ABSTRACT This paper describes a perforating gun detonation monitoring system developed to meet the need for real-time monitoring of perforation effect in the petroleum industry. A high-sensitivity acceleration sensor, serving as the response module of the physical characteristics of the tubing vibration, acquires a set of vibration signals of the whole physical process during the impact after the detonation of the shaped charge. The jump point in the monitoring process is extracted by comparing the signal’s short-time energy. The amplitude, energy, and envelope characteristics of the signal are then evaluated. From the time-frequency characteristics of the tubing vibration upon the detonation of the perforating gun, a judgment is made as to whether the perforating gun has detonated. Tubing vibration experiments were conducted involving different perforating guns. The results suggested that the proposed monitoring method is able to monitor perforating guns of different shaped charges with a perforating depth between 500m-3500m and in oil wells with an inclination of 0°-90°. As a means of vibration detection, this method also works well in other types of vibration monitoring.

INDEX TERMS Vibration detection, signal characteristics, short-time energy, perforating gun detonation, tubing vibration.

I. INTRODUCTION
In the petroleum industry, in order to accurately monitor the effect of oil well perforation, there is a steadily growing demand for perforating process monitoring. Tubing conveyed perforation is one of the most commonly used petroleum perforating technologies. In the process of tubing conveyed perforation, perforating gun is mainly used to penetrate the formation to increase oil production [1], [2]. Complete detonation is an important factor determining the success of the perforating operation [3] and also an important part of the construction safety in the petroleum industry. Therefore, it is of great significance to monitor the completion of the perforating gun detonation.

Tubing conveyed perforation figures among the most commonly used perforating technologies in the petroleum industry both in China and abroad [4]. This kind of perforation is mainly achieved with a perforating gun [1], [2]. The detection of tubing vibration caused by the detonation of the perforating gun is an important way of determining the perforation effect. Complete detonation of the perforating gun is not only an important prerequisite for successful perforating operation [3], but also an important part of safe perforation. Thus the detection of the completion of the perforating gun detonation is of great account in practical applications.

The perforating gun detonates, to produce a jet, which impacts and penetrates the tubing. Under the impact, the tubing experiences axial and radial vibrations. In the measurement of tubing vibration, the measurement model of pipeline vibration after perforating gun initiation is mainly analyzed. [5], [6]. Zhang et al. [7] puts forward a method for determining the completion of detonation by measuring the tube liquid pressure change following perforating. Shardakov et al. [8] proposes using a tailing charge at the bottom of the perforating gun, this charge detonating after the perforating gun gets detonated. The tailing charge explodes, to impact the tubing, generating a delayed vibration signal, while the tube vibration is monitored in real time from
the ground. This method works for a string of single perforating pipes. When applied to a multi-layer perforation pipes, misjudgment is likely because of the distortion of the signal. Moreover, since this method makes use of tailing charges, which are explosives, extra safety concerns arise with the transportation and use of the charges. This drives up the operation cost. At the time of perforating, there exist accompanying on-site construction activities such as pumping truck pressurization, wellhead work, and wellhead locomotive operation [9]. So, the vibration of the tubing at the moment of perforating is the result of superposition of various vibrations. Still, the propagation mode of the tubing vibration varies with the perforation work environment [10], [11]. In order to acquire the vibration signal of the tubing during the perforation, the acquisition system must be capable of acquiring complex vibration signals and have compatible processing capabilities.

In this paper, the authors propose a perforating gun detonation monitoring method based on real-time monitoring of tubing vibration signals. This method is built on the detection of the vibration signal of the tubing generated by the impact of perforation. In the course of the impact, a high-sensitivity accelerometer YD-8 is used to acquire the tubing vibration signal in real time. From the time-frequency characteristics of the tubing vibration upon the detonation of the perforating gun, the perforation shock vibration signal is determined through short-time energy signal processing. This system has been tested in an experimental monitoring of perforation operation in 15 wells, of an inclination from 0° to 90° and a perforation depth of 500m-3500m, each containing over 16 shaped charges. After checking the actual situation of the perforating gun, the accuracy of the perforating gun detonation was determined to be 100%, which proved the reliability of this method.

The perforating detonating tubing vibration detection system described in this paper has been applied to tubing vibration signal analysis on the vibrating physical effects caused by the detonation in several oil wells. The propagation law of the perforating detonating tubing vibration is established through the analysis of a large amount of data.

II. PRINCIPLE OF TUBING VIBRATION GENERATION UPON PERFORATING

To define the rotational movement of the carrier in a coordinate system, we set the carrier center of gravity at the origin o, take the vertical direction pointing upward, when in the initial position, as axis z, the carrier axis as axis x, and the line passing through the origin and perpendicular to axes x and z as axis y, with the x, y, z constituting a right-hand rule coordinate system. In its rotational movement, the carrier performs a motion described by Euler kinematical equations. A set of triaxially orthogonal magnetic induction coils are installed in the carrier, as shown in Fig. 1, in order to measure its angular rate. The set of triaxially orthogonal coils installed in the carrier rotates with it. As they are rotating in a magnetic environment, induction currents are created on the coils, which in turn create electromotive forces (EMFs). The induced EMFs are acquired as the signal fed back by the carrier in rotation. When acquired, the signal is conditioned to remove noises and then the signal phases are measured. Phase analysis helps us determine the periodicity of the induction signal, and this periodicity reflects the carrier’s rotational period.

III. LAYOUT OF TRIAXIALLY ORTHOGONAL MAGNETIC INDUCTION COILS

A. ARRANGEMENT OF PERFORATION CHARGES AS THE VIBRATION SOURCE

The detonating cord connects the perforating charges in a spiral pattern [6], [12], where a number of perforating charges together make up a perforating gun. These days, the most commonly seen loads are 12 charges/meter, 13 charges/meter, and 16 charges/meter. The detonating cord connects the perforating charges in the form of a spiral, as shown in Fig. 1.

From the formula of spiral, the length of the detonating cord between two charges is:

$$L = \sqrt{(\pi d)^2 + s^2}$$

where d is the diameter of the charge rack in the perforating gun and s is the spacing between the two charges.

At present, the loading density is generally 16 charges/meter. Taking the widely used 102 perforator as an example [3], the diameter d of the charge rack is 62mm. The length L of the detonating cord between two adjacent charges, according to the above equation, is about 79mm. The propagation speed of the detonating cords used in China is 6500m/s-7000m/s. Hence, the detonation time interval between two adjacent shaped charges is 13.17µs – 11.29µs. The detonation vibration signal is generated by the perforating gun travels at 5130m/s along the rigid oil tube casing, with an attenuation coefficient of 20 dB/km, which does not affect the vibration interval of two consecutive perforating charges [13], [14].

B. THE PRINCIPLE OF IMPACT VIBRATION OF THE PERFORATING GUN ON THE TUBING

The oil pipeline consists of the tubing, the well liquid, and the wellbore, a “sandwich” sandwich structure of metal+liquid+metal [15]. After detonation, the blasting pressure wave reflects and transmits back and forth between different interfaces of the pipe string. Under the action of the strong asymmetrical overloading impact, the perforating tube twists and oscillates radially [16], and the tubing connected to the gun body moves in response to the perforating tube. As a whole, this is a process of mechanical loading and unloading.
When the perforating gun gets detonated, the perforating charges and the detonating cord blast to create a transient shock wave, causing an impact on the tubing, which creates axial vibration along and radial vibration perpendicular to the length of the vertical pipe string [17]. As shown in Fig. 2, the axial vibration of the tubing is an up-and-down movement. As the tubing has a large weight, the attenuation in propagation along it is great. The radial vibration propagates upward along the casing string, and as the tubing is filled with liquid on both sides, the attenuation is less when compared to the axial vibration. The vibration collected by the wellhead sensor is mostly radial vibration signal [18].

The tubing, when subjected to impact vibration under continuous action of the perforating charges, experiences impact vibration, with the forced vibration of the action point propagates through the elastic metal tubing medium. The amplitude of the impact vibration depends on the amount of perforating ammunition, well depth, and well inclination [19].

From the vibration wave generated by the perforating gun, taking advantage of the physical characteristics of the vibration wave propagation, the influence of the depth of the perforation on the amplitude of the waveform is mainly seen in the weak attenuation variation of the vibration wave in the propagation process, and the vibration wave propagates along the tubing wall. The direct wave is received at the wellhead [20], [21].

**IV. ANALYSIS OF VIBRATION PROPAGATION LAW AFTER PERFORATING CHARGE DETONATION**

The perforating charges are detonated using a detonating cord. In engineering practice, a plurality of perforating charges are connected together to form a perforating gun string, and a plurality of perforating gun strings constitute a multi-layer perforating gun group, as shown in Fig. 3.

During the perforating operation, the perforating guns are ignited from the top by means of pressure, dropping rod, cable, etc., and the detonating cord ignites the perforating charges from top to bottom. In the presence of an interlayer (in which there is no perforating charge) [22], [23] in a multi-layer perforation operation, the perforating gun string detonates layer by layer from top to bottom.

If the interlayer itself contains two layers and three gun strings are involved, and the perforating signals collected at the wellhead is of this sequence: the first layer (perforating gun string one, or PGS1), the second layer (perforating gun string two, or PGS2), and then the third layer (perforating gun string three, or PGS3) and so forth.

In the case of simultaneous pressure detonation, when there are detonating devices for the three strings of perforating guns, the perforating gun strings one, two, and three impact the pipe wall simultaneously, and the resulting shock wave, because of the interval of the perforating gun strings, then impact vibration PGS1, PGS2, PGS3 simultaneously start to propagate toward the wellhead, and the wellhead receives sequentially the vibration of the perforating gun strings, that is, in a sequence of PGS1-> PGS2-> PGS3; in the case of the detonation of three perforating gun strings, if PGS2 string detonates first and PGS1 and PGS3 strings do not detonate until the impact vibration of PGS2 string passes the location of PGS1 string, then the sequence of signal received at the wellhead is PGS2-> PGS1-> PGS3; if PGS3 string detonates after PGS1 string, and PGS2 string detonates after the impact vibration of PGS3 string passes the location of PGS2, then the sequence of the signal received at the wellhead is PGS2-> PGS1-> PGS3. The above analysis suggests that the receiving sequence of signal has no corresponding relationship with the distance of the perforating gun string, that is, this sequence has no absolute proportional relationship with the position signal of the perforating gun strings.

If the perforator consists of a single layer of perforating charges, then the depth of the perforation layer has an influence on the receiving time. The deeper the perforation layer, the later the receiving time. The receiving time varies linearly with the depth of the perforation layer. The signal amplitude decreases with the depth of the perforation layer [24], [25].

**V. THE COMPOSITION OF THE PERFORATING GUN DETONATION VIBRATION MEASUREMENT SYSTEM**

Based on the above analysis, a perforating gun detonation monitoring system can be constructed that consists of a vibration acceleration sensor, a signal conditioning module, a data acquisition module, and a host computer, as shown in Fig. 4.

To deal with the detonation vibration response of two adjacent shaped charges, the sensor must be able to respond to signals spaced apart no greater than 11.29μs, that is, its response frequency should be greater than 7 kHz. In view
of the sampling principle and engineering feasibility, sensors with 5-6 times the required response frequency are desirable, that is, acceleration sensors with a response frequency of 40 kHz.

The system’s signal acquisition module is then designed on the basis of the sensor frequency response. Theoretically, in order to acquire a sinusoidal signal with a frequency of 40 kHz, an ADC with a signal frequency greater than 9 times the signal frequency is recommended. Hence, in this study the system incorporated an ADC of 400 kHz.

VI. ANALYSIS OF THE DETONATION VIBRATION SIGNAL OF SHAPED PERFORATING CHARGES
Proceeding with the above analysis, an analysis process, as shown in Fig. 5, of the vibration signal of the shaped perforating charges was constructed.

The perforating vibration signal, after entering the upper computer, is pre-processed, whereby the low-frequency and high-frequency noise signals are removed to improve the signal SNR, and the baseline fluctuation of the signal is also removed to enhance the perforation vibration signal. The pre-processed signal is then analyzed for its characteristics, and frequency analysis is performed to determine whether the local signal includes the perforating gun detonation vibration signal. If the answer is yes, the local region is expanded forward and backward to determine the scope of the signal. The local signal is analyzed for its amplitude in order to see if there exists a maximum value of the acquired signal, which is sufficient to serve as the global judgment criterion for the detonation vibration signal of the perforating gun. Then, signal energy analysis is carried out to determine whether the local signal contains the global maximum energy, which works as a criterion for determining whether this local signal carries the perforation detonation vibration characteristic.

The signal characteristics found by signal analysis are fused, during which process the frequency, amplitude and energy are subjected to combinational judgment, to locate all the signal positions corresponding the perforation detonation vibration points. If these points exist, a prompt is output informing that the perforating gun has detonated. After that, the signal of the detonation section is analyzed in more details, during which the signal characteristic analysis method is adopted. This analysis focuses on the high frequency signal in order to determine the signal interval, to remove the tail of the vibration signal, and to separate the detonation vibration signals generated by different perforating gun strings.

VII. EXPERIMENT AND ANALYSIS
Major characteristics of the perforating gun detonation signal are frequency, amplitude and energy. A comparative analysis of the acquired signals has suggested that frequency is the pre-requisite characteristic of the perforating gun detonation signal.

The designed perforation monitoring system acquired the detonation signals from perforating guns on the oil exploitation site.

Tubing conveyed perforation test: The vibration measurement sensor was connected to a strong magnet. During experimenting, the sensor was fixed along with the magnet on the wellhead tubing, as shown in Fig. 6. The well in which the experiment was carried out was an inclined well, the angle between the tubing and the vertical being 60°, and the detonation was triggered off by the pressure transmitted through the tubing. The perforation depths were 614.0m-615.6m, 617.4m-622.0m, and 623.0m-625.0m. The tubing vibration deforms the internal crystal of the sensor, which generates a voltage signal, so the radial vibration signal of the oil pipe is converted into a voltage output, and the data is saved to the computer through the serial port.
The data collected by the sensor which is shown in Fig. 6 are output in order to obtain the relationship diagram between the number of sampling points and the voltage. The relationship diagram between the sampling time and voltage as shown in Fig. 7 is obtained by the sampling frequency of the sensor. By performing spectrum analysis on the acquired signal, the signal frequencies are grouped in 0-1kHz. The signal obtained by the sensor is mixed with various field noise, so processing methods such as removing DC components, filtering, and obtaining short-term energy are needed. The analysis results of TCP vibration signal are shown in Fig. 8. Through the signal analysis, we get the vibration signal of a perforating charge and the energy distribution of the initiation signal. Based on the rate of change of signal energy, the position of the initiation signal is determined. Then we determine the initiation time of perforating gun according to the characteristics of the initiation signal.

**VIII. CONCLUSION**

This paper analyzes how the detonation vibration signal of a perforating gun is generated and proceeds to design a ground monitoring system of the perforating gun detonation signal based on high frequency response acceleration sensor and high speed PCI acquisition card. The detonation signal of the perforating gun at a depth over 500m was collected, which was able to reliably reveal the vibration characteristics of the detonation.

The collected perforation detonation vibration signal was analyzed, and it was found that in the case of cable conveyed perforation detonation the minimum energy rising edge slope was 2.32-3.32, which was 8.5 in the case of pressure transmission detonation. As the energy rising edge slope increased with the depth and inclination, the slope of the energy rising edge of the acquired signal increased linearly.

The perforating gun detonation vibration energy signal rising rapidly (a rising slope greater than 1) corresponded to the starting point of the perforation. The signal falling back to 2/3 of the current signal peak marked the end of a perforation string. After that, the signal rose again to the peak of the previous signal, symbolizing the start of the detonation of another string of perforating guns. The above process was repeated to determine the detonation of different strings of perforating guns; the vibration energy information corresponding to the start of the detonation was characterized by the largest and the strongest global intensity.

When the perforation charge interval shortened, the energy and amplitude of the signal both grew. When the length of the perforation interlayer increased, the perforation vibration signal interval increased as well. When the perforation depth increased, the perforation signal energy and amplitude both decreased. The perforation signal of an old well had a lower SNR. Where the frequency characteristics are concerned, as the signal propagated along the pipeline, the high-frequency signal attenuated more noticeably, that is the pipeline acted as a low-pass filter.

It has been demonstrated that, through analysis of the experimental results, the proposed monitoring system is capable of determining whether the detonation of various types of perforation have been completed.

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