# Remote ultrasound monitoring of underground water mains

Valery Anatolievich Zibrov, Olga Valerevna Sokolovskaya, Natalia Mikhailovna Zibrova, Irina Aleksandrovna Zanina
Don State Technical University, Gagarin Square, 1, Rostov-on-Don, 344000, Russia

**Abstract.** This paper considers the current state of the main underground water pipelines, multiphase processes that lead to the deterioration of the water pipelines structure and the increasing number of failures, ultrasound technologies for remote monitoring of energy resources, the spread of ultrasound signal inside a water pipe, the effect of radial waves reflected at the interfaces of several media having different densities, for axial wave extending inside an underground water main.

[Zibrov V.A., Sokolovskaya O.V., Zibrova N.M., Zanina I.A. **Remote ultrasound monitoring of underground water mains.** *Life Sci J* 2014;11(10):548-551] (ISSN:1097-8135). http://www.lifesciencesite.com. 74

**Keywords:** ultrasound signal, acoustic wave, main underground water pipelines, reflections, reverberation, modes

## Introduction

Current state of the main underground water pipelines (MUWP) is the result of hundreds years of development and big material inputs. The size, cost and complexity of the MUWP impose certain restrictions on their quick replacement. Multiphase processes caused by static factors (water transported through the pipelines, water pipeline laying type, etc.) and dynamic factors (climatic conditions, zones of high pressure, etc.) lead to a deterioration in the structure of water supply networks and the increasing number of failures [1]. A serious problem with the MUWP lies in the slow accumulation of organic and inorganic substances inside the pipe, which appears simultaneously with pipe corrosion. The lack of reliable internal and external waterproofing, aggressiveness of groundwater, soil and transported water, as well as the presence of stray currents result in significant corrosion of metal pipes and reduction of their actual lifespan. Corrosion products of metal water pipelines, consisting mainly of iron oxides, are deposited on the inner surface of MUWP pipes. A layer of sediments accumulated inside the pipes reaches about 15 mm, and as a result a pipe section is reduced to 50% [2]. Intense corrosion of metal water pipelines, due to the appearance in water of dissolved iron oxides, leads to a significant deterioration of water quality in urban water supply system.

Therefore, a remote monitoring of MUWP and related to them objects, representing potential environmental risks, is an important task within numerous science and technology fields. Known automated systems of MUWP monitoring and dispatching have several advantages [3,4,5,6]: sensor measurement of analogue electrical signals and converting them into the equivalent value of a physical quantity; autoranging of measurement channels; reception of digital information from smart sensors; recovery of credential for the period of system downtime, etc. Metrological characteristics of such systems are quite high, but there are drawbacks, such as the use of unreliable wireless and wireline communication systems, lack of unification of communication protocols, operation of the measurement results processing program with several drivers, etc.

Performed by the authors analysis of literary sources showed that ultrasound technologies for remote monitoring of energy resources enable diagnosis of any media and organize sonar data channel inside a water pipeline, in the case when the transmission of information performed by traditionally used methods is difficult or impossible.

## The main part

Underground water pipe is subjected to the radial compression loads and loads of circular shift, causing pipe deformation and short-term reduction in diameter.

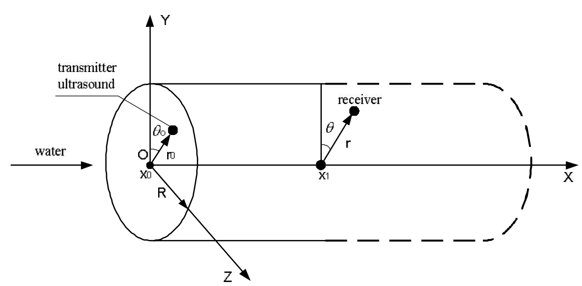


**Fig. 1.** Location of the ultrasound transmitter and receiver inside the pipe

A pipe with absolutely rigid walls can be considered as a long line, along which a one-dimensional wave is spreading. Let us consider an ultrasound transmitter with the coordinates $(r_0, \theta_0, x_0)$ and a receiver $(r, \theta, x_1)$, disposed inside an elastic cylindrical pipe completely filled with water (Fig. 1).

Expression for calculating the acoustic pressure at the receiver input is given by [7, 8, 9, 10],

$$p(r,\theta,x_1,\omega)=\frac{\rho}{cR^2}f(\omega)\sum_{n=0}^{\infty}\sum_{m=1}^{\infty}\frac{J_n(\eta_{nm}r_0)\cos(n\theta_0)J_n(\eta_{nm}r)\cos(n\theta)}{\left(\left(1-\left(\frac{n}{\eta_{nm}}\right)^2\right)J_n(\eta_{nm})\right)^2}e^{i\gamma_{nm}x_1}$$

where $R$ – pipe radius; $\gamma_{nm}$ – axial wave number; $f(\omega)$ – signal function expressed in a frequency domain; $\rho$ – water density; $c$ – sound velocity in water; $J_n$ – Bessel function of the first kind, the order of $n$; $n$ – axial mode; $m$ – radial mode.

Let us consider the case when the underground pipe (Fig. 2) is not subject to deformation and the diameter changes, and is not elastic (ultrasound extends both inside the pipe and through the pipe walls into the soil).

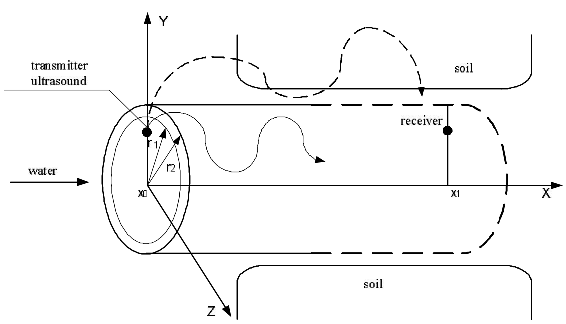


**Fig. 2.** Ultrasound extending inside an underground pipe

Let us consider a transfer function relating the phase variables of the acoustic pressure $p_r$, caused by ultrasound in the radial direction and the radial velocity $v_r$ in the internal and external borders of the pipe ( $r=r_1$ and $r=r_2$ ): $\begin{bmatrix}p_{r_2}\\ v_{r_2}\end{bmatrix}=\begin{bmatrix}L_1 & L_2\\ L_3 & L_4\end{bmatrix}\begin{bmatrix}p_{r_1}\\ v_{r_1}\end{bmatrix}$, where $L_1=\left.\frac{p_{r_2}}{p_{r_1}}\right|_{v_{r_1}=0}$, $L_2=\left.\frac{p_{r_2}}{v_{r_1}}\right|_{p_{r_1}=0}$, $L_3=\left.\frac{v_{r_2}}{p_{r_1}}\right|_{v_{r_1}=0}$, $L_4=\left.\frac{v_{r_2}}{v_{r_1}}\right|_{p_{r_1}=0}$ – coefficients; $r_1$ and $r_2$ – inner and outer radii of the pipe.

Determination of the acoustic pressure and wave velocity in the radial direction:

$$p_r(\eta,\omega,r)=-i\omega\rho\left[aH_0^1(\eta r)+bH_0^2(\eta r)\right];$$

$$v_r(\eta,\omega,r)=\frac{i\eta}{\omega\rho}\left[aH_0^1(\eta r)+bH_0^2(\eta r)\right],$$

where $H_0^1(\eta r)$ – Hankel function of the first kind for radial waves extending in the direction of the soil; $H_0^2(\eta r)$ – Hankel function of the second kind, for the reflected waves extending into the internal pipe area; $a,b$ – constants.

In matrix form: $\begin{bmatrix}p_{r_1}\\ v_{r_1}\end{bmatrix}=\left[M_{r_1}\right]\begin{bmatrix}a\\ b\end{bmatrix}$;

$$\begin{bmatrix}p_{r_2}\\ v_{r_2}\end{bmatrix}=\left[M_{r_2}\right]\begin{bmatrix}a\\ b\end{bmatrix},$$

where

$$\left[M_{r_1}\right]=\begin{bmatrix}-i\omega\rho H_0^1(\eta r_1) & -i\omega\rho H_0^2(\eta r_1)\\ \frac{i\eta}{\omega\rho}H_1^1(\eta r_1) & \frac{i\eta}{\omega\rho}H_1^2(\eta r_1)\end{bmatrix}=\begin{bmatrix}r_{11} & r_{12}\\ r_{13} & r_{14}\end{bmatrix}$$

$$\left[M_{r_2}\right]=\begin{bmatrix}-i\omega\rho H_0^1(\eta r_2) & -i\omega\rho H_0^2(\eta r_2)\\ \frac{i\eta}{\omega\rho}H_1^1(\eta r_2) & \frac{i\eta}{\omega\rho}H_1^2(\eta r_2)\end{bmatrix}=\begin{bmatrix}r_{21} & r_{22}\\ r_{23} & r_{24}\end{bmatrix}$$

The constants values $\begin{bmatrix}a\\ b\end{bmatrix}=\left[M_{r_2}\right]^{-1}\begin{bmatrix}p_{r_2}\\ v_{r_2}\end{bmatrix}=\left[M_{r_1}\right]^{-1}\begin{bmatrix}p_{r_1}\\ v_{r_1}\end{bmatrix}$. We multiply the resulting expression parts by the matrix $\left[M_{r_2}\right]$ and $\left[M_{r_1}\right]$:

$$\begin{bmatrix}p_{r_2}\\ v_{r_2}\end{bmatrix}=\left[M_{r_2}\right]\left[M_{r_1}\right]^{-1}\begin{bmatrix}p_{r_1}\\ v_{r_1}\end{bmatrix};$$

$$\begin{bmatrix}p_{r_1}\\ v_{r_1}\end{bmatrix}=\left[M_{r_1}\right]\left[M_{r_2}\right]^{-1}\begin{bmatrix}p_{r_2}\\ v_{r_2}\end{bmatrix}.$$

The product of $\left[M_{r_2}\right]\left[M_{r_1}\right]^{-1}$ – transfer matrix from an inner area to an outer area, and respectively $\left[M_{r_1}\right]\left[M_{r_2}\right]^{-1}$ – transfer matrix from an outer area to an inner area.

Let us carry out substitutions in matrices:

$$\left[M_{r_1r_2}\right]=\frac{\begin{bmatrix}(r_{21}r_{14}-r_{22}r_{13}) & (-r_{21}r_{12}+r_{22}r_{11})\\ (r_{23}r_{14}-r_{24}r_{13}) & (-r_{23}r_{12}+r_{24}r_{11})\end{bmatrix}}{\Delta r_1},$$

where $\left[M_{r_1r_2}\right]$ – transfer matrix in the direction of from the radius $r_1$ to $r_2$; $\Delta r_1=r_{11}r_{14}-r_{12}r_{13}$.

We carry out replacements in the expression $\Delta r_1$ by Hankel functions, find the Wronskian determinant for the Hankel functions, and then determine the coefficients $L_1 - L_4$:

$$L_1 = -i\frac{\pi}{4}\eta r_1\left[H_0^1(\eta r_2)H_1^2(\eta r_1) - H_0^2(\eta r_2)H_1^1(\eta r_1)\right]$$

$$L_2 = \frac{\pi}{4}\eta r_1\rho\omega\left[H_0^1(\eta r_2)H_0^2(\eta r_1) - H_0^2(\eta r_2)H_0^1(\eta r_1)\right]$$

$$L_3 = \frac{\pi}{4}\frac{\eta r_1}{\rho\omega}\left[H_1^1(\eta r_2)H_1^2(\eta r_1) - H_1^2(\eta r_2)H_1^1(\eta r_1)\right]$$

$$L_4 = -i\frac{\pi}{4}\eta r_1\left[H_1^2(\eta r_2)H_0^1(\eta r_1) - H_1^1(\eta r_2)H_0^2(\eta r_1)\right]$$

Obtained by the calculation coefficients $L_1 - L_4$, through the transmission matrix make it possible to determine the wave value in the radial direction, and to evaluate its effect on the axial wave.

Temporary fields of acoustic pressure extending inside the main water pipe, made of polyethylene and steel, are shown in Fig. 3-5. The frequency of the original signal is 55 kHz; distance to the signal receiver is 400 m. Fig. 3 shows the signals that have passed into the soil through the steel pipe.

The signal form shows that the axial wave does not extend inside the soil, so the received signal, being in the nature of noise, will be superimposed on the axial wave extending inside the pipe.

Fig. 3 shows that the input of the receiver accepts quicker than the axial wave modes arriving via the pipe walls. There are also observed other modes extending through a long transmission path, including possible reflections from the walls of a steel pipe and passed through the soil of different densities.

With decreasing of the signal frequency to 5 kHz, meanwhile not changing the pipe diameter, we can observe attenuation of reflected signals that have passed through the walls of a steel pipe and through the ground areas at14 dB.

The 55 kHz frequency signal excites more modes, which leads to serious signal reverberation, at the same time, the high-frequency modes are damped faster than the low frequency ones.

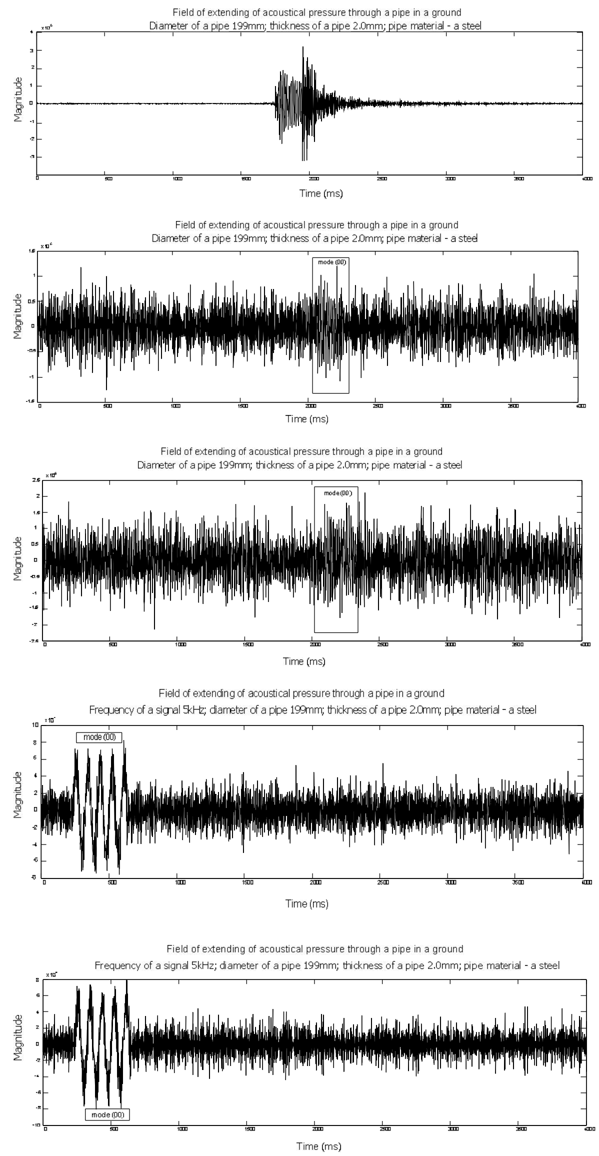


**Fig. 3.** Fields of acoustic pressure extending

**Conclusions**

Acoustic wave reflections at the interfaces of several media having different densities will reduce the energy of the acoustic pressure extending inside the pipe and increase the multipath of waves. Therefore, in a cylindrical underground pipe filled with water, the information should be transmitted by using a wave with the mode (0,0). There should be also applied a special filter for the mode (0,0) isolating from the received signals.

**Corresponding Author:**
Dr.Zibrov Valery Anatolievich
Don State Technical University,
Gagarin Square, 1, Rostov-on-Don, 344000, Russia

**References**

1. Misiunas, D., 2005. Monitoring and asset condition assessment in water supply systems, PhD thesis, Lund Univ., Lund.

2. Dermile, R. and Saniie, J., 2001. Model-based estimation of ultrasound echoes Part I: Analysis and algorithms. IEEE Transactions on Ultrasounds, Ferroelectrics and Frequency Control, 48(3): 787-802.

3. Yang, C., Liu, Y. and Yu, J., 2009. Prestressing Concrete Cylinder Pipe Monitoring Based on WSN. Journal of Information and Communication Technology, 2(2): 58-62.

4. Swamee, P. and Sharma, A, 2008. Design of water supply pipe networks. John Wiley: 347.

5. Jin, Y. and Eydgahi, A., 2008. Monitoring of distributed pipeline systems by wireless sensor networks. 2008 IAJC-IJME International Conference, International Association of Journals & Conferences.

6. O'Shea, P., 2000. Failure mechanisms for small diameter cast iron water pipes, PhD thesis, Southampton Univ., Southampton.

7. Kokossalakis, G., 2006. Acoustic data communication system for in-pipe wireless sensor networks, PhD thesis, MIT, Massachusetts.

8. Rienstra, S.W. and Hirschberg, A., 2012. An introduction to acoustics. Eindhoven University of Technology: 284.

9. Kausel, E., 2006. Fundamental solutions in elastodynamics. Cambridge University Press: 262.

10. Sullivan, E. and Candy, J., 2003. Acoustic Propagation in a Water-Filled Cylindrical Pipe, University of California, Lawrence Livermore National Laboratory, Technical Information Department.

04/06/2014