Research on clock synchronization method of marine controlled source electromagnetic transmitter base on coaxial cable

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Abstract. Marine controlled source electromagnetic (MCSEM) method is widely employed to reveal the electrical structure of shallow media below seafloor. It is an indispensable geophysical means in the exploration of marine oil, gas, natural gas hydrates and seafloor geological structures. The transmitter and receiver in electromagnetic detection equipment need to maintain a high temporal consistency, typically relying on high-stability pulse-per-second (PPS) generated by GPS or BeiDou navigation modules. Coaxial cable is a widely used tow cable, so it is necessary to design a clock synchronization method of marine controlled source electromagnetic transmitter using coaxial cable. This paper proposes a method for synchronizing the internal clock of transmitter with PPS using ship-borne power supply when coaxial cable is used as tow cable. In this method, the ship-borne high-power supply outputs a high-voltage alternating current (AC) signal that is synchronized with 400 Hz signal output from GPS; the coaxial cable transmits AC high-power electrical energy and control commands; the AC signal transmitted via coaxial cable is converted into a stable and continuous 1 Hz signal by step-down, waveform shaping and frequency division for synchronizing the internal time pulses of transmitter. The test result shows that 1 Hz signal obtained by this method has a deviation of approximately 504 ns relative to PPS. This deviation meets MCSEM transmitter's requirement for clock synchronization.

Keywords: marine controlled source electromagnetic, coaxial cable, transmitter, clock synchronization

1 Introduction

Marine controlled source electromagnetic (MCSEM) method is one of the methods in exploration of seafloor natural gas hydrates (Edwards and Chave, 1986; Cox et al., 1986). It is an indispensable geophysical means in the exploration of marine oil, gas, natural gas hydrates and seafloor geological structures (Constable and Srnka, 2007; Constable, 2010). In MCSEM method, the synchronization of internal clocks between transmitter and receiver is an very important issue (Wang et al., 2015b; Meng et al., 2009). Electromagnetic data processing and interpretation depend on synchronization between transmitter and receiver (Qiu et al., 2020). MCSEM transmitter and receiver are separated from each other (Chen et al., 2012; Chen et al., 2020), and they are not connected by any cable. Therefore, Pulse-Per-Second (PPS) signal output from GPS is used as a common synchronization signal to synchronize the internal clock of transmitter and receiver.

The tow cables commonly used in MCSEM transmission systems are photoelectric composite cables and coaxial cables. The transmitter's clock synchronization method varies based on the type of tow cable. When using coaxial cable as tow cable, clock synchronization can be achieved by controlling power supply output or transmitting PPS to transmitter before it is submerged. As an example, SUESI-500 transmitter of Scripps Institution of Oceanography uses a standard UNOLS 0.680 inch

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(17.27 mm) coaxial cable as tow cable. They use a 400 Hz output from a GPS clock to generate a 400 Hz sine wave of variable amplitude to control power supply (Constable, 2013; Constable, 2006). The clock information in power signal serves as a reference for clock-related operations within transmitter. SUESI-500 transmitter's frequency control signals is generated based on 400 Hz signal. When using photoelectric composite cable as tow cable, clock synchronization can be achieved by transmitting PPS through one channel of optical fiber. For example, the transmitter of China University of Geosciences (Beijing) uses a 32.8 mm photoelectric composite cable as tow cable, and its clock synchronization is achieved by transmitting PPS and GPS time through optical fiber (Wang et al., 2021). However, the cost of photoelectric composite cable is high and generally only large scientific research ships can be equipped. In order to enable MCSEM transmitters work on a wider variety of ships, using coaxial cable is necessary. Compared to photoelectric composite cable, coaxial cable has only one message channel and can't be assigned a separate channel to transmit PPS. The coaxial cable can transmit data and commands using power line communication, but its delay is unstable. If PPS is transmitted via coaxial cable, it will have a large deviation. Consequently, how to use coaxial cable to synchronize internal clock of MCSEM transmitter is a challenging problem. This paper proposes a clock synchronization method of MCSEM transmitter based on coaxial cable. In this method, the sinusoidal signal from power supply is synchronized with 400 Hz square wave signal from GPS. Then the sinusoidal power signal transmitted to underwater transmitter is converted into a stable and continuous 1 Hz square wave signal by step-down, waveform shaping and frequency division. The final 1 Hz square wave signal is as the synchronization signal for transmitter's internal clock.

2 Clock synchronization based on coaxial cable

In this paper, the tow cable used is coaxial cable. This coaxial cable not only transmits electrical energy but also functions as a communication link between deck monitoring terminal and underwater transmitter. Communication is achieved through power line communication technology (Ferreira et al., 2001; Amuta et al., 2020; Kaddoum and Tadayon, 2016). The power transmitted through coaxial cable is a 400 Hz sinusoidal waveform.

Fig.1 illustrates the schematic diagram of MCSEM transmission system, which is based on coaxial cable. The ship is equipped with an instrument control room used to house personal computer (PC) and deck monitoring terminal. The deck monitoring terminal is connected to the ship-borne high-power supply, allowing it to control power on/off functions and communication with underwater transmitter. It also receives GPS time messages and PPS for clock synchronization. The ship-borne high-power supply generates 0~3000 V, 400 Hz alternating current (AC) electricity to power underwater transmitter (Wang et al., 2017b). In addition to transmitting electrical energy, the coaxial cable also transmits commands to underwater transmitter by power line communication. The underwater transmitter consists of two main components: a transmission chamber and a control chamber. The transmission chamber contains step-down, rectification and inverter units, which transmit high power electromagnetic waves to the seafloor (Wang et al., 2015a). The control chamber contains control circuit of entire transmitter, allowing it to transmit frequency-switching signals to control high-current transmission and monitor transmitter's state parameters. The transmitter is also equipped with auxiliary tools such as an altimeter and an attitude module to measure safety-related parameters during underwater towing. Behind the transmitter, two electrodes are towed, with a tail fin attached to the electrodes to stabilize their orientation (Wang et al., 2013; Wang et al., 2017a; Liu et al., 2012).

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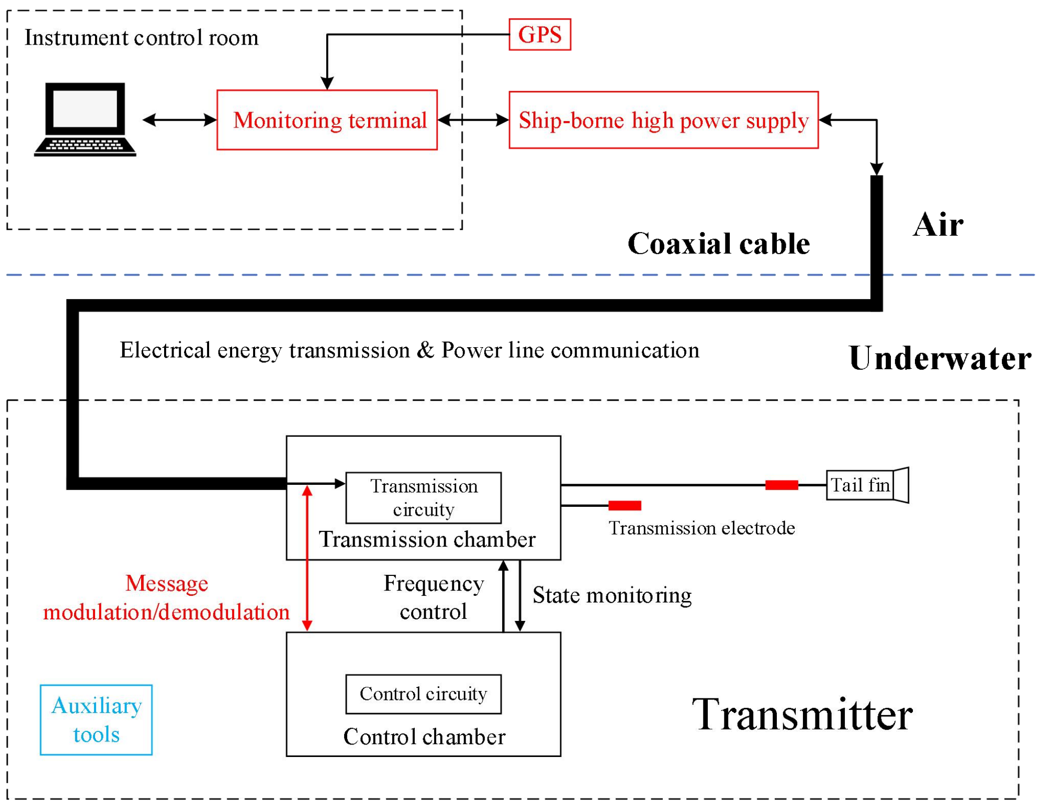

Fig.1 The schematic diagram of MCSEM transmission system based on coaxial cable.

Fig.2 illustrates the synchronization signal flow based on coaxial cable. The GPS module features a TIMEPULSE pin that can be configured to output a 400 Hz square wave, with its rising edges precisely aligned with PPS at integer seconds. The 400 Hz square wave is transmitted to the ship-borne high-power supply through deck terminal as a synchronization signal. To prevent interference from high-power supply, the signal between deck monitoring terminal and power supply is transmitted via an isolated RS485 bus. The 400 Hz sinusoidal signal generated by high-power supply is transmitted to underwater transmitter through coaxial cable, where it is converted to a sinusoidal signal in the range of 0~22 V by two transformers. The signal processing unit in transmitter's control circuit processes the 0~22 V sinusoidal signal and generates a 1 Hz square wave as the synchronization signal for control circuit. The rising edges of 1 Hz square wave are aligned with the rising edges of PPS.

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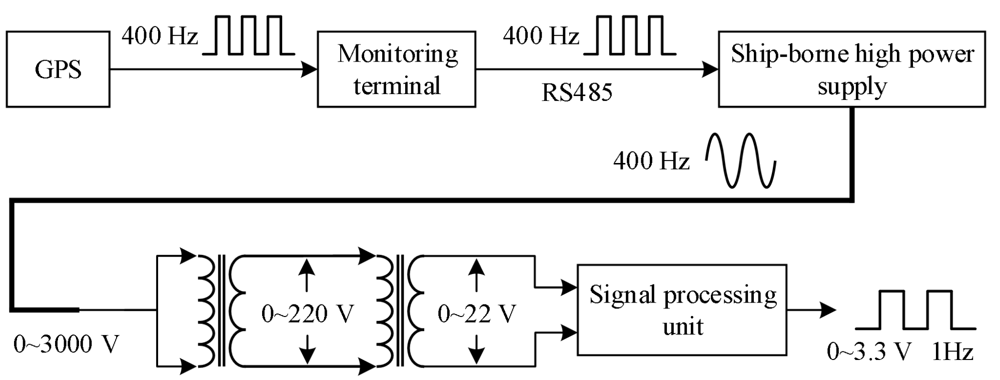

Fig.2 The flow diagram of synchronization signal.

3 Hardware design of clock synchronization method based on coaxial cable

3.1 Deck monitoring terminal

Fig.3 shows the block diagram of deck monitoring terminal. The deck monitoring terminal comprises a communication module and a coaxial cable modulation/demodulation module (modem). The communication module is responsible for interaction between monitoring software on PC and transmitter. A signal follower within communication module receives 400 Hz signal from GPS and relays it to high power supply as a synchronization signal. The coaxial cable modem modulates messages sent by PC onto two power lines of coaxial cable and demodulates messages returned by transmitter through coaxial cable.

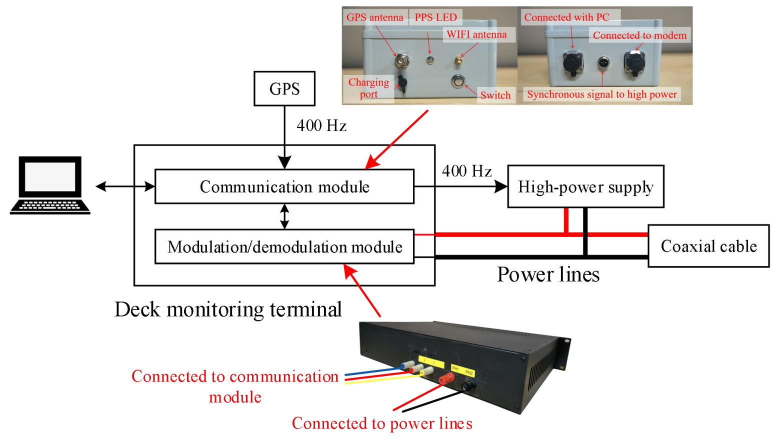

Fig.3 The block diagram of deck monitoring terminal.

3.2 High-power supply output synchronized with GPS

The high-power supply is designed with a function to accept external synchronization signals. Both the underwater transformers of transmitter and ship-borne high-power supply operate at a frequency of 400 Hz. Accordingly, the TIMEPULSE pin of GPS is configured to output a 400 Hz signal and is connected to high-power supply via a RS485 module. This RS485 module will introduce a certain delay. Fig.4 shows the comparison of PPS before and after RS485 transmission. It is observed that the delay introduced by RS485 is less than 50 ns. The power supply output voltage is set to 20 V. The TIMEPULSE pin on another GPS is configured to output a 1 Hz signal, which is monitored alongside the power supply output. Fig.5 shows the synchronized output signal waveform of power supply. It can be observed that the zero phase of power supply output signal is aligned with the rising edge of PPS. After continuous observation, the 400 Hz sinusoidal signal output from power supply remains stable relative to the rising edges position of PPS. This synchronization of power supply output is effective, and forms the foundation of entire clock synchronization method.

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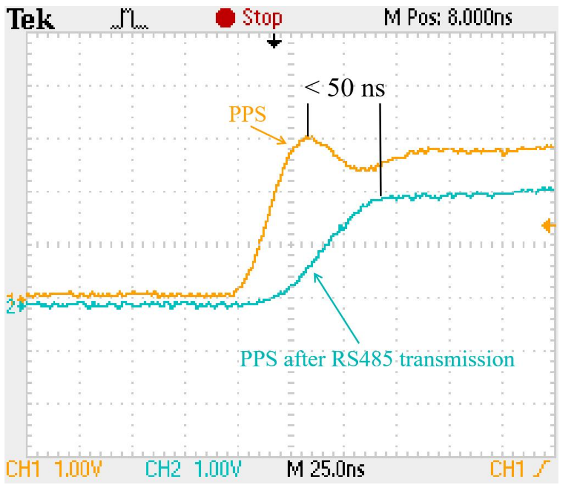

Fig.4 The comparison of PPS before and after RS485 transmission.

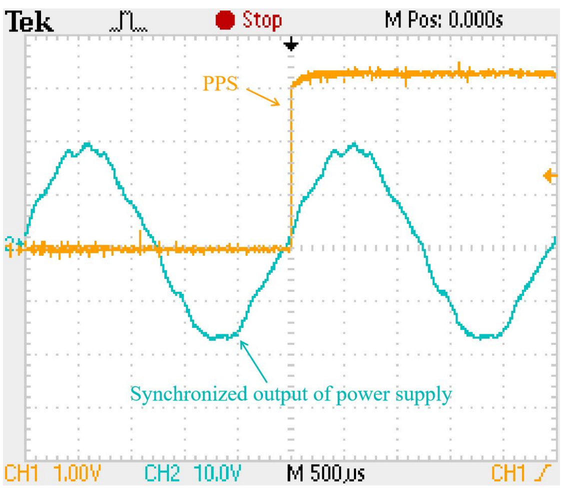

Fig.5 The synchronized output signal waveform of power supply.

3.3 Signal processing unit

The 400 Hz sinusoidal signal output from high-power supply is transmitted to transmitter via a coaxial cable. Then it passes through two transformers and is converted into a sinusoidal wave with an amplitude ranging from 0 to 24 V. This signal is converted into 1 Hz square wave with an amplitude of 0 to 3.3 V by signal processing circuit. Fig.6 shows the hardware of signal processing unit.

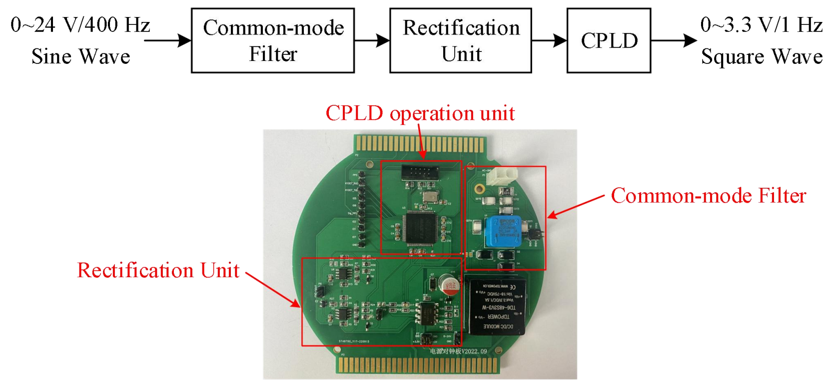

Fig.6 The hardware of signal processing unit.

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The 400 Hz sinusoidal wave, ranging from 0 to 24 V, is first processed by a common-mode filter to eliminate noise. A protective circuit consisting of gas discharge tubes (GDT) and transient voltage suppression (TVS) diodes, surrounds common-mode filter circuit to prevent over-voltage and protect subsequent stages. After filtering, the sinusoidal wave is processed through a rectification unit, which converts it into a 0~3.3 V, 400 Hz square wave signal. This rectification unit comprises an optical coupler and an operational amplifier, which rectifies signal, isolates input from output, and protects following operational circuits from sudden variations in the input signal. The square wave signal from rectifier is then processed by the operation unit of underwater signal processing system, which generates a 1 Hz square wave using a pulse counting method. The core of operation unit is a complex programmable logic device (CPLD), which outputs one rising edge for every 400 counted rising edges of 400 Hz square wave. The 1 Hz square wave output by CPLD operation unit is the final synchronization signal transmitted to control circuit.

To align the rising edges of 1 Hz square wave with the rising edges of PPS, CPLD module records the exact moment of PPS rising edges. The 1 Hz square wave is aligned with PPS only when CPLD begins counting 400 Hz square wave at the moment of a certain PPS rising edge. Therefore, before submerging transmitter, an external GPS module is connected to it. Once CPLD records the timing of PPS rising edges, it generates an internal 1 Hz signal synchronized with PPS. Afterward, the external GPS module is removed, and power supply is activated. CPLD module initially sets output pin to low and then raises it high upon detecting the first rising edge of internally generated 1 Hz signal, as illustrated in Fig.7. After this, when the rising edge count of 400 Hz signal reaches 200, output pin is set to low, generating a falling edge; when the count of 400 Hz signal reaches 400, output pin is set to high, generating a rising edge and resetting counter for next cycle. The clock synchronization of entire transmitter system depends on the rising edges of PPS, which must be generated with accuracy and stability. Therefore, this method of counting rising edges of 400 Hz signal directly to 400 ensures precise generation of these rising edges.

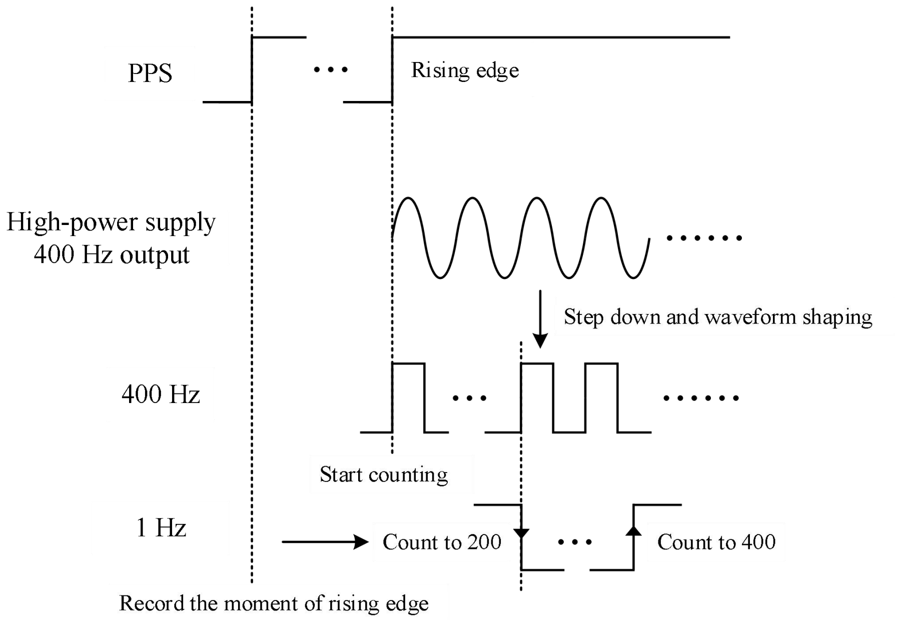

Fig.7 The schematic diagram of 1Hz synchronized signal generation.

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4 Analysis of clock synchronization deviation

No matter which clock synchronization method is used, there will be a deviation between the final 1 Hz square wave signal generated and the PPS from GPS. The main deviation in conventional MCSEM clock synchronization method comes from the crystal oscillator inside transmitter. The generation of 1 Hz signal synchronized with the rising edges of PPS relies on internal crystal oscillator. If the temperature drift of crystal is smaller, the frequency of output signal is more stable and the clock synchronization deviation is also smaller. The clock synchronization method in this paper generates a 1 Hz signal synchronized to the rising edges of PPS by counting the rising edges of 400 Hz square wave. Its frequency stability primarily is from the stability of 400 Hz output of power supply, reducing dependence on the internal crystal oscillator. The deviation of this method comes from circuit processing, cable transmission and other stages that may generate signal delay, and it can be calculated by the following formula:

$$T = T_1 + T_2 + T_3 \tag{1}$$

where T is the delay of generated 1 Hz square wave signal relative to PPS, T_1 is the delay generated by circuit processing stage, T_2 is the delay generated by cable transmission, T_3 is the delay caused by signal passing through transformers. T_1 mainly consists of three parts: chip program processing, signal transmission in all circuit, the synchronization process of power supply. T_1 can be calculated by the following formula:

$$T_1 = T_c \times n + t_1 + t_2 \tag{2}$$

where T_c is the instruction cycle of chip, i.e., the time required to execute one instruction, and n is the number of instructions, t_1 is the delay caused by signal transmission in all circuit, t_2 is the delay generated by high-power supply synchronization output. T_c is related to the crystal oscillator used by chip. In this paper, the value of T_c is 6 ns, the value of n doesn't exceed 30. t_1 is related to the components used in signal transmission path in the circuit board. In this paper, the value of t_1 doesn't exceed 4 ns. There is a slight delay in the zero phase of 400 Hz signal from power supply relative to the rising edges of 400 Hz synchronization signal, but the power supply output signal waveform is not a standard sine wave, making it difficult to precisely identify the zero phase. Therefore, it is difficult to obtain an accurate result for t_2 through separate test, but subsequent overall deviation test includes t_2. T_2 mainly consists of three parts: the delay caused by coaxial cable transmission, and delay caused by wires transmission between circuit boards, and it can be calculated by the following formula:

$$T_2 = \frac{L_{cable}}{v_{cable}} + \frac{L_{wire}}{v_{wire}} \tag{3}$$

$$v_{cable} = \eta_1 \times c \tag{4}$$

$$v_{wire} = \eta_2 \times c \tag{5}$$

where L_{cable} is the length of coaxial cable, and v_{cable} is the speed at which the signal is transmitted via coaxial cable, L_{wire} is the length of wires between circuit boards, and v_{wire} is the speed at which the signal is transmitted via wires, c is the speed of light in a vacuum, η_1 is the ratio of signal transmission speed on coaxial cable to the speed of light in a vacuum, η_2 is the ratio of signal transmission speed between circuit boards via wires to the speed of light in a vacuum. The typical value of η_1 ranges from 0.67 to 0.75, and the typical value of η_2 ranges from 0.6 to 0.9 (when using 22AWG wire). Therefore, for every 1 km of coaxial cable, the delay typically falls within a range of 4.48 to 4.98 μs. The total length of wires between circuit boards inside transmission chamber doesn't exceed 1 m, resulting in a delay typically range from 3.7 to 5.56 ns.

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The 400 Hz signal output from high-power supply passes through two stages of transformers and is reduced to low voltage ranging from 0 to 22V for processing by underwater signal processing unit. The transformers are not ideal transformers, so there is a certain phase shift between the primary input voltage and the secondary output voltage of each transformer, which is the cause of T_3. Due to limited test condition, T_3 can't be tested separately in this paper, but subsequent overall deviation testing includes T_3. All deviations described above can be combined and measured in the overall test of the clock synchronization method.

5 The test of clock synchronization method

In accordance with the clock synchronization method using power supply signal based on coaxial cable, as discussed in this paper, a test platform was built in laboratory to evaluate the effectiveness of clock synchronization. The test setup is shown in Fig.8. Due to the high voltage output of power supply and the low voltage requirement of modem, a coupler is needed to connect the two (Giraneza and Abo-Al-Ez, 2022; Costa et al., 2017). This coupler is a capacitive coupler, which presents significant impedance to 400 Hz AC signal. Consequently, the voltage in power carrier loop primarily accumulates at the coupler's ends. Since the frequency of power line communication exceeds 100 kHz, coupler's impedance is relatively low. Therefore, the power line communication signal can pass through coupler, but the 400 Hz synchronization signal of high-power supply does not. This coupler does not cause a delay.

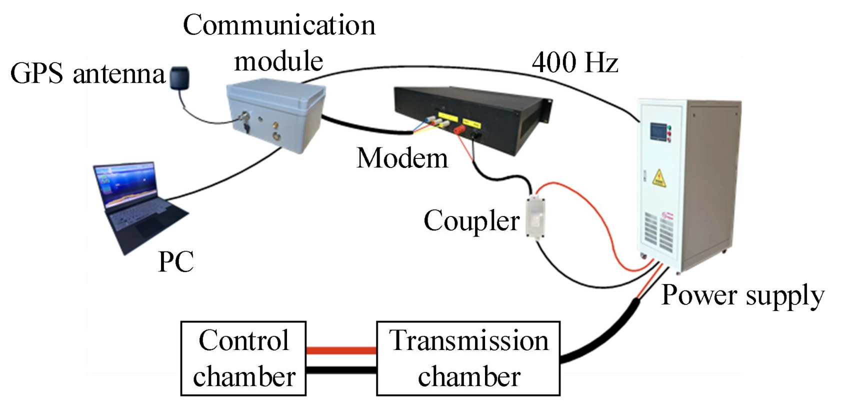

Fig.8 The diagram of test setup.

Fig.9 shows the clock synchronization process based on coaxial cable. First, control chamber is connected to a GPS module. Once control circuit receives PPS and records the specific timing of rising edges, GPS module is removed. Next, high power supply is activated. The 400 Hz AC signal output from power supply is converted into 1Hz square wave by the signal processing unit inside control chamber. Finally, PC sends a synchronization command and transmitter's internal clock realigns with 1 Hz square wave.

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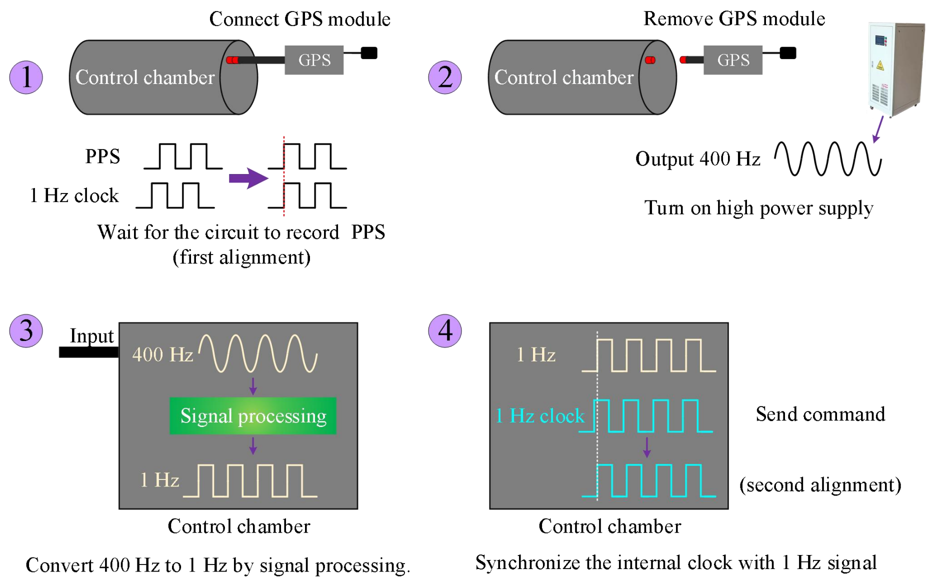

Fig.9 The clock synchronization process based on coaxial cable.

Fig.10 shows the internal clock synchronized with PPS and the clock synchronization deviation. To facilitate observation, the duty cycle of internal clock signal generated by underwater signal processing unit was set to 50%, while the duty cycle of PPS output from GPS module was set to 40%. After continuous observation, the deviation between the rising edge of internal clock signal and the rising edge of PPS was approximately 504 ns. Fig.11 presents the results of multiple tests, showing that the synchronization deviation fluctuated around 504 ns with a range of 34 ns. The coaxial cable used in test was relatively short. In marine operations, a 10 km length of coaxial cable can introduce a maximum delay of approximately 49.8 μs. In this case, the maximum delay of internal clock signal relative to PPS would be approximately 50.3 μs. During the measurement of internal clock signal, some interference pulses were observed, likely caused by test pins being too close to high power equipment in laboratory environment. Fig.12 shows some photos of the test scene.

Unlike Scripps transmitter, this study employs a ship-borne high-power supply to transmit 400 Hz signal and generate a 1 Hz square wave synchronized with PPS as the synchronization signal for transmitter circuit. The transmission waveform frequency control signal is generated based on the internal crystal oscillator of circuit, with its rising edge aligned with the rising edge of 1 Hz synchronization signal.

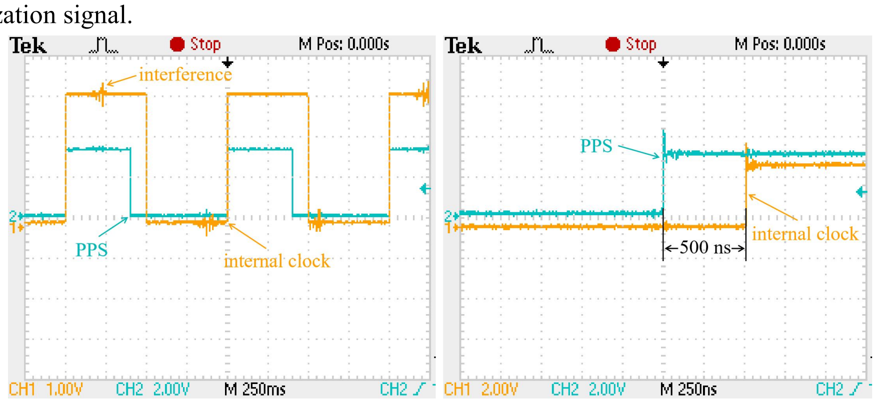

Fig.10 Internal clock synchronized with PPS (left); clock synchronization deviation (right).

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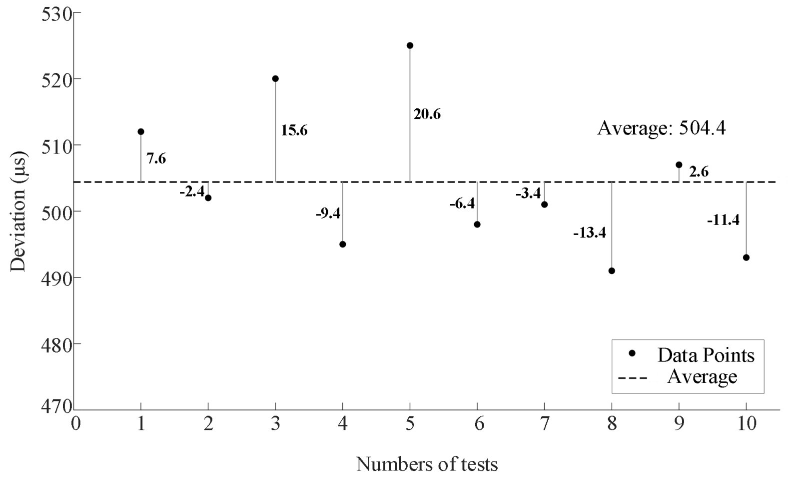

Fig.11 The graph of multiple tests results for synchronization deviation, shows the difference between each result and the average value.

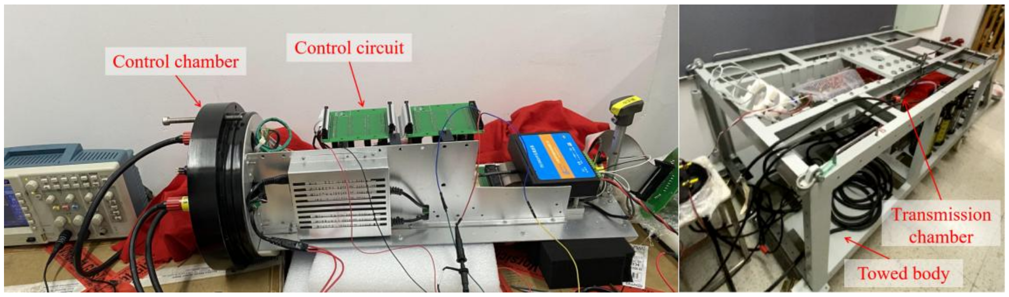

Fig.12 Control chamber (left); transmission chamber (right).

6 Conclusion

This paper introduces a clock synchronization method of marine controlled source electromagnetic transmitter base on coaxial cable and builds related hardware system. In this method, the ship-borne high power-supply outputs 400 Hz signal synchronized with PPS, and transmits it to underwater transmitter. The transmitter control circuit can generates a 1 Hz square wave signal synchronized with PPS for clock synchronization. The delay deviation of 1 Hz square wave signal obtained by this method relative to PPS is less than 1 ms, which meets the requirement of synchronization accuracy better than 1 ms in practical operations and can be used for internal clock synchronization of transmitter. This method can facilitate the use of coaxial cables in MCSEM operations, and expand transmitter's application scenarios. This method can also provide a reference for the design of other underwater equipment that uses coaxial cables.

7 Statement

This manuscript satisfies the following statements that: 1) all authors agree with the submission, 2) the work has not been published elsewhere, either completely, in part, or in another form, and 3) the manuscript has not been submitted to another journal.

Data availability

No data sets were used in this article.

Author contributions

M. Wang is the project applicant and a key participant in the testing process. K. Chen provided some

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optimization suggestions for the test scheme. C.T. Wang and R.Y. Yu, as the research assistants, had helped complete the testing. Z.B. Ren is the project leader, primarily responsible for the test scheme design, hardware circuit design, and other related tasks.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Financial support

This work was supported by the National Natural Science Foundation of China (42374221), the Key Technologies R&D Program (2022YFC2807900), Marine Economic Development in Guangdong Province (Grant Number: GDNRC[2023]40).

Acknowledgement

Thanks to the editors and reviewers. Additionally, this paper was supported by south China sea institute of oceanology, cas and Fujian earthquake agency. The authors express thanks to the two mentioned institutions.

References

Amuta, E., Awelewa, A., Olajube, A., Somefun, T., Afolabi, G., and Uyi, A.: Power line carrier technologies: a review, IOP Conference Series: Materials Science and Engineering, Ota, Nigeria, 27th-28th July 2020, 012062, doi: 10.1088/1757-899X/1036/1/012062, 2021.

Chen, K., Deng, M., Wu, Z., Jing, J., Luo, X., and Wang, M.: Low Time Drift Technology for Marine CSEM Recorder, Geoscience, 26, 1312-1316, doi: 10.3969/j.issn.1000-8527.2012.06.027, 2012.

Chen, K., Deng, M., Yu, P., Yang, Q., Luo, X. H., and Yi, X. P.: A near-seafloor-towed CSEM receiver for deeper target prospecting, Terrestrial Atmospheric and Oceanic Sciences, 31, 565-577, doi: 10.3319/tao.2020.08.03.01, 2020.

Constable, S.: Marine electromagnetic methods—A new tool for offshore exploration, The Leading Edge, 25, 438-444, doi: 10.1190/1.2193225, 2006.

Constable, S.: Ten years of marine CSEM for hydrocarbon exploration, Geophysics, 75, 75A67-75A81, doi: 10.1190/1.3483451, 2010.

Constable, S.: Review paper: Instrumentation for marine magnetotelluric and controlled source electromagnetic sounding, Geophysical Prospecting, 61, 505-532, doi: 10.1111/j.1365-2478.2012.01117.x, 2013.

Constable, S. and Srnka, L. J.: An introduction to marine controlled-source electromagnetic methods for hydrocarbon exploration, Geophysics, 72, WA3-WA12, doi: 10.1190/1.2432483, 2007.

Costa, L. G. d. S., Queiroz, A. C. M. d., Adebisi, B., Costa, V. L. R. d., and Ribeiro, M. V.: Coupling for power line communications: A survey, Journal of Communication and Information Systems, 32, doi: 10.14209/jcis.2017.2, 2017.

Cox, C., Constable, S., Chave, A., and Webb, S.: Controlled-source electromagnetic sounding of the oceanic lithosphere, Nature, 320, 52-54, doi: 10.1038/320052a0, 1986.

Edwards, R. and Chave, A.: A transient electric dipole-dipole method for mapping the conductivity of the sea floor, Geophysics, 51, 984-987, doi: 10.1190/1.1442156, 1986.

Ferreira, H. C., Grové, H. M., Hooijen, O., and Vinck, A. H.: Power line communication, Wiley Encyclopedia of Electrical and Electronics Engineering, 16, 706-716, doi: 10.1002/047134608X.W2004, 2001.

Giraneza, M. and Abo-Al-Ez, K.: Power line communication: A review on couplers and channel characterization, AIMS Electronics and Electrical Engineering, 6, 265-284, doi: 10.3934/electreng.2022016, 2022.

Kaddoum, G. and Tadayon, N.: Differential chaos shift keying: A robust modulation scheme for power-line communications, IEEE Transactions on Circuits and Systems II: Express Briefs, 64, 31-35, doi: 10.1109/TCSII.2016.2546901, 2016.

Liu, Y., Yin, C., Weng, A., and Jia, D.: Attitude effect for marine CSEM system, Chinese Journal of Geophysics, 55, 2757-2768, doi: 10.6038/j.issn.0001-5733.2012.08.027, 2012.

Meng, W., Ming, D., Qi-sheng, Z., Kai, C., and Jin-ling, C. U. I.: The technique of time synchronization operation to control marine electromagnetic emission, Progress in Geophysiscs, 24, 1493-1498, doi: 10.3969/j.issn.1004-2903.2009.04.043, 2009.

Qiu, Y., Yang, Q., Deng, M., and Chen, K.: Time synchronization and data transfer method for towed electromagnetic receiver, Review of Scientific Instruments, 91, doi: 10.1063/5.0012218, 2020.

Wang, M., Deng, M., Zhao, Q., Luo, X., and Jing, J.: Two types of marine controlled source electromagnetic transmitters, Geophysical Prospecting, 63, 1403-1419, doi: 10.1111/1365-2478.12329, 2015a.

WANG, M., DENG, M., WU, Z.-L., LUO, X.-H., JING, J.-E., and CHEN, K.: New type deployed marine controlled source electromagnetic transmitter system and its experiment application, Chinese Journal of Geophysics, 60, 4253-4261, doi: 10.1111/1365-2478.12329, 2017a.

Wang, M., Deng, M., Wu, Z., Luo, X., Jing, J., and Chen, K.: The deep-tow marine controlled-source electromagnetic transmitter system for gas hydrate exploration, Journal of Applied Geophysics, 137, 138-144, doi: 10.1016/j.jappgeo.2016.12.019, 2017b.

WANG, M., WU, Z.-l., DENG, M., MA, C.-w., LIU, Y., and WANG, S.-x.: The high precision time stamp technology in MCSEM transmission current waveform, Progress in Geophysics, 30, 1912-1917, doi: 10.6038/pg20150452, 2015b.

Wang, M., Zhang, H.-Q., Wu, Z.-L., Sheng, Y., Luo, X.-H., Jing, J.-E., and Chen, K.: Marine controlled source electromagnetic launch system for natural gas hydrate resource exploration, Chinese Journal of Geophysics, 56, 3708-3717, doi: 10.6038/cjg20131112, 2013.

Wang, M., Ming, D., Li, X., Zhang, Z., Yue, H., Zhang, T., Duan, N., and Ma, X.: The latest development of Marine controllable source electromagnetic transmitter, IOP Conference Series: Earth and Environmental Science, Changchun, China, 11-14 October 2020, 012137, doi: 10.1088/1755-1315/660/1/012137, 2021.