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Realization to Extend the Orientation Estimation Range of Moving Target on the Ground by a Single Vector Sensor

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Abstract

The DOA (direction of arrival) estimation of seismic signals from the moving target on the ground bears great significance for unattended ground systems. The traditional DOA estimation of seismic signals is achieved by a sensor array and its corresponding algorithms. MEMS (Micro-Electro-Mechanical Systems) vector vibration sensor, however, gets the vector information over the propagation of seismic signals and therefore can get a DOA estimation within a certain range through a single vector sensor. This paper proposes a new method to extend the orientation range through the rotation of the MEMS vector vibration axis. The experiment shows that this method shares the merits with simple systematic structure, high sensitivity and less than 5 degrees of error on average, which has an extensive wide application prospect.

Keywords: *MEMS, vector vibration sensor, seismic signal, direction of arrival*

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1. Introduction

Ground target motion, artificial excavation mining or other activities induce stimulus signals to the ground and cause a non-rigid earth medium deformation, which then forms seismic waves over its propagation through the earth medium [1-2]. When there is a vertical excited signal to the ground, generally, it will cause longitudinal wave (P wave), transverse wave (S wave) and Rayleigh wave [3-4], among which the Rayleigh wave propagates over a free surface, and it is of the most energy, lower frequency, slower attenuation, so the Rayleigh wave is more applicable for the target detect and DOA estimation for seismic signals, compared with the longitudinal wave and transverse wave.

The traditional seismic wave detector takes the Rayleigh wave’s vertical component as its perception target object, while the DOA estimation of the target signal is done through the sensor array. The four-beam cylinder structure, the vector vibration sensor, based on meso-piezoresistance effect and MEMS technology, has higher sensitivity, smaller size, lower energy consumption and better low-frequency response, and 8 font dipole directivity, so it is widely used in engineering [5-6]. Because the vector vibration sensor can get the vector information of a vibration signal, the DOA estimation of ground vibration signal through a single sensor has become engineering preferred and has a significant influence on the development and improvement of unattended ground systems and perimeter security system. This paper first introduces the propagation characteristics of seismic signals and the operational principle of MEMS vector vibration sensor. It also shows the experimental research of the DOA estimation of seismic signals and gives a data analysis to verify that the method to extend the orientation range is applicable.

2. The Characteristics of Seismic Signals and its Propagation

The activity of a moving target is a process of the target’s giving excitation to the ground; this excitation causes surface medium particle vibrations to form a seismic source and propagate to a farther distance in waves. The seismic waves can be divided into body waves

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and surface waves based on the characteristics of the movement of particle and its propagation. There are two kinds of body waves: P wave and S wave. The propagation direction of P wave is consistent with the vibrating direction of particle, it forms because of the compressive strain; the propagation direction of S wave is in vertical to the particle's vibrating direction, which is caused by shear strain. Surface wave with the low-frequency, strong energy secondary wave formed by a certain condition of the body wave's constructive interference and its energy shows exponential decay with the increase of its depth. Rayleigh wave is the main pattern of surface wave and is formed by P wave and S wave's superposition on a semi-infinite elastic medium and its propagation directions have anticlockwise oval shapes [1-2], as shown in Figure 1.

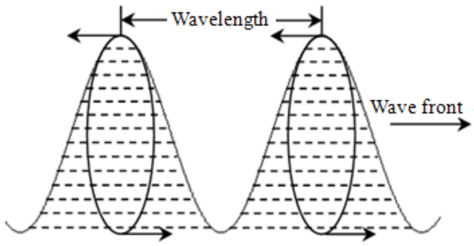


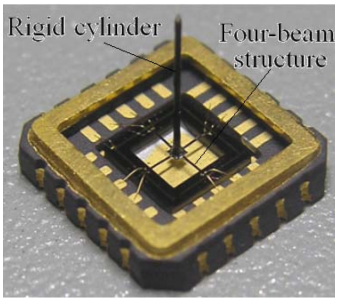
Figure1. The Locus of the Rayleigh Wave Particle's Motion

When a seismic wave propagates, the wave front of P wave and S wave have a hemispherical surface, and its area is in direct proportion to the square of the radius; therefore, the wave's energy attenuates according to the law of $1/r^2$ (r is the distance from the seismic source to the wave front of the seismic wave). The wave front of Rayleigh wave is a cylinder, its wave front area is in direct proportion to r, which indicates that the energy of Rayleigh wave attenuates according to law 1/r. This shows that the attenuation of body wave's amplitude is in direct proportion to 1/r, surface wave's amplitude attenuates in direct proportion to $1/r^2$. Therefore, the attenuation of Rayleigh wave is slower than that of body wave.

The main energy of seismic wave focuses on P wave, S wave and Rayleigh wave, among which Rayleigh wave takes 67% of the total energy and body wave takes 33% of the total energy [2]. Because the Rayleigh wave has stronger energy, attenuates comparatively slowly on a free surface and propagates to a greater distance, it is often used in seismic signals identification and detection.

3. The Operational Principle and Orientation Mechanism of MEMS Vector Sensor

MEMS vector vibration sensor is formed by four-beam microstructure and rigid cylinder. Figure 2(a) is a structure diagram and Figure 2(b) is a packed structure diagram and physical map of it. The four-beam micro structure is made with a standard silicon micro-machining MEMS technology. The piezoresistors are put at the sensitive position of the four beams; the rigid cylinder is fixed at the joint of the micro four-beam structure.



(a)

(b)

Figure 2. Structure Diagram and Physical Map of MEMS Vector Vibration Sensor

Mr. Guojun Zhang etc. have well elaborated the operational principle of MEMS vector vibration sensor in related documents [5-7]. Based on Piezo-resistance effect principle the strain of the sensitive structure on the elastic beam is reflected through the change of the resistance of piezoresistors. Therefore, when a vibration signal acts on the rigid cylinder, the cylinder will send the signal to the sensitive structure then it causes stress change on the beam, the resistance of the piezoresistors that is placed on the beam changes accordingly. Meanwhile, the Wheastone-bridge has comparatively higher sensitivity, better temperature compensation and higher output linearity, so the sensitive resistors are connected by a Wheastone-bridge. When the vibration signal acts on the rigid cylinder, the piezoresistors's change will be detected and the vibration signal will then be detected through the X and Y axis output of the Wheastone-bridge supplied by direct-current power.

When doing the DOA estimation, the vector vibration sensor is put at the coordinate origin, and it takes the two perpendicular axis of the Wheastone-bridge as the vertical and horizontal axes of the coordinate, S(x,y) is the seismic source, as Figure 3 shows. The vector sensor's rigid cylinder is put vertically to the ground surface. Based on its operational principle and the characteristics of the propagating of Raleigh wave, what the sensor measures is the horizontal component of Raleigh wave, that is, the DOA is the orientation of the seismic source. Within the detected area, the propagating medium of the seismic wave is thought uniform, and there is no frequency dispersion property when the Rayleigh wave exists in the isotropic medium [8].

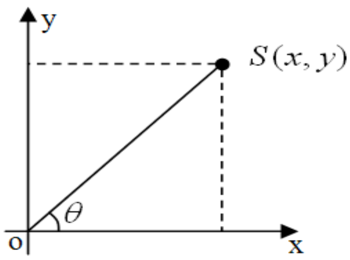


Figure 3. Seismic Source DOA Estimation Schematic

The azimuth angle of seismic source can be found through formula (1):

$$\theta = \arctan(\frac{\mathbf{v}_y}{\mathbf{v}_x}) \quad (1)$$

Where Vy is the Y channel component of vibration speed of the vector vibration sector; Vx is the X channel component of vibration speed of the vector vibration sensor. This is the fundamental principle of the DOA estimation by single vector vibration sensor.

4. DOA Estimation Experiment

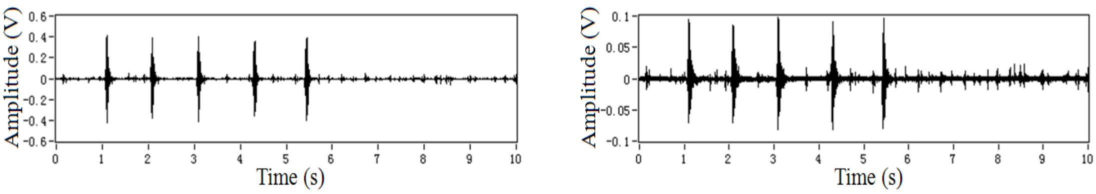
The sensitivity of the vector vibration sensor is in direct proportion to the height of the rigid cylinder and the natural frequency is in inverse proportion to the height of the rigid cylinder: the higher the rigid cylinder, the higher the sensitivity, the lower the natural frequency [7]; meanwhile, the sensitivity is inversely proportional to the beam thickness of the micro structure: the thicker the beam, the lower the sensitivity. Taking the measuring requirements of sensitivity and natural frequency into consideration, the sensor parameters is defined as the beam's thickness10um, the rigid cylinder's height 5mm. The experiment is carried out on an open flat land. The sensor is perpendicularly buried into the soil, which is then filled and leveled up to ensure that the sensor and the soil are well coupled together. As shown in Figure 4(a). At the semicircle which is of an equal distance toward the sensor, take an angle of 10 degrees as interval aliquots arc, use a hammer to tap the division point as an analog seismic source.

In Figure 4(b), the vector vibrate sensor is placed in O point and the black spots on the semicircle arc represents seismic source S. The seismic signals convert into electrical signals through the vector vibration sensor. The host-computer program adopts the LABVIEW virtual instrument language programming and acquires the signals by the multiplex data sampling card. The sampling system uses a model PXIe-1071(National Instruments, TX, USA) that interfaces with the host-computer via its PXI Express bus, the data-sample module and terminal box use BNC-2110(National Instruments, TX, USA). The sampling rate is 50kHz, and sampling time is 10s.

(a) (b)

Figure 4. The Embedded Sensor and Experimental Schematic Diagram

Through experiments the sensor can acquire the seismic signal at a distance of 30 meters, which meets the general engineering requirements. Figure 5 shows the signals acquired by vector sensor's X channel and Y channel when the included angle of the seismic source and X axis of the vector sensor is 10 degree.



(a) X channel signal (b) Y channel signal

Figure 5. The Two Channel Seismic Signals Acquired by the Vector Sensor

5. Data Analysis and Processing

Unavoidably, the seismic signal acquired is affected by the environmental noise, so the characteristics of the target signal cannot be used directly. Therefore, it's the prerequisite of subsequent analysis that the target signal is acquired through a filter. To determine the cut-off frequency of the filter, the spectrum analysis is done first. The result of the spectrum analysis is shown by Figure 6.

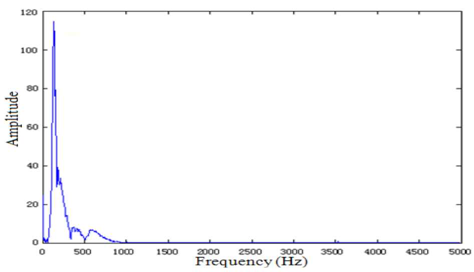


Figure 6. Seismic Signal Spectrum

Based on the spectrum analysis, the frequency of the seismic signal mainly focuses within 120--170Hz, so the 7th order Buterworth filter with a 200Hz upper frequency value and an 80 Hz lower frequency value is adopted. The seismic source orientation estimation result is shown by Table 1.

Table1. Single Vector Vibration Sensor Direction Angles Analysis (range: 0-90 degree)

Theoretical angle	measured angle	error
0	8.2646	8.2646
10	12.7513	2.7513
20	17.9750	-2.0250
30	25.5965	-4.4035
40	36.4033	-3.5967
50	52.0634	2.0634
60	57.1101	-2.8899
70	72.8763	2.8763
80	77.9960	-2.0040
90	82.0382	-7.9618

The directed results show that the single vector vibration sensor does a fairly good DOA estimation towards the seismic source under the first quadrant of the coordinate system; the average error is less than 5 degrees. Closer to the sensor’s axis the error is bigger because of the packaging technique of the sensitive cylinder and the cross beam [9].

The structure of the vector vibration sensor itself determines that the seismic signals at the symmetry area of the axis definitely cause the same output response: the sensor cannot distinguish the quadrant of the seismic source under the same coordinate system. In engineering application, the location of the signal that causes the output of the sensor remains constantly at the same side of the sensor; therefore, if the quadrant of the seismic source can be detected within 0--180 degrees range, it can meet the general requirements.

During the experiments, rotating the vector vibration sensor axis to transfer the coordinate system can do the DOA estimation within a 0--180 degree range. Figure 7 shows the basic principle. In Figure 7, ***XOY*** is the original coordinate, and ***xoy*** is the new coordinate after the sensor rotates counterclockwise a specific angle.

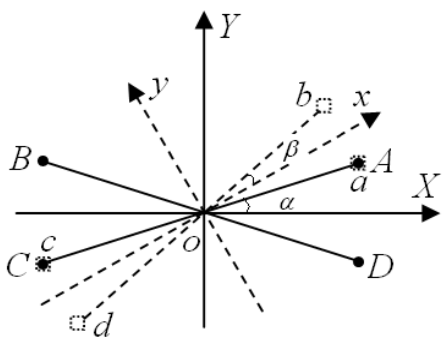


Figure 7. Schematic of DOA Estimation by Rotating Sensor

Suppose the seismic source is at spot ***A*** of Figure 7, according to formula (1), the DOA estimation result α is an acute angle. If the seismic source is at spot ***B***, spot ***C***, or spot ***D***, the result is also α. Rotate the sensor coordinate system counterclockwise a certain angle (for example, 30 degrees), the possible location of seismic source ***A*** under the new coordinate system can be spot ***a***, spot ***b***, spot ***c***, and spot ***d***, as shown in Figure 7. Apparently, line ***AC*** and line ***ac*** should coincide theoretically. If the seismic source location can be determined at one side of the sensor, the location can be solely determined.

Due to measurement error in processing the experiment, line ***AC*** and line ***ac*** cannot coincide completely. Suppose the four possible angels under the original coordinate system are α , $180-\alpha$, $180+\alpha$ and $360-\alpha$, the rotation angle is θ , the four possible angles under the new coordinate system after rotation are β , $180-\beta$, $180+\beta$ and $360-\beta$ (β is the DOA result under the new coordinate). Transfer the angles under the new coordinate system to the original coordinate system, the results are $\beta+\theta$, $180-\beta+\theta$, $180+\beta+\theta$ and $360-\beta+\theta$. All the angles are valued within a 0--360 degree, and then there will be four possible angles in the first and second quadrants of the original coordinate system. Take the average of the two closest angles as the result of the DOA estimation of the seismic source, the directed data is shown in Table 2, when the system is rotated 30 degrees.

Table 2. Single Vector Vibration Sensor Direction Angles Analysis (range: 0-180 degree)

Theoretical angle	angle under original coordinate	angle under new coordinate	directed result	error
0	8.2646	24.8983	6.6832	6.6832
10	12.7513	16.4403	13.1555	3.1555
20	17.9750	15.4907	16.2422	-3.7578
30	25.5965	9.6945	22.9510	-7.0490
40	36.4033	14.9437	40.6735	0.6735
50	52.0634	25.5439	53.8037	3.8037
60	57.1101	34.1187	60.6144	0.6144
70	72.8763	43.1617	73.0190	3.0190
80	77.9960	54.7656	81.3808	1.3808
90	82.0382	58.2886	85.1634	-4.8366
100	77.0057	64.8954	98.9449	-1.0551
110	66.2525	75.6195	109.6835	-0.3165
120	55.4813	79.0692	127.7248	7.7248
130	46.4543	76.6732	133.4363	3.4363
140	43.8282	73.0061	136.5829	-3.4171
150	27.9704	56.3832	152.8232	2.8232
160	22.9409	51.0226	158.0182	-1.9818
170	13.5456	44.0802	166.1871	-3.8129
180	11.9891	33.7382	172.1363	-7.8637

6. Conclusion

Seismic sensor array is usually used in DOA estimation of ground seismic signal. The seismic signal DOA estimation system discussed in this paper adopts a single MEMS vector vibration sensor, which can do the DOA estimation of seismic signal within 0-180 degree range. It is applicable and it has a high sensitivity with an average error of less than 5 degrees; thus well meeting the engineering application.

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