APPLICATION OF ULTRASONIC TECHNIQUE IN CORE FLOW MONITORING AND CONTROL

Guilherme Rosário dos Santos
State University of Campinas - UNICAMP-FEM-DEP-Cx.P. 6122- 13083- 970- Campinas, Brazil
guilherm@dep.fem.unicamp.br

Paulo Seleguim Jr.
University of São Paulo - Engineering School of São Carlos
seleghim@sc.usp.br

Antonio Carlos Bannwart
State University of Campinas - UNICAMP-FEM-DEP-Cx.P. 6122- 13083- 970- Campinas, Brazil
bannwart@dep.fem.unicamp.br

Abstract. *The development of heavy oil field, onshore and offshore, is becoming a strong need worlwide. For the production and transportation of heavy oils, one of the proposed methods is the use of water-assisted flow techniques such as core flow, which consists in the injection of small quantities of water, in order to get a lubrificated oil core in the pipe. The purpose of this work is to investigate the possible use of ultrasonic probes for monitoring and control of the water annulus thickness in oil-water core flow. The ultrasound technique was selected because it is safer and simpler than existing techniques such as γ-ray and X-ray. An ultrasonic measurement probe (pulse-receiver) is combined with analog-digital conversion and data are transmitted to a PC for processing and analysis. After a suitable treatment, this data can provide both time of flight of ultrasound through the pipe wall and the liquid film. Previous calibration provides the propagation velocities of ultrasonic waves through the wall and the liquid film. With these data, it is possible to determine the liquid film thickness.*

Keywords*: Petroleum engineering, heavy oil, oil-water flow, core flow, ultrasound*

1. Introduction

Global hydrocarbon demand has grown from 90 million boe/d in 1980 to around 128 million boe/d presently (McKay, 2003). Current world hydrocarbon proven reserves are broadly 1100 billion bbl oil, 750 million boe of gas and 3000 billion boe of unconventional oils like bitumen and oil sands. Sooner or later, heavy oils will have to be extensively used (Kawata & Fujita, 2001).

The density of heavy oils is under API 20 degrees (934 kg/m^3) and their viscosity ranges from 100 cP to 10000 cP. Density of extra heavy oils is under API 10 degrees (1000 kg/m^3) and their viscosity is over 10000 cP (Kamei & Serizawa, 1998).

For the production and transportation of heavy oils, water-assisted techniques such as 'core flow' have been proposed. It consists in a lateral injection of water, so as to create a lubricating water film around the oil, which is kept from wall contact. Ideally, the water flow rate is much smaller than oil, requiring a suitable monitoring and control of the water annulus thickness to keep the flow stable under typical disturbances that usually occur in two-phase flow. The core flow technique makes possible to reduce drastically the pump power needs in comparison with single phase oil flow (Vanegas Prada, 1999).

Recent advances in the capability for both analogical-digital converters and computers, combined with cost reductions, make real-time data collection and analysis a cost-effective and technically attractive option. Ultrasonic signals successfully interrogate many fluids, optically opaque slurries, dense suspensions, penetrate vessels and process chamber walls and are not significantly degraded for a wide range of process conditions (Bond et al., 2003).

Ultrasonic devices provide *in situ* measurements or real-time visualizations, and the sensing systems are compact, rugged and relatively inexpensive. Furthermore, they provide other advantages such as high accuracy and rapidity. This technique is safer and simpler to use in comparison to other techniques such as γ-ray and X-ray (Vatanakul et al., 2004).

The objective of this work is to develop a measurement technique for the instantaneous water film through the emission-reception of ultrasound signals in a horizontal water-oil flow, so as to determine if the ultraviscous core keeps lubricated or not. The sonic pulse speeds in the water and wall are determined by previous calibration. The ultrasonic device is installed on the outside of the pipe, a feature that makes this technique useful in oil pipelines.

Chang, Ichikawa and Irons (1982) applied an ultrasonic technique to measure liquid film thicknesses in stratified water-air and air-mercury horizontal flows. The results were compared with the thickness calculated from the known amount of liquid (water or mercury) in the pipe, showing good agreement.

Chang and Morala (1990) determined the interfacial area in an air-water flow through an ultrasonic technique. The flow patterns in their work were: stratified smooth, stratified wavy, plug flow and slug flow. Liquid level histograms for each flow pattern were constructed. The time averaged liquid level was plotted as a function of void fraction. An approach by polynomial regression model was applied and the comparison between them gave good results, having a variance of 0,063 for plug and slug flows with void fraction less or equal to 0,95.

Lu, Suryanarayana e Christodoulu (1993) performed film thickness measurements with an ultrasonic transducer using R-113 and FC-72 in a rectangular duct at several locations. It was proposed a power law relation for evaluating the film thickness based on the experimental data. This technique can be applicable in stratified smooth and stratified wavy flows.

Kamei and Serizawa (1998) measured local instantaneous liquid film thickness around a simulated nuclear fuel rod by ultrasonic transmission technique. A rotating reflector for two dimensional analysis was adopted. The local liquid film thickness at any circumferential position around the tube surface was detected every 4 ms in the form of a time series of signals (in a spiral way). Preliminary tests were carried out in air-water annular film flow and the results clearly indicated very promising natures of this new technique.

Fiedler, Yildiz e Auracher (2001) determined the film thickness of steam condensate in an inclined tube by using the pulse-echo technique. Results were compared with the needle probe technique with good agreement between them. Tests were carried out at inclination angles of 30°, 60° and 90° with 10 kPa at the inlet of test section. This study concluded that local film thickness increases with decreasing inclination angles. The average film thickness is not affected significantly with changes in inclination angles. The pulse-echo technique showed itself applicable to determine film thickness.

Wurfel, Kreutzer e Fratzscher (2003) run experiments to determine local film thickness in a circumferential direction by ultrasonic technique in an inclined tube. Working fluids were n-heptane and air. They proposed a correlation for evaluating film thickness as a function of liquid kinematic viscosity and dimensionless parameters such as Reynolds and Weber numbers. The values provided by the correlation application were in agreement with those found in the literature.

2. Experimental Apparatus and Methodology

The measurement principle of film thickness is based on the pulse-echo technique, that is, the film thickness is determined from the arrival time of specific echoes. More precisely, when an acoustic wave travels through a multilayered medium, at every interface reflection waves are generated which can be detected and related to the travel length by knowing travel velocities. Figure 1 illustrates this principle.

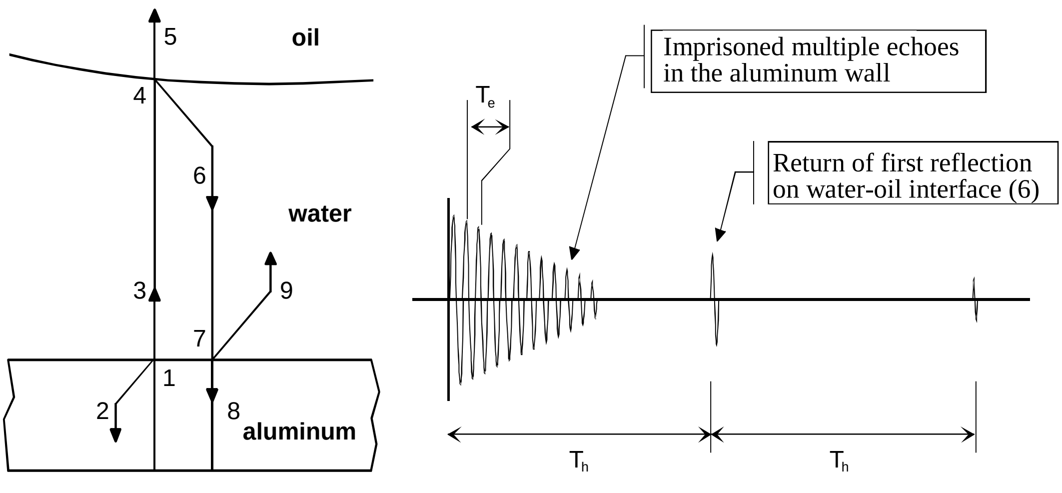

Figure 1. Basic structure of acoustic signal and proposed model for wave path.

The acoustic pulse is generated at the outer surface of the pipe wall, denoted by 0 in the schematic diagram in Fig. 1, and reaches the metal/water interface at 1 where an echo and a transmitted wave are generated, respectively denoted by 2 and 3. The transmitted wave 3 crosses the water film and reach the water/oil interface at 4, producing the echo 6 which, after traveling back through the water film, reaches the water/metal interface at 7. The corresponding transmitted wave 8 reemerges at 0 and is captured by the acoustic receiver. Since the velocity of sound in the metallic medium is generally 7 to 12 times higher then the corresponding speed in liquid media, and also because the travel length is much smaller, several echoes from the transmitted wave 2 will be observed before the first echo from the water/oil interface can be detected at the external surface. These multiple echoes are measured by a data acquisition system and processed in a PC in order to extract transit times and to calculate the resulting water film thickness.

As can be seen in Fig. 1, T_e and T_h are the transit times representing respectively the arrival times of the echoes produced at the metal/water (1) and water/oil (4) interfaces. It is important to emphasize that the identification of T_e and

T_h demands specific signals analysis algorithms because of the presence of noise and secondary oscillations, due to the piezoelectric transducer, which can trouble the arrival time identification.

Considering the basic structure of signal, it is possible to calculate T_h time as a function of wall pipeline e and water film h thicknesses, knowing propagation velocities in the aluminum and water V_{al} and V_{ag}, i.e.:

$$h = \frac{V_{ag}}{V_{al}}\left(\frac{2e}{T_e}\right)\left(\frac{T_h}{2} - \frac{T_e}{2}\right) \tag{1}$$

Water film thickness values found were compared to the visual measurement made with the help of a fast video camera. The propagation velocities in the aluminum and water were taken such as 6320 m/s and 1480 m/s at 20°C, according to Kinsler et al. (1980). Figure 2 shows an original signal with multiple echoes.

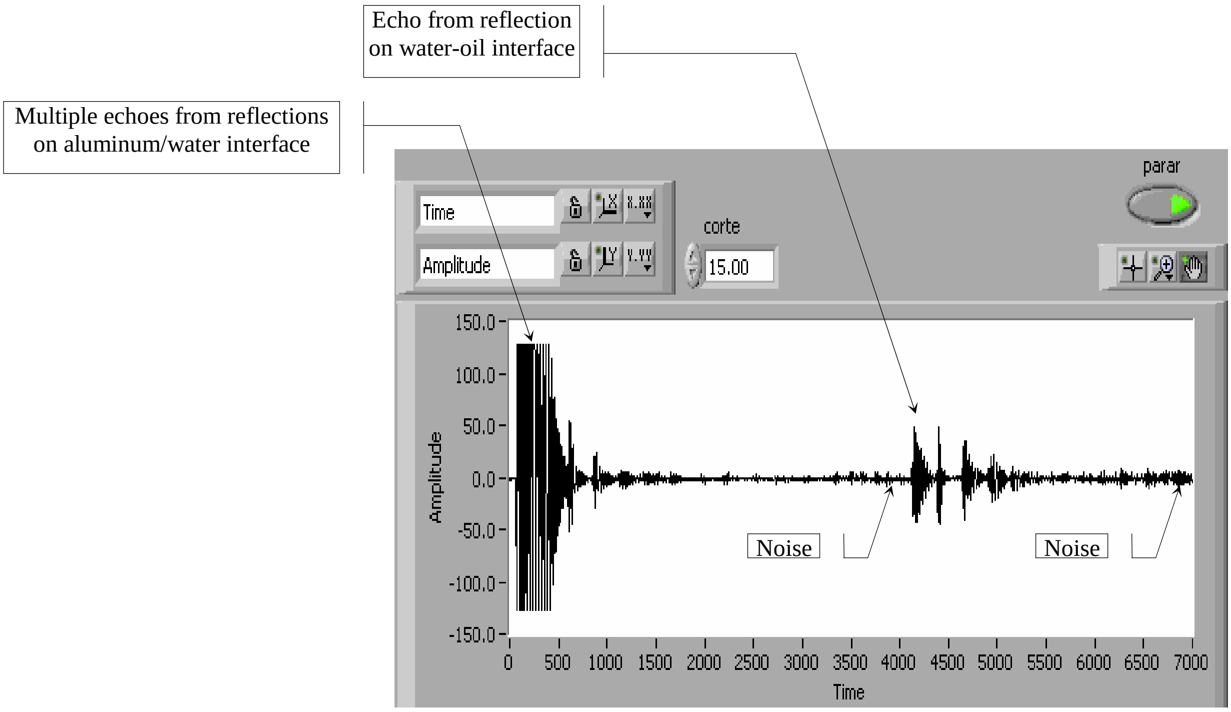

Figure 2. Original signal with secondary echoes and noise.

The measurement of T_e and T_h times was achieved in three stages:

I - Cross correlation between measured signal (multiple echoes) and characteristic form of excitation pulse;
II - Calculus of the instantaneous amplitude associated with the cross-correlation signal's analytic extension;
III - Identification of local maxima through a peak identification algorithm.

Let $x(t)$ be the measured signal and $\psi(t)$ the characteristic form of excitation pulse. The cross correlation between them is evaluated by:

$$R(t) = \int_{sup} x(t)\psi(\tau - t)\,d\tau \tag{2}$$

The associated analytic extension is generated by Hilbert transforming the cross correlation signal according with the following definition:

$$z(t) = R(t) + i\,H[R(t)] = R(t) + \frac{i}{\pi}\int_{sup}\frac{R(t)}{t-\tau}d\tau \tag{3}$$

where *i*, *H[R(t)]* and τ are the imaginary unit, Hilbert Transform of cross correlation and delay time, respectively. The envelope of acoustic signal can be determined through amplitude *A(t)* and instantaneous frequency $\omega(t)$ of *z(t)*. Rewriting it in a polar way:

$$z(t) = A(t)exp[i\phi(t)] \tag{4}$$

where

$$A(t) = \sqrt{R^2(t) + \left[\frac{1}{\pi}\int_{sup}\frac{R(t)}{t-\tau}d\tau\right]^2} \tag{5}$$

$$\omega(t) = \frac{d\phi(t)}{dt} = \frac{d}{dt}arctg\left\{\frac{1}{\pi R(t)}\int_{sup}\frac{R(t)}{t-\tau}d\tau\right\} \tag{6}$$

The instantaneous amplitude *A(t)* is shown in the Fig. 3, calculated from Eq. (5) from the original multiple echo signal shown in Fig. 2. It is possible to observe that the arrival time T_h is clearly identified with the first peak of the local envelope, around 42 μs, associated with the echo produced at the water/oil interface indicated by point (6) in the diagram of Fig. 1.

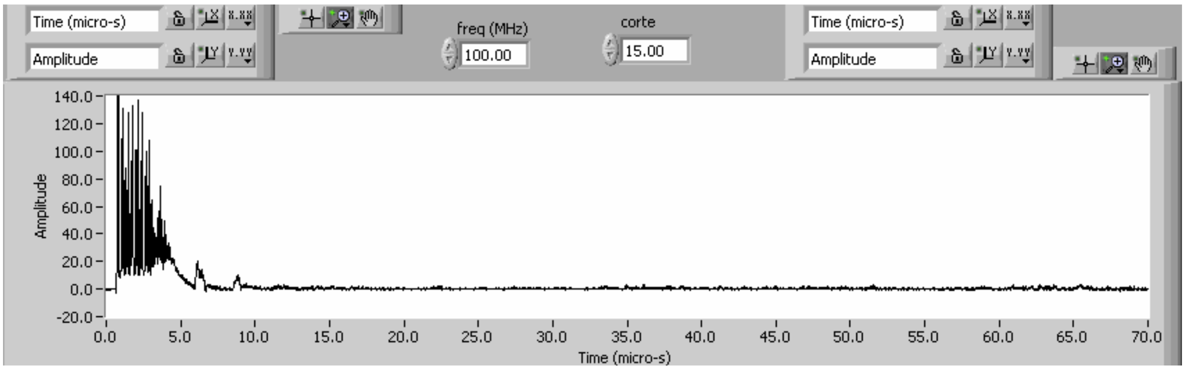

Figure 3. Instantaneous amplitude correspondent to the signal from Fig. 2

Experimental apparatus is composed basically by: core flow circuit, ultrasonic device, personal computer for signals acquiring and a video camera. The core flow is composed by (Vanegas Prada, 1999):

a) Water-oil gravity separator
b) Fluids pump system
c) Instrumentation system
d) Fluids injection system
e) Pipeline

The core flow circuit is shown in the Fig. 4. From the separator, water and oil are led to the injection nozzle individual pumps (a gear pump for water and a progressive cavity pump for oil) each one controlled by frequency inverter. Water flow is measured by using rotameter while oil flow is measured through a Coriolis mass flowmeter. The two-phase mixture flows through a 2.84 cm i.d. glass pipe, first in a vertical section 1.70 m long, then in a horizontal section 5.43 m long and finally in a vertical downward section back to the separator.

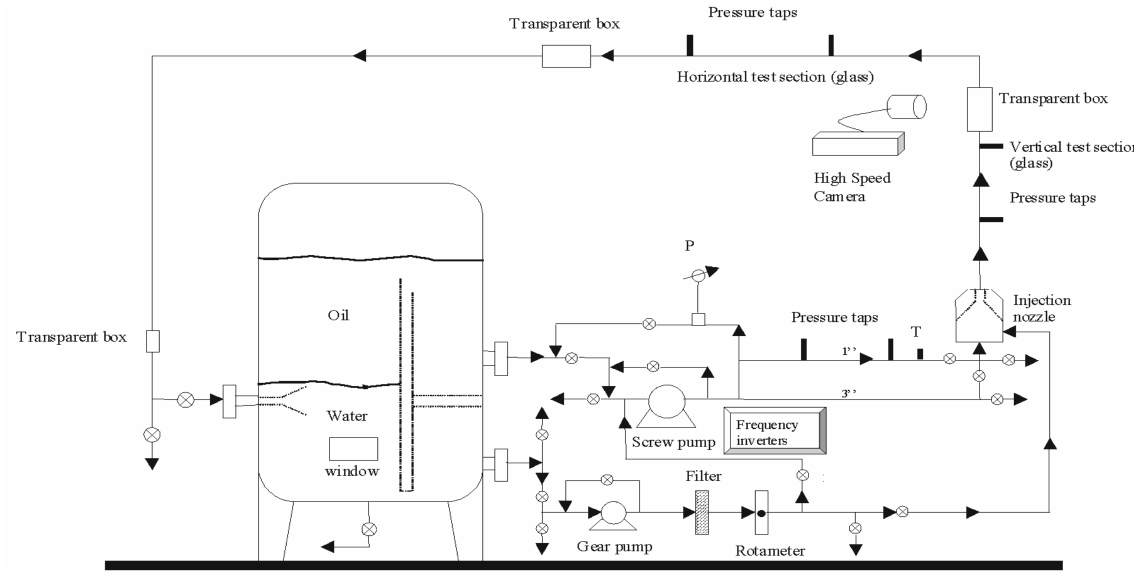

Figure 4 – Schematic diagram of the oil-water flow circuit

The ultrasonic device was dimensioned to provide an ideal acoustic coupling between piezoelectric transducers and the flow (Fig. 5) The above described methodology was implemented in LabView plataform, which allows treatment and processing of the electric signal.

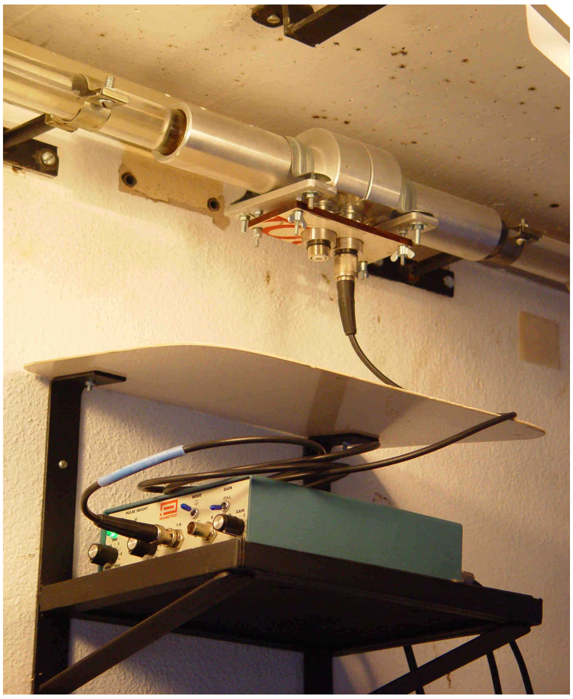

Figure 5. Ultrasonic device for measurement film thickness

The ultrasonic pulser/receiver model is model 500 PR Panametrics with 25 MHz of frequency and can generate form 500 to 5000 pulses per second. The video camera model is Encore Olympus model 9400-0020.

3. Results and Discussion

Figure 6 shows the instantaneous film thickness of core annular and slug regions. Figures 7 and 8 show a portion of pipeline with rulers for visual estimation of water film thickness for slug and core annular flows, respectively.

Figure 6. Water film thickness for slug and annular regions

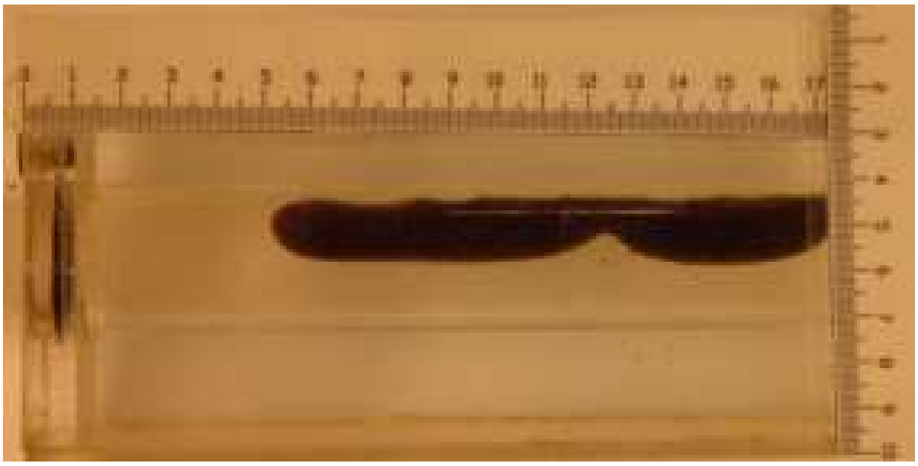

Figure 7. Portion of pipeline with rulers for estimating water film thickness for slug flow

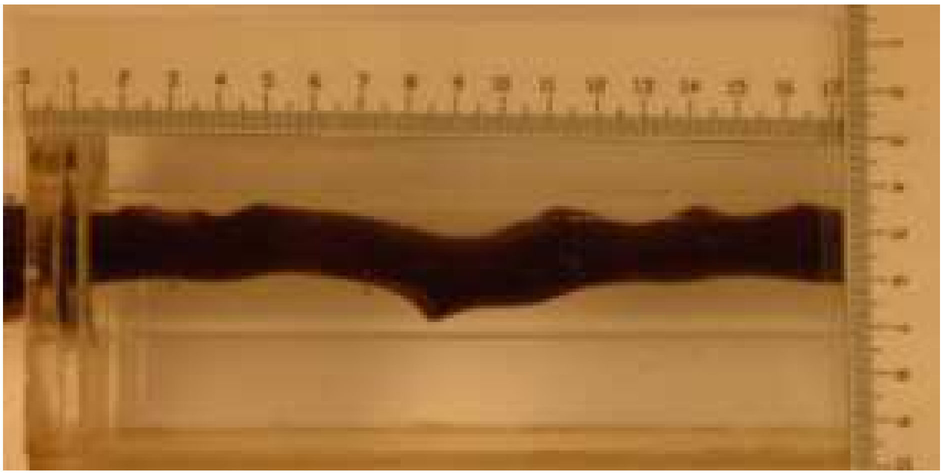

Figure 8- Portion of pipeline with rulers for estimating water film thickness for core flow

As it can be seen from Figs. 6 and 7, water film thicknesses are ranging from 5 to around 10 mm, when the "oil bubble" is passing and ultrasound pulse reaches the interface water-oil and is reflected back. On the other hand, water thickness will be 20 mm between two consecutive "oil bubbles", when just water is passing and ultrasound pulse is reflected back in the other wall pipeline. Visual estimation is in a good agreement with theoretical water film calculated by LabView program. The varying of water film thickness values can be explained by irregularities of water-oil interface such as shown in Figs. 7 and 8.

4. Conclusion

The main objective of this work was to demonstrate the possibility of determining the interface positions in an oil-water flow through ultrasonic technique and processing of signals in real time. Tests were carried out with aluminum ultrasonic device to reproduce oilfield conditions in which petroleum pipelines are usually metallic. This work can be continued in a different ways, depending on the specific technology interest. For example, it could be carried out a sensibility study with temperatures changes. Corrections can be done analyzing the signal portion of multiple echoes correspondent to the reflections in internal walls of ultrasonic device. Another perspective could be the development of ultrasonic device inner piezoelectrics, whose acoustic impedance will be suitable to maximize the acoustic energy.

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