A method for acoustic measurement of length, diameter and internal condition of transportation pipelines

S A Borminsky¹, A V Parshina² and B V Skvortsov³

Samara University, 34, Moskovskoye shosse, Samara, 443086, Russian Federation

E-mail: ¹ b80@mail.ru, ² parhina.av@ssau.ru, ³ aps@ssau.ru

Abstract. The paper investigates the problem of development of theoretical substantiation and practical implementation of an acoustic method of measurement of geometrical parameters of pipes as the main facilities of pipeline transport used in production, transportation and consumption of thermal energy systems. The method is based on the application of mathematical processing of the acoustic signal reflected from the open end of the pipe and makes it possible to obtain information about the length and diameter of the pipe and provides quality control of the internal surfaces. The algorithm for diameter measurement proposed in the paper increases the functional capability of the measuring equipment and makes it possible to automatically calculate the phase shift of the acoustic signal reflected from the open end of the pipe, thereby completely automating measurement of the length of pipes of any given diameter. Experimental studies applying the developed algorithm demonstrate that the relative length measurement error for 3 m pipes does not exceed 0.15%, and the diameter measurement error for pipes with the diameter of 110 mm does not exceed 7%.

1. Introduction

Pipelines play an important part in systems for production, transportation and consumption of thermal energy. As the main objects of pipeline transport systems, pipes are subject to stringent requirements for the quality of the manufacturing materials, production technology, strength, coating quality, as well as their geometric dimensions: length, diameter, wall thickness, etc. In order to provide final inspection and inventory management of pipes at all stages of their logistical movement from rolling mill to installation site, it is necessary to find a measurement method that can quickly measure pipe length and diameter in the conditions of limited access to it. Considering the wide range of pipes used for heat and power systems and pipelines, this method of measurement must be unaffected by manufacturing materials of the objects being measured. The paper proposes an acoustic method of simultaneous measurement of length and diameter of open pipes, with accessing the pipe for measurement only at one side, which makes it possible to measure stacked pipes of different lengths.

At the present day, there are various methods of pipe length measurement, which can be divided into several groups:

- Mechanical. The principle of operation is based on use of contact sensors, and in most cases the measurement requires moving the pipe using special rollers. This method is convenient in industrial facilities with existing systems for pipe loading and moving.
Optical. As a rule, these methods apply optical sensors for positioning the ends of the pipe with uniform movement of the pipe using a special drive. There are also methods making it possible to carry out measurement of up to 50 pipes at the same time, provided they are placed on a rolling table in one layer in the field of view of a camera [20]. Another option is the use of a laser ranging device, however, this method also presupposes the arrangement of pipes in one layer.

Acoustic. These inspection methods use propagation of an acoustic wave along the internal surfaces of the pipe. An important feature of the method is the possibility of reflecting an acoustic wave from the opposite open end of the pipe, which makes it possible to create devices using access to the pipe from one end only.

2. Relevance, scientific significance of the problem with a brief review of literature
In most cases, pipes are stacked during storage and transportation, and ends of pipes do not align with each other. Most pipe length measurement methods require arranging the pipes in one layer and providing access to them from both sides. This operation requires additional time, equipment and space.

The advantages of the acoustic method for pipe length measurement are well known [1-9, 14-19]: most notably, it is the possibility of carrying out measurements when the sensor is accessed from one end of the pipe, as well as the ability to measure curved or rolled up coiled tubing, as well as simplicity of the device design. In addition, the measurement is not affected by the pipe material. These advantages provide for inventory management of stacked pipes without the need for restacking, as well as measurement of curved and rolled up pipes or flexible conduits.

The drawbacks of the method include a significant dependence of the sound velocity on the ambient conditions, in particular air temperature, which gives a measurement error of at least 5% in the temperature range of -20°C...+40°C. Another drawback of the acoustic method is the dependence of the phase of the reflected signal on the pipe diameter when reflected from the open end of the pipe.

To compensate for the effect of sound velocity, there are several methods [16, 17, 19] based on measuring the air temperature or the actual sound velocity in a small section of the waveguide, usually located inside the device. In an actual operating environment, using the data of the conducted experiments, this makes it possible to reduce the relative measurement error to 0.5-1%. Another method of compensation is calibration in the current ambient conditions using a reference pipe before the actual measurement. This approach makes it is possible to obtain a relative measurement error not exceeding 0.2%.

3. Problem Statement
While the problem of the effect of sound velocity on the results of measurements is well studied, the problem of the application of the reflection phase from the open end of the pipe for measuring pipe parameters has not been thoroughly researched; only various compensation methods have been used. The measurement error results from the shift in the phase of the reflected signal from the open end, depending on the diameter of the pipe and the frequency of the emitted pulse. Existing methods [18, 19] are based on calibration of the reflection phase separately for each pipe diameter, resulting in the operator's need to select the diameter of the pipe before measurements. Additional settings of the measuring instrument complicate the operation and may lead to human error. Thus, to reduce the error in length measurement and expand the instrument functionality, we investigate the problem of measurement of the pipe diameter.

Classical works on physical acoustics [10-13] provide formulas describing the changes in the phase of the signal reflected from the open end of the pipe, depending on its diameter and the wave frequency. However, these formulas are not applicable in real instruments due to their mathematical complexity. In addition, unknown pipe lengths make it impossible to measure the phase of the reflected signal from the open end; therefore, the measurement should be carried out at two different frequencies. To solve the problem, it is necessary to obtain a transformation function for the signal parameters and to develop an algorithm of operation.
4. Theoretical part

Works [10-13] provide analytic methods for determining the phase of the reflected signal. To simplify the expressions, we introduce a dimensionless parameter $\chi$, which is equal to the ratio of the pipe perimeter to the wavelength:

$$\chi = \frac{\pi D}{\lambda}$$  \hspace{1cm} (1)

where $D$ is the pipe diameter;

$\lambda$ is the length of the wave emitted by the instrument.

Then the phase $\theta$ of the reflected signal can be found using the formula [13]:

$$\theta = \frac{2\chi}{\pi} \int_{0}^{\infty} \frac{\psi(\sqrt{\chi^2 + y^2})}{\chi^2 + y^2} dy$$  \hspace{1cm} (2)

where $\psi(x) = \arctg \frac{J_1(x)}{Y_1(x)}$, $0 \leq \psi(x) < \pi$ is the wave function consisting of Bessel functions $J_1(x)$, $Y_1(x)$ of the first and second kind, respectively.

The phase shift increases the wave propagation time. The total propagation time $t_p$ required for the wave to propagate along the pipe to the open end and back, taking into account the wave phase, is as follows:

$$t_p = \frac{2L}{c} + \frac{1}{f} \cdot \frac{\theta}{2\pi} = \frac{2L}{c} + \frac{2\chi}{\pi} \int_{0}^{\infty} \frac{\psi(\sqrt{\chi^2 + y^2})}{\chi^2 + y^2} dy$$  \hspace{1cm} (3)

where $L$ is the length of the measured pipe;

$f$ is the frequency of the wave emitted by the device.

Taking into account (1), the formula (3) can be represented in the following form:

$$t_p = \frac{2L + D}{c} + \frac{1}{f} \cdot \frac{\theta}{2\pi} = \frac{2L + D}{c} + \frac{2\chi}{\pi} \int_{0}^{\infty} \frac{\psi(\sqrt{\chi^2 + y^2})}{\chi^2 + y^2} dy$$  \hspace{1cm} (4)

Calculation of the integral in expression (4) is possible only by numerical methods and is a cumbersome task. For practical use, it is advisable to investigate the following function:

$$g(\chi) = \frac{1}{\pi} \int_{0}^{\infty} \frac{\psi(\sqrt{\chi^2 + y^2})}{\chi^2 + y^2} dy$$  \hspace{1cm} (5)

The heavy line in Figure 1 shows plotted function (5) calculated by numerical methods. The dotted line shows a linear approximation with an error not exceeding 0.6% in the range $0.3 < \chi < 3$.

The range $0.3 < \chi < 3$ has been chosen taking into account the use of actual pipe diameters, wave frequencies, and also attenuation on reflection, which is considered below. The linear approximation represented in Figure 1 is described by the following expression:

$$g_1(\chi) = -0.108 \chi + 0.63$$  \hspace{1cm} (6)

In some cases, more accurate interpolation (7) can be useful, however, the application of this formula complicates the final formulas and does not lead to an increase in accuracy in practice.

$$g_2(\chi) = -0.112 \chi + 0.645 - \frac{1}{150\chi + 31}$$  \hspace{1cm} (7)
By substituting (6) into (4) while using (1) we obtain:

\[
t_p = \frac{2L - 0.108 \frac{\pi D^2}{\lambda} + 0.63D}{c} = \frac{2L + 0.63D}{c} - \frac{0.108 \pi D^2 f}{c^2}
\]  

(8)

By measuring sound propagation time at two different frequencies, starting from (8), we obtain:

\[
\Delta t_p = t_{p2} - t_{p1} = \frac{0.108 \pi D^2 (f_1 - f_2)}{c^2}
\]  

(9)

Accordingly, the pipe diameter can be obtained as:

\[
D = \sqrt{\frac{(t_{p2} - t_{p1})c^2}{0.108 \pi (f_1 - f_2)}}
\]  

(10)

Taking into account the known diameter, the pipe diameter can be obtained from (8):

\[
L = \frac{ct_{p1}}{2} - 0.315D + \frac{0.054 \pi D^2 f_1}{c}
\]  

(11)

Formulas (10)-(11) make it possible to measure both length and diameter in automatic mode without input of any additional data.

Another important parameter necessary for the study is the attenuation of the probing acoustic signal, comprising of attenuation in sound propagation through the pipe and attenuation on reflection from the open end of the pipe. The amplitude of the acoustic wave returning to the instrument end can be described by the expression:

\[
A = A_0 e^{-2\alpha L} Ko(\chi)
\]  

(12)

where \(A_0\) is the amplitude of the probe pulse; \(\alpha\) is the wave attenuation coefficient for propagation through a pipe, \(Ko(\chi)\) is the reflection coefficient for the acoustic wave reflection from the open end of the pipe.
Sound attenuation on propagation is an extremely variable parameter in real pipe operating conditions. In clean metal pipes at a length of 12 m and frequencies of 2-5 kHz, the value $e^{-2\alpha L}$ can reach values up to 0.95. If the pipe is contaminated with wax tailings, this value may be 0.3 or less. In addition, the pipe material and its roughness also affect the attenuation. Significant effect of the above factors prevents pipe length measurement using attenuation measurement method. However, while knowing previously measured parameters $D$ and $L$, there is a way to measure the contamination of the pipe internal surface. To achieve this, it is necessary to calculate the reflection coefficient $K_0(\chi)$ for the reflection of the acoustic wave from the open end of the pipe in the expression (12). This coefficient can be obtained by the formulas [13]:

$$K_0(\chi) = e^{M(\chi)}, \quad M(\chi) = -\frac{2\chi}{\pi} \int_{\chi}^{\infty} \frac{\psi(\frac{x^2 - y^2}{x^2 - y^2})}{x^2 - y^2} dy$$

(13)

Figure 2 shows a $K_0(\chi)$ plot calculated using the numerical methods. The plot data is limited to the range $\chi<3$, since for the parameter values $\chi>3$, the amplitude of the reflected signal is small, which complicates the recording of the reflected pulse time and makes the measurement method too affected by noise.

![Figure 2. Dependence of the reflection coefficient $K_0(\chi)$](image)

When used in real devices, interpolation can also be used to calculate the reflection coefficient, providing error not exceeding 2% in the range $0.3 < \chi < 3$.

$$K_0(\chi) = 0.035\chi^3 - 0.118\chi^2 - 0.246\chi + 1.02$$

(14)

The obtained formulas make it possible to develop an algorithm for operation of a measuring device. For portable devices, taking into account various dimensions of pipes, it is preferable to limit the range of measured diameters at $D_{max} = 160$mm.

5. **Practical significance**

Based on the obtained patterns, we develop an algorithm for performing acoustic measurements of pipe length and diameter with quality control of its internal surface.

1. Initially, two frequencies of the probe pulse are selected, $0.3 < \chi < 3$. For the maximum measurable diameter $D_{max} = 160$mm we select $f_1 = 2000$ Hz ($\chi_1 = 3.04$), $f_2 = 500$ Hz ($\chi_2 = 0.76$) A sine wave with
frequency $f_1$ is emitted, then the device waits for a reflected pulse to measure its amplitude and propagation time $t_{p1}$. We can use methods described in the literature [13] to determine the pulse origin. After a pause necessary to attenuate the wave due to multiple reflections from the ends of the pipe, the emission occurs at a frequency $f_2$ and the propagation time $t_{p2}$ is determined.

2. By using the formula (10), the diameter of the pipe $D$ is obtained. Metrological analysis of the formula shows that the maximum accuracy of diameter measurement is achieved at the maximum frequency difference $f_1$ and $f_2$. The first diameter measurement with the frequencies selected at the previous stage can be used as a preliminary one, then select $f_1$ so that parameter $\chi_1$ at previously measured diameter tended to three, and the frequency $f_2$ is selected to ensure $0.3 < \chi_1 < 0.5$. In practice, several table values were used as $f_1$ and $f_2$ frequencies, which made it easier to generate probe signal using a microcontroller. In addition, there were no undesirable frequencies in the table, for example resonance frequencies for the acoustic part of the instrument.

3. Similarly to item 1, the pipe diameter is measured with new frequencies $f_1$ and $f_2$, then the formula (10) is used once again to determine the more accurate diameter $D$ which is used in further calculations.

4. The pipe length is determined from (11). It usually makes sense to use the propagation time $t_{p1}$ for calculation, since at a higher frequency there is a smaller error in determining the wave front arrival. In the case of low amplitude of the reflected pulse, it is better to use $t_{p2}$, as this provides better noise immunity. It should be noted that (11) gives major advantages in accuracy over the classical formula ($L = ct/2$) for short pipes, while with pipe length $L > 20m$ the instability in the sound velocity results in an error that is much greater than the effects of reflection from the open end.

5. The attenuation coefficient $\alpha$ is determined using the formula (12), which describes the state of the sound channel and provides information about the state of the pipe internal surface. In order to achieve this, we use (14) to determine $K_0$, and then substitute known values $A, A_0, L$ to the expression (12) to determine the required coefficient $\alpha$. For determining $\alpha$ in practice, it is better to use signals with lower frequency $f_2$, since the reflection from the open end at a lower frequency will have higher amplitude.

Taking into account the developed algorithm, an experiment was conducted to confirm the efficacy of the proposed method. Three pipes with a diameter of 40, 65 and 110 mm and a length of 3 m were chosen as the test objects. Piton pipe length acoustic measuring tool (Certificate of the Russian Federation for approval of a type of measuring instruments No. 29726), developed by the authors of this article, was chosen as the measuring instrument. A schematic diagram of the test bench is shown in Figure 3.

![Figure 3. Test bench schematic diagram](image)

We have developed a software tool to record the acoustic signal received by the microphone in a computer file for further analysis. A half-cycle sine wave with a frequency from 1 to 5 kHz was used as the emitted signal. The choice of this frequency band was due to the technical limitations of the existing equipment. It is desirable to have a frequency range of 500 Hz to 10 kHz to improve the accuracy of measuring the diameter over a wide range. The receiving path was based on a capacitance microphone with a bandwidth of 100 Hz to 50 kHz, the ADC speed was chosen at the value of 150 kHz. Figure 4 shows the reflected signal received by the device.
This signal was obtained with a 1 kHz wave sent in a pipe with the diameter of 40 mm, the digit 1 indicates the emitted signal and 2 indicates the received signal. Two important facts should be noted:

1. After the half-cycle sine wave reaches the speaker, the emission does not end immediately. A process of membrane settling occurs, resulting in continuing oscillations, usually at the resonant frequency of the acoustic system. When designing the measuring instrument, it is necessary to make the membrane settling time as low as possible, which will make it possible to measure shorter pipes.

2. When reflected from the open end of the pipe, the received signal 2 changes its polarity, and in case of reflection from a solid obstacle the reflected signal comes in the same polarity as the emitted one. In addition, the shape of the received signal is distorted due to non-uniform attenuation of the acoustic signal at different frequencies. The frequency spectrum of a single half-cycle sine wave is not a single line like a periodic harmonic signal, although it is close to it. Therefore, even in the case of emission of a perfect half-cycle sine wave, the receiving signal is stretched in time and converted into several harmonic oscillations. However, it turns out in practice that the first received half-cycle was, in fact, not distorted.

To check the obtained formula (10), measurements at frequencies of 1 kHz and 4 kHz were made. At ADC frequency of 150 kHz for a pipe with an internal diameter of 40 mm, the propagation delay of a 1 kHz signal in comparison with a 4 kHz signal was 4 counts or 26 μs. Substituting the values in formula (10), we obtain a pipe diameter of 53 mm. For a 65 mm pipe, the delay was 7 counts, and according to the formula (10), we obtain a diameter of 71 mm. For a 110 mm pipe, the delay was 15 counts, and according to the formula (10), we obtain a diameter of 103 mm. Experiments were also carried out on longer pipes, and generally similar results were obtained.

In addition, it was experimentally found that when a solid reflector installed at the end of the pipe the propagation time of the signal does not depend on the frequency. The relative error in measuring length of 3 m long pipes did not exceed 0.15% with constant ambient condition providing stable sound velocity. In the case of measuring longer pipes, the relative error in length measurement will decrease.

6. Conclusion

The conducted experiments demonstrated that measurement of pipe length and diameter by a single sensor at the same time is possible. However, the experimental error for 40 mm pipe diameter measurement was 30%, which is a very inaccurate result for any measuring system. It should be noted that because of the technical limitations for a thin pipe the experiment involved too low emission frequencies and ADC. While an exhaustive metrological analysis is beyond the scope of this paper, it follows from (10) that an increase in the frequency difference leads to an increase in the accuracy of the measurement. With an increase in the radiated frequency and ADC frequency at the same time, the error in pipe diameter measurement can be reduced to 5-6%. An important achievement is the ability to measure pipe length with high accuracy without additional input of the diameter value, which simplifies the operator’s work.
The obtained formulas and algorithms make it possible to develop a portable device for pipe length and diameter measurement. In addition, attenuation of the acoustic signal makes it possible to assess the condition of the pipe interior. It should be noted that the proposed method can also be used to determine waveguide parameters of acoustic systems for monitoring density and viscosity of liquid media.

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References
[1] Peters M C A M, Hirschberg A, Reijnen A J and Wijnands A P J 1993 Damping and reflection coefficient measurements for an open pipe at low Mach and low Helmholtz numbers Journal of Fluid Mechanics 256 499-534
[2] Chung J Y and Blaser D A 1980 Transfer function method of measuring in-duct acoustic properties The Journal of the Acoustical Society of America 68 914
[3] Silva A R, Scavone G P and Lefebvre A 2009 Sound reflection at the open end of axisymmetric ducts issuing a subsonic mean flow: f numerical study. Journal of Sound and Vibration 327 507-528
[4] Papadopoulou K A, Shamout M N, Lennox B, Mackay D, Taylor A R, Turner J T and Wang X 2008 An evaluation of acoustic reflectometry for leakage and blockage detection Journal of Mechanical Engineering Science 222 959-966
[5] Duan W, Kirby R, Prisutova J and Horoshenkov K 2015 On the use of power reflection ratio and phase change to determine the geometry of a blockage in a pipe Applied Acoustics 87 190-197
[6] Kasper L., Vogt P and Strohmeyer C 2015 Stationary waves in tubes and the speed of sound The physics teacher 53 523-524
[7] Kino G S 1987 Acoustic waves: devices, imaging, and analog signal processing: (Bergen: Prentice-Hall)
[8] Newman J W 1986 Method and apparatus for pipe length measurement (US Grant) US4584676A
[9] Krasilnikov V A and Krylov V V 1984 Introduction to physical acoustics (Moscow: Nauka)
[10] Landau L D and Lifshits E M 1986 Hydrodynamics (Moscow: Nauka)
[11] Vanshteyn L A 1976 Propagation of impulses Advances of Physical Sciences 118 339-367
[12] Vanshteyn L A 1953 Diffraction of electromagnetic and sound waves at the open end of the waveguide (Moscow: Sovetskoe Radio publishing house)
[13] Soldatov A I, Sorokin P V and Makarov V S 2009 Determination of the transitional position of an acoustic pulse using the method of waveform envelope approximation Bulletin of the Southern Federal University. Engineering Sciences 10 178-184
[14] Borminskiy S A and Skvortsov B V 2006 Electronic acoustic device for liquid level and pipe level measurement (Moscow: Rospatent) RU 52635.
[15] Borminskiy S A and Skvortsov B V 2006 Electronic acoustic device for pipe length and liquid level measurement (Moscow: Rospatent) RU 58694
[16] Soldatov A I et al 2008 Acoustic range finding method (Moscow: Rospatent) RU 2315335
[17] Skvortsov B V, Zhiganov I Yu and Skorobogatov E G 1998 Electronic acoustic device for pipe length measurement (Moscow: Rospatent) RU 7492.
[18] Skvortsov B V, Zhiganov I Yu and Sinnikov S G 2002 Electronic acoustic measuring device (Moscow: Rospatent) RU 24550
[19] Kalinchuk Yu A, Butkevich L M, Vtorova L V and Kalinchuk F A 2008 Method for pipe length measurement (Moscow: Rospatent) RU 2321827
[20] Borminskiy S A and Skvortsov B V 2010 Device for photo-optical measurement of geometrical dimensions of objects (Moscow: Rospatent) RU 100228