Study on the Influence of Temperature on Ultrasonic Pressure Measurement Technology

Yuqing Zhang, Tingfeng Ming* and Jing LI

College of Power Engineering, Naval University of Engineering, Wuhan, Hubei, 430033, China

*Corresponding author’s e-mail: hgming@126.com

Abstract: Ultrasonic pressure measurement is an advanced measurement technology, but it has a great influence on temperature. Aiming at the problem that the pressure of ultrasonic measurement pipeline is affected by temperature, the pipeline is modeled and simulated by finite element method. The ultrasonic transducer is used to transmit and receive sound waves. The time difference of sound waves received by the transducer under different temperatures is simulated to determine the corresponding sound velocity. The data is analyzed and processed to establish the mathematical model of sound velocity and temperature, The influence of temperature on pressure measurement is analyzed, which plays an important role in reducing the pressure error of ultrasonic measurement pipeline.

1. Introduction

Hydraulic pipeline is widely used in various equipment and instruments. Pressure measurement of hydraulic pipeline is an important means to prevent accidents caused by pipeline overpressure [1]. Conventional pressure measurement technology has accurate measurement and stable performance, and is suitable for many fields [2]. However, there are some limitations. In some special applications, such as some marine systems, there are very complex and precise pipeline systems, so it is inconvenient to use conventional measurement methods.

Ultrasonic pressure measurement is a new measurement method, in which it is more common to measure the pressure by using the change of the transmission speed of sound wave in the pipeline liquid [3-12], but the transmission speed of sound wave in the pipeline is not only affected by the pressure, but also related to the temperature of the fluid in the pipeline, and the temperature has a great impact on the transmission speed of sound wave. In the actual measurement process, the ambient temperature will fluctuate to a certain extent, which will cause a negative impact on the measurement results. It is particularly important to reduce the measurement error caused by temperature.

Because there are many physical forms in the process of sound wave transmission during ultrasonic pressure measurement, it is complex to theoretically calculate the relationship between sound velocity and temperature, and the technology of ultrasonic finite element simulation has been relatively mature [13-19]. This paper uses the method of multi physical field finite element simulation to study the influence of temperature on ultrasonic transmission velocity in water.

2. Simulation Model of Ultrasonic Pressure Measurement

2.1. Simulation Computing Physical Model

Taking a pressure measurement structure model of an ultrasonic pipeline as an example, the effect of...
temperature on sound velocity under hydrostatic pressure in a straight pipeline is studied. Because the geometric model (two-dimensional model or three-dimensional model) of the simulation has no impact on the results, the two-dimensional model is adopted in the simulation, which can reduce the amount of calculation and save the calculation time. The inner diameter D of the pipe is 100 mm and the wall thickness h of the pipe is 5 mm. When modeling, the two-dimensional axisymmetric form is selected, the model is separated along the axis of symmetry, and the model on one side is retained, which can greatly reduce the amount of calculation. The established simulation model is shown in Figure 1. The rightmost PML layer in the figure (perfect match) is used to simulate an open boundary, that is, an infinitely extending pipe.

During measurement, transducer 2 emits ultrasonic wave, and transducer 1 receives ultrasonic wave. By obtaining the transmission time of ultrasonic wave in the pipeline, the propagation speed of ultrasonic wave at a certain temperature is calculated. It is assumed that the time of the first arrival of an emitted ultrasonic wave at transducer 1 is \( t_1 \), the time of the second arrival at transducer 1 is recorded as \( t_2 \), the time difference between two sound waves received by transducer 1 \( \Delta t = t_2 - t_1 \), the distance of sound wave transmission is \( 2(d + 2h) \), the material of the pipe wall is known, and the transmission speed of ultrasonic wave in the pipe wall is \( c_1 \). Thus, the speed of sound can be obtained

\[
C = \frac{2d}{d_{t_2 - (4h/c_1)}} \tag{1}
\]

2.2. Simulation Condition Setting

The fluid medium in the pipeline is water, the environmental conditions are set to a standard atmospheric pressure, the pipe wall material is stainless steel, the transducer is piezoelectric material, the material model is PZT-5H, the outer side of the piezoelectric material is set as grounding, the inner boundary in contact with the pipe wall is set as potential boundary and surface charge density boundary respectively, and the potential boundary of the transmitter gives an excitation signal \( 1 \) (T). The initial value of the surface charge density boundary of the receiver is set to zero.

2.3. Frequency of Ultrasonic Probe

The ultrasonic waves of 40 kHz, 100 kHz and 200 kHz are selected for simulation research in water, and Figure 2 is obtained. It can be seen from Figure 2 that when the ultrasonic frequency is low, the sound wave clustering is not good, and it is not easy to observe the complete sound wave in the surface sound pressure distribution diagram of the calculation result, which is not conducive to the detection of sound wave. Considering that in the process of simulation calculation, the division of grid is related to the frequency of ultrasonic wave, the higher the frequency of the transmitted sound wave, the denser the mesh, and the greater the amount of calculation of the model. On the other hand, the higher the frequency of ultrasonic, the faster the attenuation. Based on the above analysis, the frequency of this simulation is 100 kHz.
3. Analysis and Verification of Simulation Results

3.1. Analysis of Simulation Results

Figure 4 shows the received signal of transducer 1. It can be seen from Figure 4 that the amplitude of sound pressure gradually decreases, which is consistent with the actual situation, which is caused by the loss of sound wave during transmission in the medium. The first two waveforms in the figure are the two ultrasonic signals successively received by transducer 1, and the time difference between the first two signals is the time required for ultrasonic wave to transmit back and forth in the pipeline $dt$.

Figure 4 (a) shows the comparison between the simulation calculation and the sound velocity value in the acoustic manual. From the figure, it can be seen that the change trend of the sound velocity calculated by the simulation is consistent with the actual sound velocity, which is slightly smaller as a whole, but the error of the corresponding sound velocity value at the same temperature is very small, which proves the accuracy of the simulation results\cite{20}.

Figure 4 (b) shows the absolute error of sound velocity calculated by simulation under different temperatures. It can be seen from the figure that compared with the actual sound velocity value, the maximum error of the simulation result is 0.269%, and the minimum error is 0.019%. The overall error is controlled within 0.3%, indicating the correctness of the simulation model and method and the accuracy of the simulation result.
According to the temperature fluctuation during ultrasonic pressure measurement, the simulation calculation is carried out when the temperature changes in a small range around 20 °C, 30 °C and 40 °C. It can be seen from Figure 6 that when the temperature fluctuates in a small range, the relationship between sound velocity and temperature is approximately linear. Comparing the changes of sound velocity under different temperatures in the figure, it can be seen that when the temperature changes in a small range at 40 °C, the change of sound velocity should be the smallest. When the temperature fluctuates around 20 °C, the change range of sound velocity is the largest. This is consistent with the gradual decrease of the slope of the fitting curve with the increase of temperature shown in Figure 5 (a).

3.2. Effect of Temperature on Ultrasonic Pressure Measurement
The relationship between sound velocity in water and its bulk modulus $k$ and density $\rho$ is

$$c = \sqrt{k/\rho}$$ (3)

The transmission speed of ultrasonic in water and the density of water at different temperatures at 0 MPa are obtained by finite element simulation, so the bulk modulus of water and air at different temperatures can be obtained, as shown in the figure below. It can be seen from Figure 7 that the bulk modulus of water increases with the increase of temperature. Fitting the data in Figure 7, the bulk modulus of water is.

$$k_1 = -0.0836T^6 + 12.911T^5 - 759.39T^4 + 21628T^3 - 431250T^2 + 1.528 \times 10^7T + k_0$$ (4)

Where, $t$ is the temperature of water,$k_0$ is the bulk modulus of water at 0 °C under 0mpa, and its value is $1.97 \times 10^9$ pa.
20 °C, 30 °C and 40 °C, the relationship between density and pressure [21] is shown in Figure 8. Thus, the relationship between pressure and sound velocity can be obtained, as shown in Figure 9.

It can be seen from Figure 6 that when the temperature is around 20 °C, the sound velocity change caused by every 0.1 °C change in temperature \( \Delta C_{20} \) is about 0.2 M / s. It can be seen from Figure 9 that when the pressure changes by 0.1 MPa at 20 °C, the change of sound velocity is about 0.4 m / s. Compared with Figure 6 and Figure 9, it can be seen that when the temperature fluctuates in a small range, that is, the temperature changes by 0.1 °C, it will produce an error of about 0.05 MPa for ultrasonic pressure measurement.

### 3.3. Experiment

304 stainless steel with outer diameter of 100 mm and wall thickness of 5 mm is selected as the experimental pipe material. The experimental results are shown in Figure 10 below. Keep the temperature constant. By changing the pressure of water in the pipe, different receiving times can be obtained. The results are shown in Figure 10. It can be seen from Figure 10 that when the pressure is constant, the receiving times corresponding to different temperatures are different. The higher the temperature, the shorter the receiving time, reflecting the transmission speed of sound waves. When the temperature is constant, the receiving time of the receiver is linear with the pressure.

Corresponding receiving time at 0 MPa \( t_0 \). It is known that the relationship between the corresponding pressure and the receiving time at different temperatures is linear, so it can be obtained that the relationship between the receiving time and the pressure is

\[
T = K_t P + t_0
\]  

Using this method, the corresponding pressure measurement model under different temperatures can be established, which can greatly reduce the error of temperature on the measurement results and improve the measurement accuracy.
4. Conclusion

(1) The simulation results show that when the temperature is lower than 75 °C, the transmission speed of ultrasonic in water gradually increases with the increase of temperature. When the temperature is higher than 75 °C, the transmission speed of ultrasonic in water gradually decreases with the increase of temperature, and the sound velocity reaches the maximum value of 1553.10 M/s at 75 °C. When the temperature fluctuates in a small range, the change of sound velocity caused by pressure is larger than that caused by pressure, it will have a great impact on ultrasonic pressure measurement.

(2) When using ultrasonic to measure pressure, the temperature of the measured medium is consistent with the external ambient temperature. Because the ambient temperature will not change greatly in a short time, the temperature of the measured medium will not change greatly and will only fluctuate in a small range. In this paper, an error correction model of the influence of temperature on ultrasonic pressure measurement is established to obtain a certain temperature. In this paper, a method for analyzing the measurement error of ultrasonic pressure measurement is provided.

Reference

[1] BAI X H, YANG J, GENG M F. Research on non intrusive pressure measurement method [J]. China Equipment Engineering. 2019 (24): 104-105.

[2] WANG Y, LIU D S. Research and development of non-contact measurement methods for pressure and flow of hydraulic system [J]. Hydraulic and Pneumatic. 2005 (7): 58-61.

[3] WANG S L, CHEN B, LIU C F. Identification and Simulation of ultrasonic non-contact detection hydraulic system pressure [J]. Hydraulic Pneumatic and Sealing, 2001 (1): 25-27.

[4] WANG D, SONG Z X, WU Y, JING Y. Ultrasonic wave based pressure measurement in small diameter pipeline [J]. Ultrasónica 63 (2015) 1-6.

[5] KONG Q J, LIU J X. Research on flow and pressure measurement of ultrasonic hydraulic system [J]. Electronic Technology. 2009, 36 (12): 49-51.

[6] Emre Gorgun, Mehmet Baki Karamis. Ultrasonic testing to measure the stress statement of steel parts [J]. Journal of Mechanical Science and Technology. 2019, 33(7).

[7] 1. Bray D.E. Ultrasonic Stress Measurement with the LCR Technique. www.breyengr.com.

[8] Yu F, Gupta N. A novel method for computer-controlled condition monitoring of hydraulic systems. INSIGHT. 2003(8):536-538.

[9] 1. Yu F, Gupta N, Hoy J. Non-intrusive pressure measurement based on ultrasonic waves. INSIGHT. 2005(5):285-288.

[10] 1. Diodati P. Ultrasonic Method for Static Pressure Measurement[J]. Review of Scientific Instruments, 1986, 57(2):293-295.

[11] Guers M J, Fontana C J, Zilinski D R, et al. Investigation of noninvasive approaches for pressure measurement[J]. Review of Progress in Quantitative Nondestructive Evaluation. 2007, 26:1653-1659.

[12] 3. Rosenkranz E, Ferrandis J Y, Leveque G, et al. Ultrasonic measurement of gas pressure and composition for nuclear fuel rods[J]. Nuclear Instruments and Method in physics Research Section A. 2009, 603(3):504-509.

[13] MA X L. Pattern recognition of ultrasonic testing of material defects based on COMSOL simulation [D]. Nanchang: Nanchang Aviation University, 2019.

[14] WANG H M. Simulation and experimental study on ultrasonic standing wave atomization sound field [D]. Harbin: Harbin Institute of technology, 2019.

[15] LI D. Research on ultrasonic flow measurement technology based on coupling of flow field and sound field [D]. Jinan: Shandong University, 2018.

[16] YANG Y. Research on measurement technology of ultrasonic gas flowmeter based on coupling of flow field and sound field [D]. Jinan: Shandong University, 2020.
[17] ZHAI Y R, ZHAO Y, LIU Y, et al. Simulation study on the internal structure design of industrial ultrasonic gas meters [j]. China test. 2020, 46 (2): 87-90.

[18] TANG X Y, ZHANG HJ, XIE X, et al. Model simulation and experimental study on the influence of the sound plane installation angle of multi-channel ultrasonic gas flowmeter on measurement [j]. Journal of South South University (NATURAL SCIENCE EDITION).2017, 48 (7): 1923-1929.

[19] FAN J, NI Y, BI X Q. Theoretical model and Simulation of blood flow measurement based on dual frequency ultrasonic Doppler [j]. Life Science Instrument.2007 (12): 44-46.

[20] DU G H, ZHU Z M, GONG X F. Fundamentals of acoustics. 3rd Edition [M]. Nanjing: Nanjing University Press, 2012.

[21] Wang Yongxiang 9. Density of water under different pressure and temperature 2.2014.04.18. https://wenku.baidu.com/view/983b69a2e009581b6bd9ebc1.html.