measuring instrument indicates that the Smart Phone has some difficulty in measuring the cables shorter than 40m; however, a less than 5% error is detected where the cables are longer than 40m.

Keywords: Smart Phone; natural frequency; cable-stayed bridge; Fourier transform

1 Instruction

The natural frequency method is currently the most-utilized method in light of measuring the tension force[1-4]. The theory behind it is that the tension force is determined by way of measuring the natural frequencies and analyzing the physical connection between the force and the natural frequencies. Common measurements of cable frequencies include a coordinative application of an acceleration transducer, a signal collector, a amplifier and computers, which causes inconvenient and inefficient site installation as these instruments are usually not portable or easy to install. Even the portable JMM-268 cannot work without large-size signal collectors and vibration pickups, let alone the JMM-268 is poorly valued in terms of the man-machine interface, the data processing and the extensibility.

With the combination of an accelerometer and a Micro-Electro-Mechanical System (MEMS), a micro-accelerometer measures the acceleration change of the built-in devices by detecting the variation of the capacitance, the resistance and the current in the acceleration field[5]. Compared with a regular accelerometer, a micro-accelerometer has the advantage of being smaller, lighter and more integratable and it is extensively utilized in the military and civilian fields such as the space system, the missile guidance, the automobile collision detection and the civil engineering structures detection. Up to now, the accuracy of the micro-accelerometer can reach $1\times10^{-4}g$ and there is still room for improvement. The application of micro-accelerometer calls upon a development of an embedded system, including amplifying, filtering, adjusting and A/D converting of the signal, which poses the drawbacks of high cost, long development cycle and heavy workload. In recent years, micro-accelerometers are universally integrated in Smart Phones to support functions such as the screen rotation, the motion detection and gravity games. The HAL(Hardware Abstraction Layer) of the Smart Phone operating system supplies the upper layer with numerous API (Application Programming Interface) and in turn provides developers with easy access to the bottom hardware and enables them to set the sensor sampling rate, accuracy, read the data and focus on the realization of these functions without paying attention to the implementation details of the bottom hardware. The development of the application of a micro-accelerometer in a Smart Phone not only saves the trouble of hardware design of an embedded system but also allows the adoption of advanced programming language for development, which has the advantage of a short development cycle, a light workload and great extensibility. Many researches on the application of Smart Phones in the field of civil engineering have been done by scientists and institutions. The patent "A Vibration Measuring Instrument and Detection on the Basis of a Android Platform" by Special Equipment Testing Institute in Hangzhou offers a highly-accurate and low-cost way of measuring the vibration parameters with the implementation of Android Smart Phones[6]; Jiangbo Chen and others analyze the features of a motor's vibration and evaluate its performance by detecting the motor vibration with the application of Smart Phones[7].

A browse of literature at home and abroad finds no corresponding researches on the application of a Smart Phone in light of the measurement of the cable tension of a cable-stayed bridge. This article makes an attempt to integrate the micro-accelerometer in the Android platform, measure the cable tension with the application of Smart Phones and offer reference for similar engineering practices.

2 Steps of collecting the cable vibration signal with the application of an Android Smart Phone

Most micro-accelerometers integrated in the Android Smart Phone can detect the acceleration of the X, Y, Z axis at the same time, where the direction is defined as: for a vertical screen, X axis refers to the horizontal direction; Y axis refers to vertical direction and Z axis refers to the direction from the inside to the outside of the screen. See FIGURE 1. The positive value of the acceleration represents the positive direction and vice versa. While measuring, fixate the back of the Smart Phone on the cable (see FIGURE 2), and read the acceleration data of the Z axis according to the pre-set sampling rate[8]. Below are the detailed steps to access the built-in micro-accelerometer:

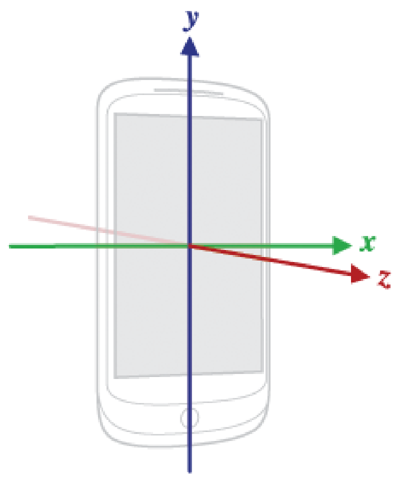


FIGURE 1 The coordinate system of the Android Smart Phone

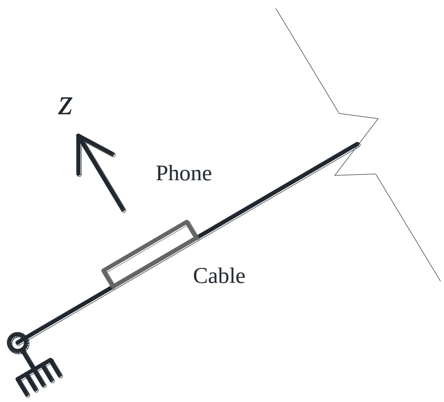


FIGURE 2 The fixation of a mobile phone on the cable

(1) Create a system service called SensorManager to manage sensors;

(2) Obtain the Sensor object of the micro-accelerometer from the SensorManager;

(3) Add SensorEventListener to the Sensor object by calling function registerListener of SensorManager.

(4) Realize the callback of SensorEventListener, obtain the acceleration value and execute the business code.

In step (3), parameters to specify the sampling rate are required while registering "SensorEventListener". According to Nyquist sampling theorem, "half-wave loss" can be avoided only under the condition when the sampling rate is at least twice the amount of the interested frequencies. Normally 5 to 10 times of the interested frequencies will be sampled. As for the cable, people are often interested in the natural frequency less than 10 Hz, which determines the sampling rate to be more than 50 Hz. Four sampling rates are available on the Android platform

(1) SENSOR_DELAY_NOMAL (5Hz)

(2) SENSOR_DELAY_UI (15Hz)

(3) SENSOR_DELAY_GAME (50Hz)

(4) SENSOR_DELAY_FASTEST (100Hz or above, depending on the performance of sensors)

Both the sampling rate SENSOR_DELAY_GAME and SENSOR_DELAY_FASTEST meet the requirement of the sampling rate of the cable vibration.

In step (4), there are two callback functions of the SensorEventListener: onAccuracyChanged and onSensorChanged, invoked when the sensor accuracy or data are changed. OnSensorChanged is the more important one of the two, which concerns major business codes including data processing, graphics rendering. The parameter passed when onSensorChanged is invoked is referred to as SensorEvent, involving sensor data of all directions from the current micro-accelerometer.

SensorEvent.values[SensorManager.DATA_Z] refers to the acceleration values on Z axis, meanwhile acceleration values on X, Y axis do not influence much in terms of tension measuring, which leaves them unused.

3 Key technologies in the process of measuring he tension with the application of Smart Phones

3.1 THE PRETREATMENT OF THE SAMPLING DATA

Define time as the independent variable in the case of vibration signal $x(n)\left(n=0,1,\cdots,N-1\right)$. The Fourier transform algorithm is adopted here to convert the time domain to frequency domain and obtain the frequency spectrum. The discrete Fourier transform formula is[9-12]:

$$X(k)=\sum_{n=0}^{N-1}x(n)e^{-j2\pi kn/N},\quad k=0,1,\cdots,N-1 \tag{1}$$

The complexity of discrete Fourier transform algorithm is $O(N^2)$ The calculation increases exponentially given to the signal length. The FFT algorithm is able to reduce the complexity to $O(N\log N)$. This article utilizes the serial iterative algorithm to realize the FFT. Below are the detailed steps:

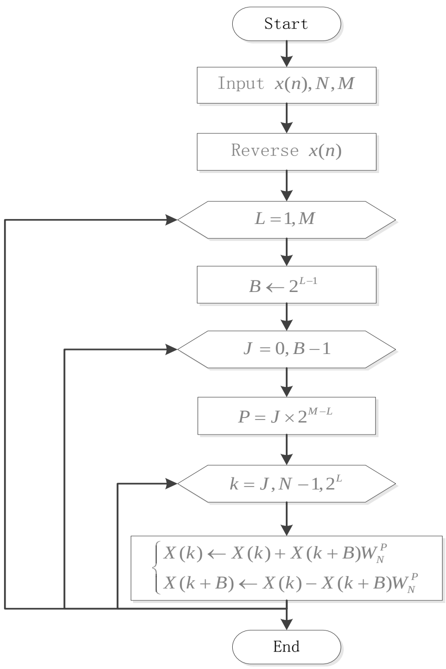


FIGURE 3 The flow chart of the FFT algorithm

(1) Extend the length of $x(n)$ to 2^M by adding zeros at the end of the sequence. $N \leftarrow 2^M$. M meets condition where $2^{M-1} < N$, $2^M \geq N$

(2) Put $\{x_n\}$ in inverse order.

(3) Enter the L circulation and L is valued from 1 to M , $B = 2^{L-1}$;

(4) Enter the J circulation and J is valued from 0 to $B-1$, $P = J \times 2^{M-L}$;

(5) Enter the k circulation and k is valued from J to 2^L . Obtain $X(k)$ by running the following formula:

$$\begin{cases} X(k) <= X(k) + X(k+B)W_N^P \\ X(k+B) <= X(k) - X(k+B)W_N^P \end{cases}$$

(6) End the L , J , k circulation, and we get $X(k)(k = 0,1,\cdots,N-1)$.

FIGURE 3 is the flow chart of FFT algorithm. Step (3), step (4) and step (5) are the butterfly algorithm of the time radix-2 FFT,where M represents the total progression of the butterfly algorithm, L represents the current progression, B represents the interval between two data in each butterfly, W_N^P represents the rotation factor, P represents the rotation factor index and $N = 2^M$ represents the extended data length.

4 The method of determining the frequencies and the fundamental frequency

With ambient excitation, the natural frequency spectrum will look like FIGURE 4(a), where no dominant peaks of fundamental frequency components can be noticed and the natural frequencies are accompanied by powerful false peaks, which make it more difficult to determine the natural frequency [13, 14]. According to the theory of string vibration, the natural frequencies are integral multiples of the fundamental frequencies and the intervals between neighboring frequencies equal to the fundamental frequency. Below are the steps of determining natural frequencies adopted in this article based on the above law:

(1) Enlist the peaks with relatively large value into a tabulation, and group the selected peaks into several clusters. Make sure the intervals between neighboring cluster is close to the fundamental frequency;

(2)Identify the peaks that are close to each other and save the largest peaks while shifting the others out. Then the left ones in the tabulation are the natural frequencies;

(3) Determine the main vibration frequency (the peak with the largest value) and the fundamental frequency based on the fact that the high order frequencies are the multiples of the fundamental frequency.

The steps of indentifying the natural frequencies are presented in FIGURE 4.

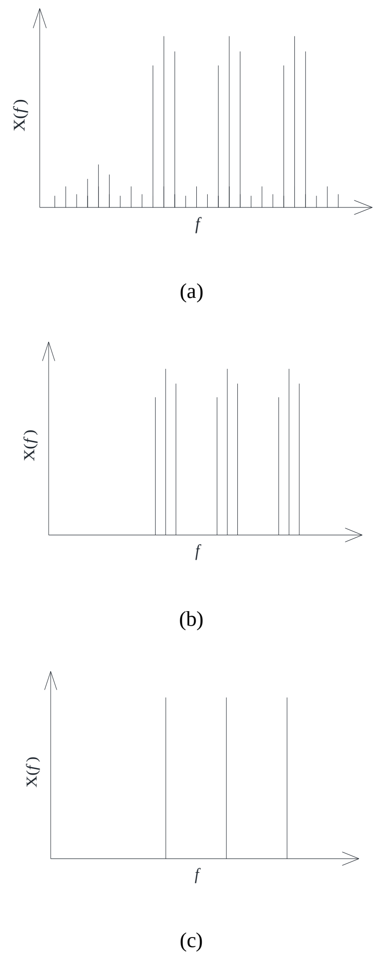


FIGURE 4 The steps of determining the natural frequencies

5 The calculation of the tension force

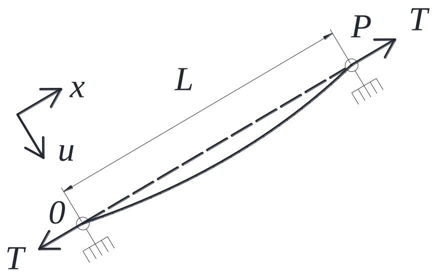


FIGURE 5 Schematic diagram of a stressed stayed-cable

Assuming the length of the cable is L, the linear density is ρ, the flexural stiffness is EI and the tension is T. As is shown in Fig.5, the dynamic stationary differrential equation of the stayed-cable can be described as below:

$$\rho\frac{\partial^2 u(x,t)}{\partial t^2}+EI\frac{\partial^4 u(x,t)}{\partial x^4}-T\frac{\partial^2 u(x,t)}{\partial x^2}=0, \tag{2}$$

where x refers to the coordinate in the longitudinal direction, $u(x,t)$ refers to the coordinate in the perpendicular direction to the longitudinal direction and t refers to time.

Approximately, if we regard the two ends of a stayed-cable as the hinges, then under the boundary condition, where $x(0)=0$, $x'(0)=0$, $x(L)=0$, $x'(L)=0$ the solution of the equation , (2) is:

$$T=\frac{4\rho L^2 f_n^2}{n^2}-EI\left(\frac{n\pi}{L}\right)^2, \tag{3}$$

when $n=1$, equation , (3) can be converted to

$$T=4\rho L^2 f_1^2-EI\left(\frac{\pi}{L}\right)^2 \tag{4}$$

where f_n refers to the n^{th} natural frequency, f_1 refers to the fundamental frequency. Equation (4) is used to calculate the tension force in this article.

6 An analysis of the mimic vibration

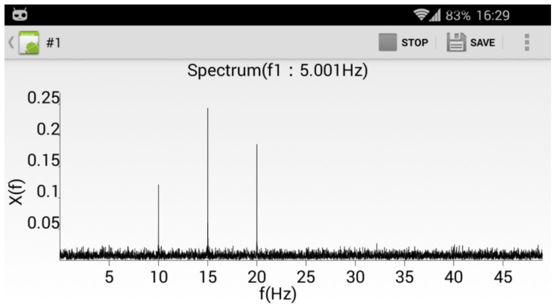
Generate expected vibration signals with software method and test validity of the method of recognizing natural frequencies adopted here.

7 The recognition of natural frequencies with the absence of false peaks

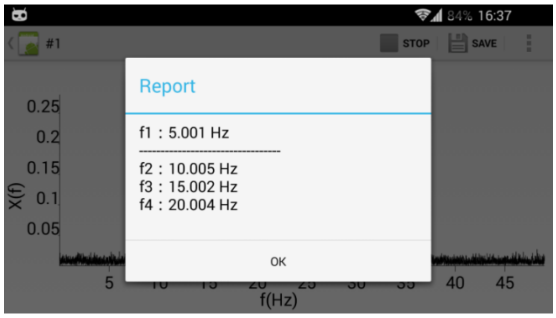
Assuming below is the expression of the simulated signals:

$$a_1(t)=0.05\sin(2\pi\times 5t)+0.4\sin(2\pi\times 10t)$$
$$+0.9\sin(2\pi\times 15t)+0.6\sin(2\pi\times 20t)+z(t),$$

where $z(t)$ is white Gaussian noise. Supposing the sampling rate is 100 Hz and the sampling length is 5000. It is not difficult to find out that the theoretical solutions of the $a_1(t)$ natural frequency is 5 Hz, 10 Hz, 15 Hz and 20 Hz, respectively.



(a)



(b)

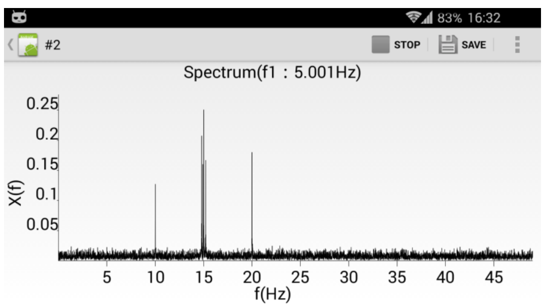
FIGURE 6 The recognition of natural frequencies with the absence of false peaks

FIGURE 6 (a) is the spectrum of $a_1(t)$. As we can see the power of the 1st component is so weak that it can be hardly identified in the figure.; however insular peaks occur at 10 Hz, 15 Hz and 20 Hz. Accordingly we get 10.005 Hz, 15.002 Hz and 20.004 Hz from our program. The solutions of our program are shown in FIGURE 6 (b) and as we can see the fundamental frequency is 5.001 Hz, very close to the theoretical solution.

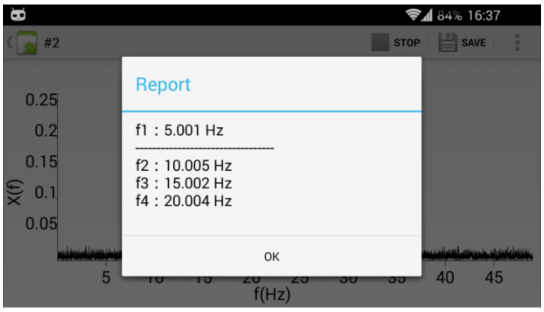
8 The recognition of the natural frequencies with the existence of false peaks

Add several powerful components mimic false peaks to $a_1(t)$ and supposing the expression of $a_2(t)$ is :

$$a_2(t)=a_1(t)+0.7\sin(2\pi\times 14.8t)$$
$$+0.5\sin(2\pi\times 14.9t)+0.6\sin(2\pi\times 15.2t)$$



(a)



(b)

FIGURE 7 The recognition of the natural frequencies with the existence of false peaks

Compared to $a_1(t)$, $a_2(t)$ has 3 more powerful component around 15 Hz, that is to say multiplets occurs around 15 Hz. The results are shown in FIGURE 7 (b), which is exactly the same with the results in FIG.6 (b).

9 The application in civil engineering

The Fanhe Bridge is a two-towered concrete beam cable-stayed bridge, the entire length is 604m, with the span being (152+300+152)m. FIGURE 8 is an overall layout of the main bridge. It is single-column-tower styled bridge and the tower above the pile caps is 120.2m high. $\phi 7-121 \sim \phi 7-253$ Semi parallel wire strands are implemented in the bridge and there are 92 of them, with 23 cables on both the side span and the middle span. We apply an Android Smart Phone (Samsung S3) to detect the tension and compare the results with the ones from the JMM-268 tension dynamic measuring instrument.

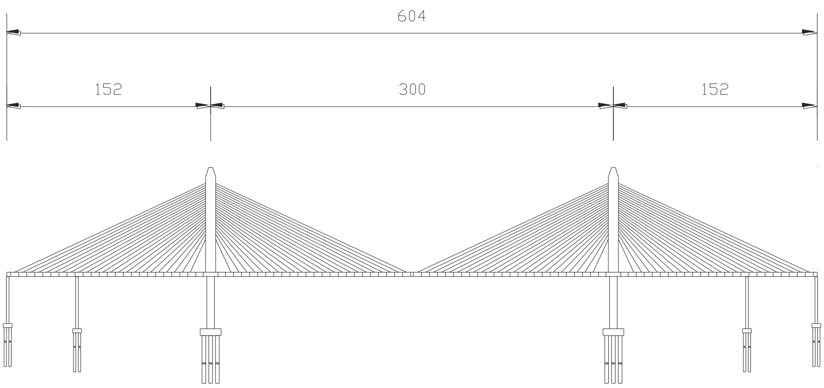


FIGURE 8 The elevation of Fanhe bridge (unit: m)

10 Specifications of the measuring device

The parameters of a Samsung S3 and a JMM-268 cable dynamic measuring instrument are enlisted in Table 1.

It can be seen from the above table that the properties of sensors on JMM-268 cable dynamic measuring instrument are slightly better than those of Samsung S3 in terms of noise and resolution parameters, however Samsung S3 is much lighter than JMM-268.

TABLE 1 The parameters of Samsung S3 and JMM-268 cable dynamic measuring instrument

Parameters	Samsung S3	JMM-268 dynamic measuring instrument
Sampling rate	5Hz,15Hz,50Hz, 100Hz, four choices available (100Hz selected for the test)	12.5Hz, 25Hz, 50Hz, 100Hz, 200Hz, five choices available (100Hz selected for the test)
Measuring range	±2g	±2g
Sensibility	±2.5V/g	±2.5V/g
Root mean square of noise	≤10-3g	≤10-5g
Resolution	0.2mg	0.2mg
Frequency response range	0.5~500Hz	0.3~500Hz
Axis	Three axes	Single axis
Weight	135g	>2.5kg

11 Results and analysis

For the purpose of represented cables, A1 ~ .A23 (length range: 34.7m~162.2m) are selected. Some spectrums of cables are shown in FIGURE 9. Material parameters and geometric parameters are enlisted TABLE 2.

The tests have found that the vibration of short cables is so weak under ambient excitation that it is almost submerged by the noise, owing to the fact that ends provides more constraint on short cables. Even artificial excitation can generate stronger vibration, it soon fades and no long enough signals can be collected. No dominant peaks can be found in the spectrum, which makes it hard for the programs to identify the natural frequencies. As the cables lengthen, there is an obvious increase in signal-to-noise ratio and dominant peaks occur. The intervals between neighboring peaks are basically the same, which is in accordance with the natural frequency spectrum. The natural frequency recognition by the program is remarkably accurate and the error between the phone-tested fundamental frequency and the JMM-268 tested one is less than 5%.

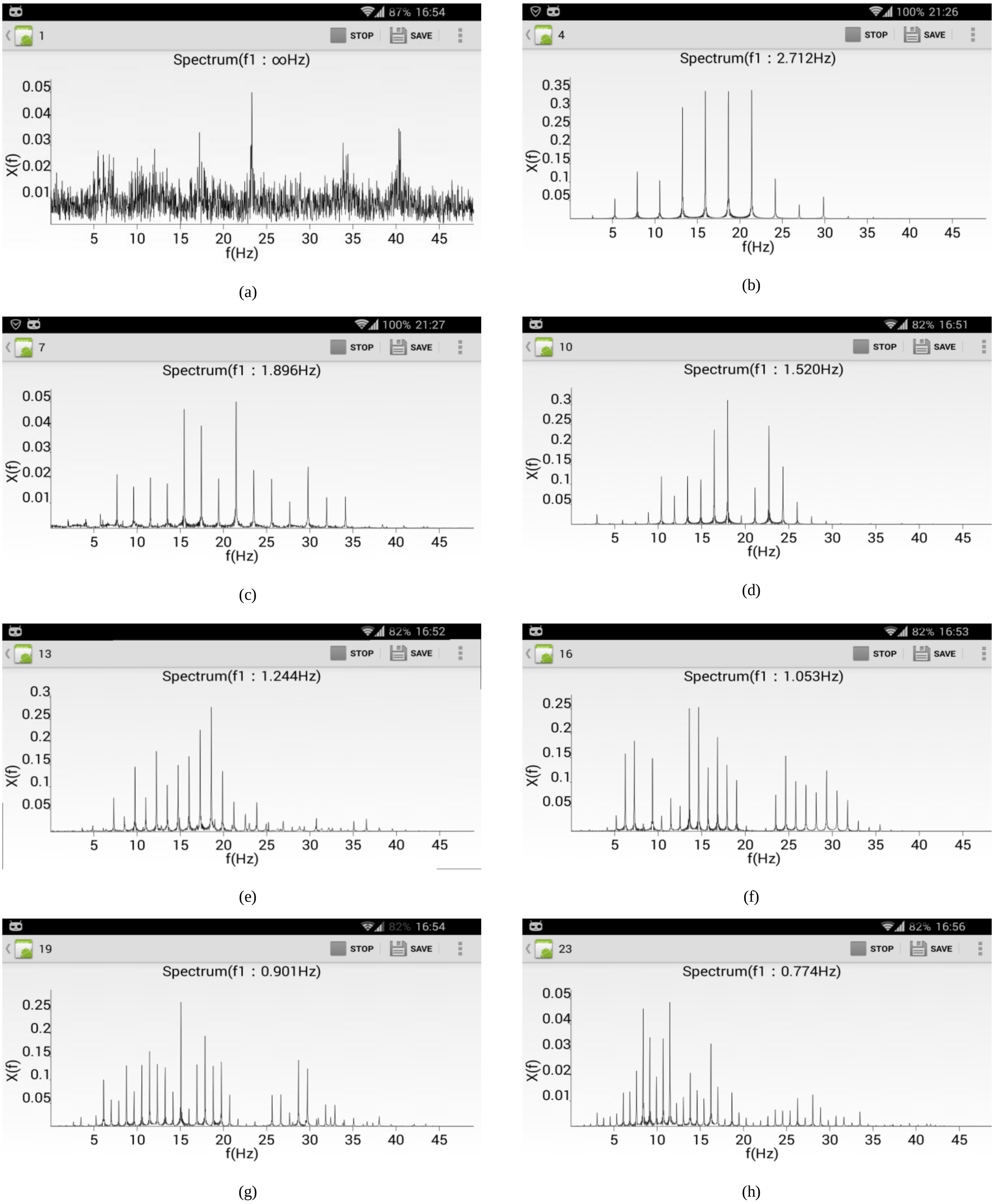


FIGURE 9 Spectrums of cables

TABLE 2 Cable parameters and the measured tension force

Cable number	ρ(kg/m)	EI (10^6N·m^2)	L(m)	fundamental frequency(Hz)		tension force(kN)		relative error of tension
				device 1*	device 2**	device 1	device 2	
1	35.7	0.85	34.70114	-	3.789	-	2462	-
2	35.7	0.85	39.52301	3.296	3.268	2418	2377	1.74%
3	35.7	0.85	44.49965	3.01	2.981	2558	2508	1.97%
4	35.7	0.85	49.50758	2.712	2.673	2571	2497	2.98%
5	39.7	1.08	54.97783	2.307	2.315	2551	2569	0.71%
6	39.7	1.08	60.52603	2.005	2.036	2336	2408	3.00%
7	39.7	1.08	66.18216	1.896	1.905	2498	2522	0.94%
8	45.7	1.45	71.92615	1.66	1.641	2603	2542	2.39%
9	45.7	1.45	77.65969	1.586	1.559	2771	2679	3.43%
10	45.7	1.45	83.53111	1.52	1.506	2945	2890	1.88%
11	49.2	1.56	89.44825	1.387	1.371	3027	2958	2.35%
12	49.2	1.56	95.40396	1.323	1.337	3134	3198	2.02%
13	49.2	1.56	101.3914	1.244	1.220	3129	3009	4.01%
14	53.2	1.86	107.4064	1.159	1.137	3296	3172	3.90%
15	53.2	1.86	113.8614	1.114	1.133	3422	3543	3.40%
16	53.2	1.86	119.4797	1.053	1.066	3367	3452	2.45%
17	53.2	1.86	125.5544	1.034	1.019	3585	3482	2.97%
18	60.8	2.34	131.6447	0.929	0.922	3636	3579	1.60%
19	60.8	2.34	137.7473	0.901	0.886	3745	3621	3.41%
20	60.8	2.34	143.8615	0.834	0.830	3500	3470	0.87%
21	60.8	2.34	149.985	0.836	0.852	3823	3973	3.78%
22	60.8	2.34	156.118	0.789	0.776	3689	3569	3.37%
23	64.5	2.57	162.2601	0.774	0.782	4068	4149	1.94%

Note *Device 1 refers to Samsung S3
**Device 2 refers to JMM-268 cable dynamic measuring instrument

The comparison of the results indicates that relative accurate measurement can be obtained when Samsung S3 is implemented to measure cables longer than 40m and the error is less than 5%. It also indicates difficulty in measuring cables shorter than 40m, which is caused by the louder noise of the integrated micro-accelerometer in the phone that submerges the vibration signals of the cables. The best option to solve this problem is to utilize a Smart Phone with lower noise.

12 Conclusion

This article introduces a method of measuring the cable tension force of a cable-stayed bridge by utilizing Android device. A Smart Phone (Samsung S3) is chosen to collect the cable vibration signal and the Fourier transform algorithm is adopted to obtain the frequency spectrum. Determine the fundamental frequency of the natural vibration and calculate the tension force. Compared to the measurements of the JMM-268 tension dynamic measuring instrument, the test of this method on an real bridge shows the Smart Phone has trouble measuring cables shorter than 40m; however there is less 5% error when the cables are longer than 40m.

The method introduced in the article is based on the Android platform, and the only essential hardware is a Smart Phone. All controls of micro-accelerometer are taken of by calling APIs provided by Android. Compared to the development of embedded system, it has a shorter development cycle yet greater portability.

It is low-cost to measure the tension force of a cable-stayed bridge with the application of a Smart Phone. While there is still some drawbacks in light of the micro-accelerometer embedded in the Smart Phone, which poses constrain in the tension measurement of shorter cables; however it can be foreseen that the performance of the micro-accelerometer can be much improved in the near future. Hence, the method introduced in this article is of great practical significances.

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