Manuscript Details

Manuscript number ULTRAS_2017_279

Title Differentiate low impedance media in closed steel tank using ultrasonic wave tunneling

Abstract

Ultrasonic wave tunneling through seriously mismatched media, such as steel and water, is possible only when the frequency matches the resonance of the steel plate. But it is nearly impossible to realize continuous wave tunneling if the low acoustic impedance media is air because the transducer frequency cannot be made so accurate. The issue might be resolved using tone-burst signals. Using finite element simulations, we found that for air media when the cycle number is 20, the -6dB bandwidth of energy transmission increased from 0.001% to 5.9% compared with that of continuous waves. We show that the tunneling waves can give us enough information to distinguish low acoustic impedance media inside a steel tank.

Submission Files Included in this PDF

File Name [File Type]

ResponseToReviewer.doc [Response to Reviewers]

Highlights.docx [Highlights]

Manuscript6.20.2017.docx [Manuscript File]

Fig.1.tif [Figure]

Fig.2.tif [Figure]

Fig.3.tif [Figure]

Fig.4.tif [Figure]

Fig.5.tif [Figure]

Response to Reviewer's Comments

We appreciate the constructive comments of the reviewer. Please see itemized response below. Changes in the manuscript were heighted in purple color.

1. On my opinion, Continuous Wave (CW) must be introduced at the beginning.

Re: The continuous wave definition has been added in the manuscript.

2. Fig.3 relates to the transmission coefficient of steel plate only, is not it? It is not evident from the caption.

Re: Yes, the information has been added in the caption of Fig. 3.

3. In the practical case, the measurements must be done at different temperatures. Some discussion about AETC.

Re: Thanks for this insightful suggestion, however, we cannot obtain the media property parameters at different temperatures right now, we will pursue this in the near further. The change of AETC with temperature will not change the fundamental characteristics and will not affect the conclusions.

4. Figures 4 and 5 are not good in the gray scale case.

Re: Thanks for this good comment, these two figures have been revised using different symbols and different types of liens to distinguish different cases in addition to different colors.

5. Page 8, 2-nd row from the top: "in the inset figure of Fig.4b". The inset is absent on the Figure 4b.

Re: Thank you for finding this typo, it should be Fig. 4a).

6. How does amplitude of tone burst change from one cycle to another? How does the amplitude change law affect on an ultrasound tunneling. It is necessary to give some detail on this topic.

Re: The amplitude of tone burst does not change, which is controlled by the signal generator and the amplifier. Higher amplitude of tone burst will lead to higher receive voltage, but relative ratios will not change for linear media.

7. Conclusion, first sentence: " An ultrasound tunneling method was analyzed

and used to detect the level of different media in a closed steel tank". But any discussion about level is absent in the paper. What does word "level" mean?

For the configuration, which is shown on Fig.1, the location of water surface with regard to transducer can be determined only. But such binary information ("above" or "below") can be obtained by using CW too. Namely, if received voltage equals to zero, then air is located near transducer. And water is located near transducer in the opposite case. Therefore the advantage of the tone-burst signal using is not evident.

Re: Thank you for this insightful comment. As discussed in the manuscript, theoretically, CW can be used to dectect the level in closed tank at the resonace frequency or harmonic frequencies of the steel plate. However, using CW to detect very low impedance media, the tolerance for requirement of transducer is impossible to achieve. For example, in the air case, the -6dB bandwidth of enery transmission coefficient is only 0.001% (Fig. 4a)) for CW, the energy could not transmit the steel plate if the transducer frequency is slightly deviated from the resonance frequency. Because resonance frequency of ultrasonic transducers cannot be made so accurate, it will be difficult to achieve this purpose. On the other hand, the 20 cycles tone burst signal has a 5.9 % bandwidth, which is possible for transducer engineers to achieve. Please see more detailed discussions in Section 3.2.

8. 2-nd highlights does not reflect main results of the article.

Re: Thank you for this comment. The highlights has been revised based on your suggestion.

9. Mention of the Comsol software would look well in the Setup, not in the Conclusion.

Re: Comsol Multiphysics software is now mentioned at the end of Setup section.

1. An ultrasound tunneling method was proposed to detect very low acoustic impedance media in a closed steel tank.
2. 20 cycle tone-burst is sufficient to generate tunneling effect with broad enough bandwidth.
3. The method can clearly distinguish water, air and foam inside the steel tank.

Differentiate low impedance media in closed steel tank using ultrasonic wave tunneling

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Abstract

Ultrasonic wave tunneling through seriously mismatched media, such as steel and water, is possible only when the frequency matches the resonance of the steel plate. But it is nearly impossible to realize continuous wave tunneling if the low acoustic impedance media is air because the transducer frequency cannot be made so accurate. The issue might be resolved using tone-burst signals. Using finite element simulations, we found that for air media when the cycle number is 20, the -6dB bandwidth of energy transmission increased from 0.001% to 5.9% compared with that of continuous waves. We show that the tunneling waves can give us enough information to distinguish low acoustic impedance media inside a steel tank.

Keywords: wave tunneling; bandwidth; ultrasonic NDE; optimization.

1. Introduction

Ultrasound has been widely employed in the detection and diagnosis of defects or details of structures, such as medical imaging [1-4], nondestructive testing [5-7], food safety inspection [8-10], etc. However, in some applications, the ultrasound transducer cannot directly in touch with the object, such as monitoring the oil level in the pipeline [11], detecting the level of different media in a closed tank, etc. In these cases, especially when the impedance difference between the media and the tank is very large, the acoustic energy transmission will be very small [12]. According to the T-matrix theory, if the system was excited at resonance frequency or the corresponding harmonic frequencies of the steel palate, the whole energy can go through the mismatched impedance layers [13-14]. Hence, this resonance tunneling method should be explored.

In this work, we will discuss how to detect the level of different liquid media in a closed steel tank by the resonance tunneling method. The T-matrix theory is based on continuous wave (CW) which is a wave of fixed amplitude and frequency. However, in practical measurements, tone burst is preferable because the tunneling bandwidth is very narrow for CW waves and it is impossible to make an ultrasonic transducer of exact frequencies. Therefore, it is essential to know the least number of tone burst cycles which can excite the resonance condition. In this work, we have simulated the tone-In addition, the relationship between the -6dB bandwidth of energy transmission coefficient and the impedance media has been comprehensively investigated.

2. Setup and Methods

2.1. Setup and Materials

In the closed tank showed in Fig. 1, assuming there are three possible media in the tank, water, air and foam of soup water, respectively. The tank is made of steel plate and the designed thickness is 2.89 mm. A pair of pitch-catch transducers are used to send and receive the ultrasound signals. All the material parameters are listed in Table I.

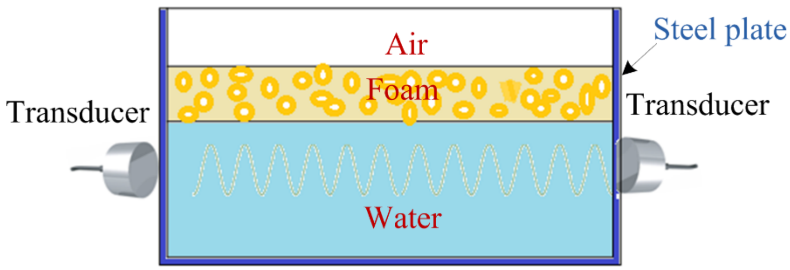

Fig. 1. Schematic diagram of the measurement system, the media in the steel tank are water, air and foam.

Table I. Material properties at room temperature

Materials	Density(kg/m^3)	velocity(m/s)	Impedance(MRayl)
Steel	7850	5780	46.6
Water	~1000	1500	1.5
Air	1.239	340	4.2×10^{-4}
Foam	20	1000	2×10^{-2}

The impedance of the steel, water and air are 46.6 MRayl, 1.5 MRayl and 4.2×10^{-4} MRayl, respectively. The acoustic energy transmission coefficient (AETC) is given by [12],

$$T = \frac{4Z_1Z_2}{(Z_1+Z_2)^2} \tag{1}$$

where Z_1 and Z_2 are impedances of the incident material and transmitting material, respectively, and $Z= \rho\ v$, where ρ and v are the density and velocity of the media, respectively. Hence, the energy transmission coefficient from the steel to water is 12%, and to air is only 0.38%. Taking consideration of other factors, such as scattering and absorption, the catch transducer can hardly receive any signal for the air case. In order to solve this problem, the resonance tunneling method is used to excite the resonance propagation in the steel plate.

2.2. Determination of the AETC

First, we used the finite dimension T-matrix model to perform the calculations. Our experimental setup can be simplified as a steel-water-steel system. Assuming a longitudinal acoustic wave enters into the steel layer, then to the water layer and transmit through the other steel layer. The wave function in each layer is in the following form:

$$u(x,t) = \left[A_+^j e^{ik^j x} + A_-^j e^{-ik^j x} \right] e^{-iwt}, \tag{2}$$

where the wave number k=ω/v, ω and v are the angular frequency and velocity of the corresponding layer, respectively. Also, assuming there is no reflection after the wave transmitting through the second steel layer into the air.

The transfer matrix for layer i is T_i, and it has the following form,

$$T_i = \begin{bmatrix} \cos(k^j d^j) & (1/Z_i)/\sin(k^j d^j) \\ -Z_i/\sin(k^j d^j) & \cos(k^j d^j) \end{bmatrix}, \tag{3}$$

And the total transmission T is the product of transfer matrices as follows,

$$T = T_n T_{n-1} \ldots T_1, \tag{4}$$

For the steel-water-steel system, the total transfer matrix is given by

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cos(k^s d^s) & (1/Z_s)/\sin(k^s d^s) \\ -Z_s/\sin(k^s d^s) & \cos(k^s d^s) \end{bmatrix} \begin{bmatrix} \cos(k^{\mathrm{w}} d^{\mathrm{w}}) & (1/Z_{\mathrm{w}})/\sin(k^{\mathrm{w}} d^{\mathrm{w}}) \\ -Z_{\mathrm{w}}/\sin(k^{\mathrm{w}} d^{\mathrm{w}}) & \cos(k^{\mathrm{w}} d^{\mathrm{w}}) \end{bmatrix} \begin{bmatrix} \cos(k^s d^s) & (1/Z_s)/\sin(k^s d^s) \\ -Z_s/\sin(k^s d^s) & \cos(k^s d^s) \end{bmatrix} \tag{5}$$

where k^s and k^w are the wave numbers and d^s and d^w are layer thickness of steel and water, respectively, the superscript w represents water, s represents steel.

Both displacement continuity and stress continuity are satisfied at the layer interface, the acoustic energy transmission coefficient of the above system is as follows,

$$t=\left(\frac{A_{N+1}}{A_0}\right)^2=\left(1-\frac{-w\mathrm{i}Z_sT_{11}-w^2Z_s^2T_{12}-T_{21}+w\mathrm{i}Z_sT_{22}}{w\mathrm{i}Z_sT_{11}-w^2Z_s^2T_{12}+w\mathrm{i}Z_sT_{22}}\right)^2, \tag{6}$$

where A_0 and A_{N+1} are the amplitude of incident and transmission waves, respectively.

The finite element simulations were performed using Comsol Multiphysics® finite element package (COMSOL, Inc.).

3. Results and Discussion

3.1. The relationship between AETC and excited frequency

The calculation results in Fig. 2a) show that, when the steel plate is excited at its resonance frequency or harmonic frequencies，the energy can transmit 100%. Our simulation results verified the T-matrix calculations. Fig. 2b) shows the steel plate resonates at its resonance frequency 1.0 MHz, second harmonic 2.0 MHz and third harmonic 3.0 MHz, which corresponding to the (½) λ (λ is wavelength is steel), λ, and (3/2) λ vibrations, respectively. At other frequencies, the vibration displacements are irregular.

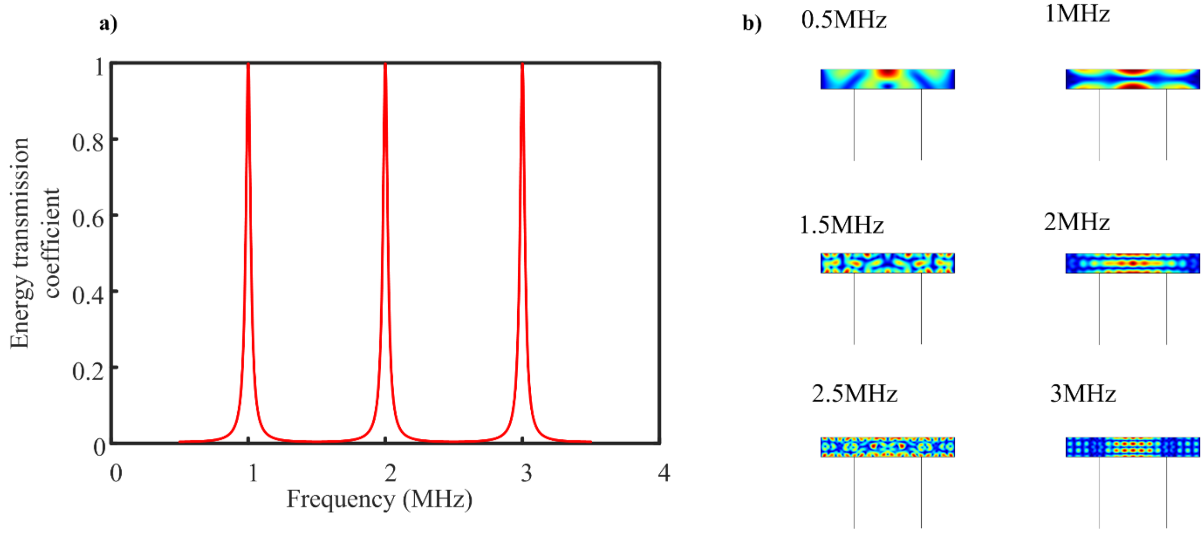

Fig. 2. a) The energy transmission coefficient from steel plate to water excited by a range of frequencies, b) The vibration displacement distribution of steel plate at several representative frequencies with a finite size transducer in the center, simulated using finite element software.

3.2. The relationship between AETC and excited cycle number

However, in practical measurements, it is very difficult to make a transducer with exact 1.0 MHz and the transmission will be drastically reduced if the transducer frequency is slightly off the resonance due to the extremely narrow bandwidth of the transmission coefficient. Hence, we need to study the cycle number of tone burst signal which can excite the resonance. The steel plate was excited by tone burst of different number of cycles with the center frequency 1.0 MHz in a cycle number ranging from 1 to 40. The energy transmission coefficients were calculated for each case, and the vibration displacement of steel plate was simulated using finite element software. As showed in Fig. 3, the energy transmission coefficient monotonically increases with the number of cycles, and reaches 45% when the burst signal is about 20 cycles. In addition, the steel vibration displacement pattern gradually approaches 1/2 λ resonance as the number of cycle increases.

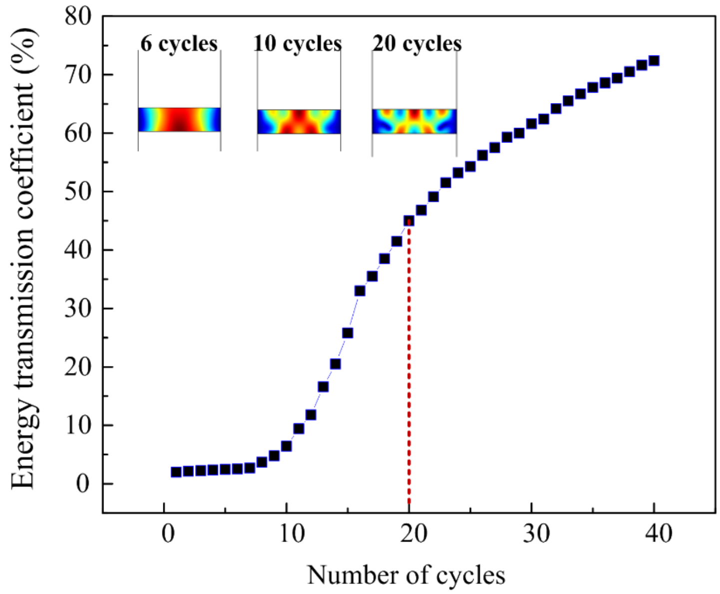

Fig. 3. Relationship between energy transmission coefficient from steel plate to water and the number of tone burst cycles. The inset figure is the vibration displacement distribution of steel plate excited at different number of tone burst cycles.

3.3. The relationship between AETC and media impedance

Based on the design of our measurement system, the relationship between -6 dB bandwidth of transmission coefficient and the acoustic impedance of the media was investigated. Fig. 4 shows the bandwidth of the transmission peaks with media water, foam and air, they were 4.2%, 0.05% and 0.001%, respectively. When the impedance difference between the steel plate and media is very large, the bandwidth almost linearly decreases with the decrease of media acoustic impedance. Since the bandwidth of the air case for the CW wave is much narrower than that of the water case, the energy could not transmit through the steel plate if a tiny deviation from the resonance frequency occurred, which is an unpractical demand for the ultrasonic transducer. In this case, the tone burst signal has an advantage compared to the CW since its relatively broader bandwidth will give enough tolerance of the transducer frequency resonance frequency. Sinusoidal wave with a center frequency of 1MHz was used its bandwidth was obtained with different number of cycles using the Fourier transform. The results in Fig. 4b) shows that when the number of cycles increases, the bandwidth decreases and the center frequency approaches 1MHz. When the number of cycle number was 20, the bandwidth and center frequency were 5.9% and 1.025MHz, respectively. Besides, the commercial broad bandwidth (BW) transducers could achieve the -6dB bandwidth more than 80% [15-16], it is therefore easy to satisfy and adjust the frequency to excite the resonance of the steel plate. In other words, to excite the steel plate resonance, the transducer frequency band must cover this resonance frequency.

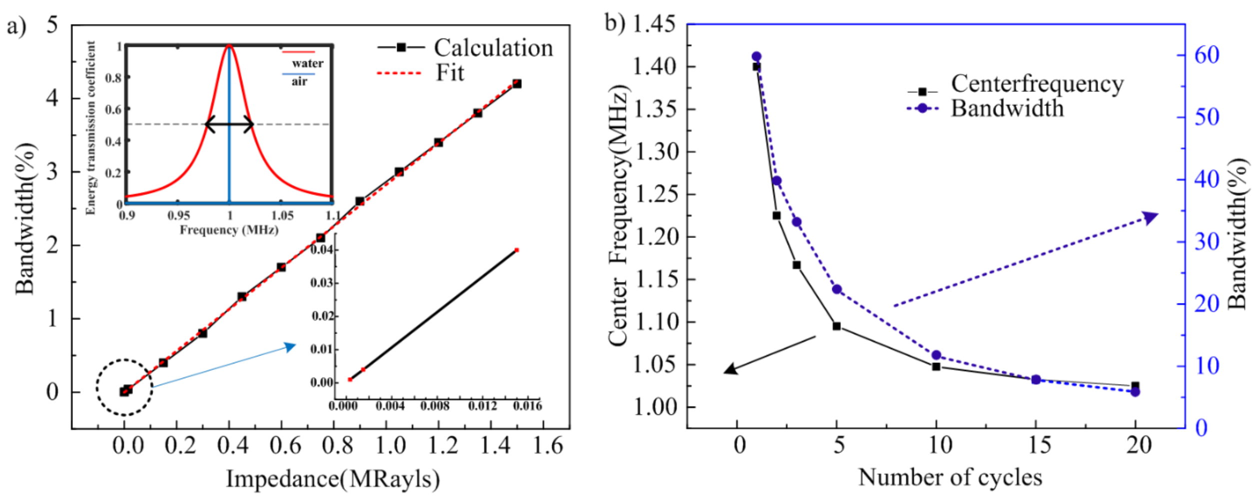

Fig. 4. The relationship between a) -6dB bandwidth of energy transmission coefficient and impedance of media, b) -6dB bandwidth of different period of 1MHz sine wave signal, the two insets in Fig. 4a) are the definition of -6dB bandwidth and the enlarged region of data line, respectively.

3.4. Simulation of AETC through three different media tank

Based on the above analysis, we know that the energy can transmit 100% irrespective of the media inside the steel tank for a CW wave. However, the premise is to neglect the attenuation of the media and the steel plate. In reality, the ultrasonic wave suffers attenuation, for a plane wave the acoustic attenuation can be expresses as

$$P = P_0 e^{-2\alpha x}, \tag{7}$$

where P_0 is the incident power, and x is the propagation distance, α is the attenuation coefficient given by,

$$\alpha = \frac{\eta\omega^2}{2v^3\rho}, \tag{8}$$

where η is the dynamic viscosity, ω, ρ and v are the angular frequency, phase velocity and density of the media[12]. The dynamic viscosity of air and water are 1.8×10^{-5}Pa·s and 1×10^{-3}Pa·s, respectively.

Using the finite element software, we simulated the steel tank filled with different media. For example, the pitch transducer was excited by 20 cycles tone burst with 1.0 MHz center frequency, the excitation voltage is 1.0 V and the catch transducer was used to receive the transmission signal on the other side of the tank as illustrated in Fig. 1. In order to reduce computation time, the media thickness was set as 20mm, which was much smaller than practical systems.

As showed in the Fig. 5a), these three kind of media can definitely be distinguished due to different wave propagation velocities in the three media. The received signals showed phase difference, with the water case signal being the front whereas air case signal at a much delayed time. However, according to Eqs. (5) and (6), $P_{water} = P_0 e^{-2\times9.3\times10^{-4}x}$, if the x is very small, the difference between P_{water} and P_{air} is also very small. As the distance increases, the voltage amplitudes of the received signals, which reflect the media attenuation, will show obvious difference.

When the excitation signal cycle decreases to 10 cycles, the receive voltage is about half of the value of 20 cycle cases, as showed Fig. 5b). Besides, due to the ringdown effect after specified number of cycles, higher voltage can be achieved compared with analytic value.

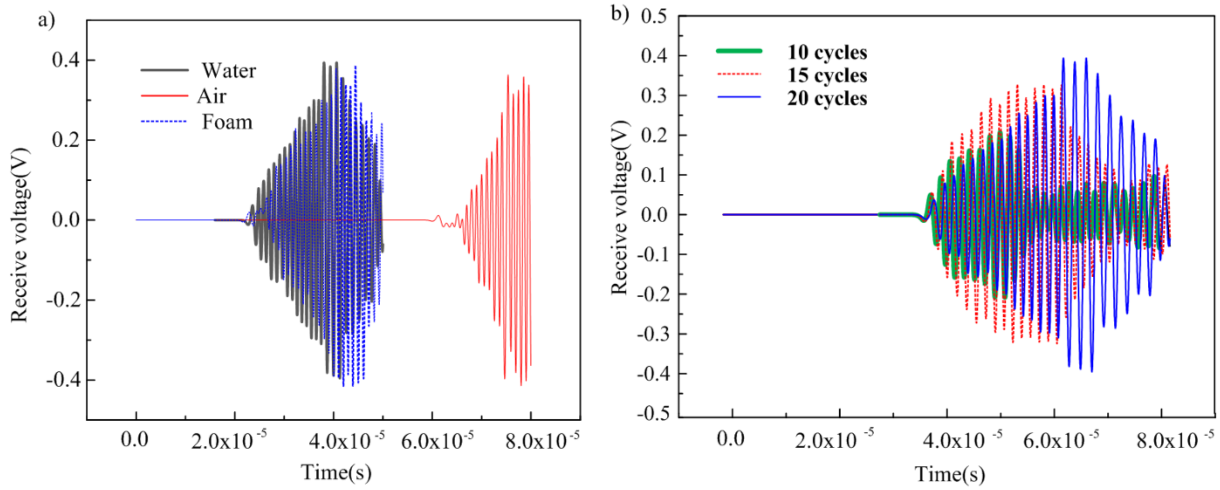

Fig. 5. The receive voltage a) after the 20 cycles excitation signal transmit through three different media, b) with different cycles in the water tank.

4. Conclusion

An ultrasound tunneling method was analyzed and used to detect the level of different media in a closed steel tank. High transmission through the tank is possible when the outer steel plate was excited at its resonance frequency based on the T-matrix theory. However, the -6dB bandwidth of energy transmission coefficient for CW waves was too narrow when the impedance of media was very small, which makes it impossible to make such accurate frequency transducers. In order to solve this issue, the tone burst with center frequency 1.0 MHz was used to excite the steel plate, our finite element simulations showed that such tone burst signal can have a bandwidth reaches 5.9% for air media when the number of tone burst signal is 20, which is broad enough to cover the transducer frequency uncertainty. Due to different attenuation and propagation velocity in the media, three different media were accurately distinguished by this tunneling method. In reality, this method can be extended to other practical applications, such as oil level detection, fluid and gas media detection, etc., which cannot be directly measured in a closed tank. We only need to know the property and thickness of the outer container, which will determine the excite frequency, the possibly media inside. Based on the wave propagation time and received signal amplitude, it is easy to detect the level of media inside.

Acknowledgments

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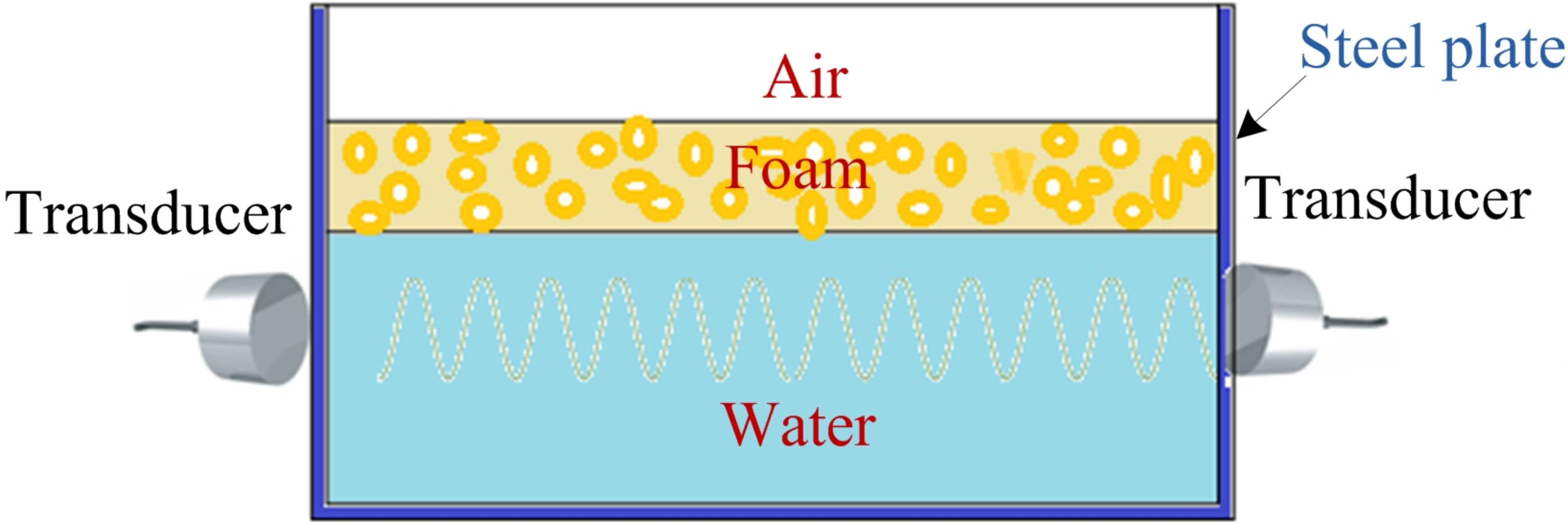
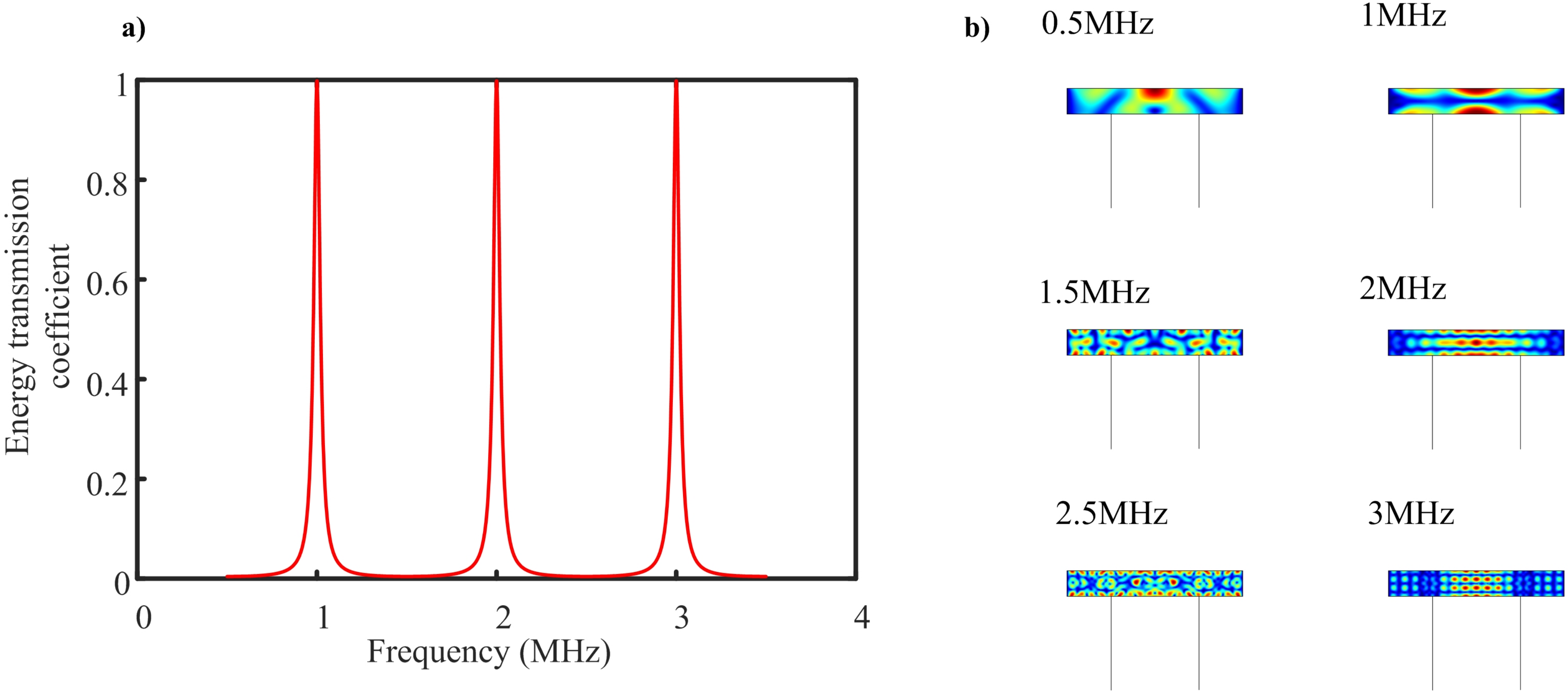
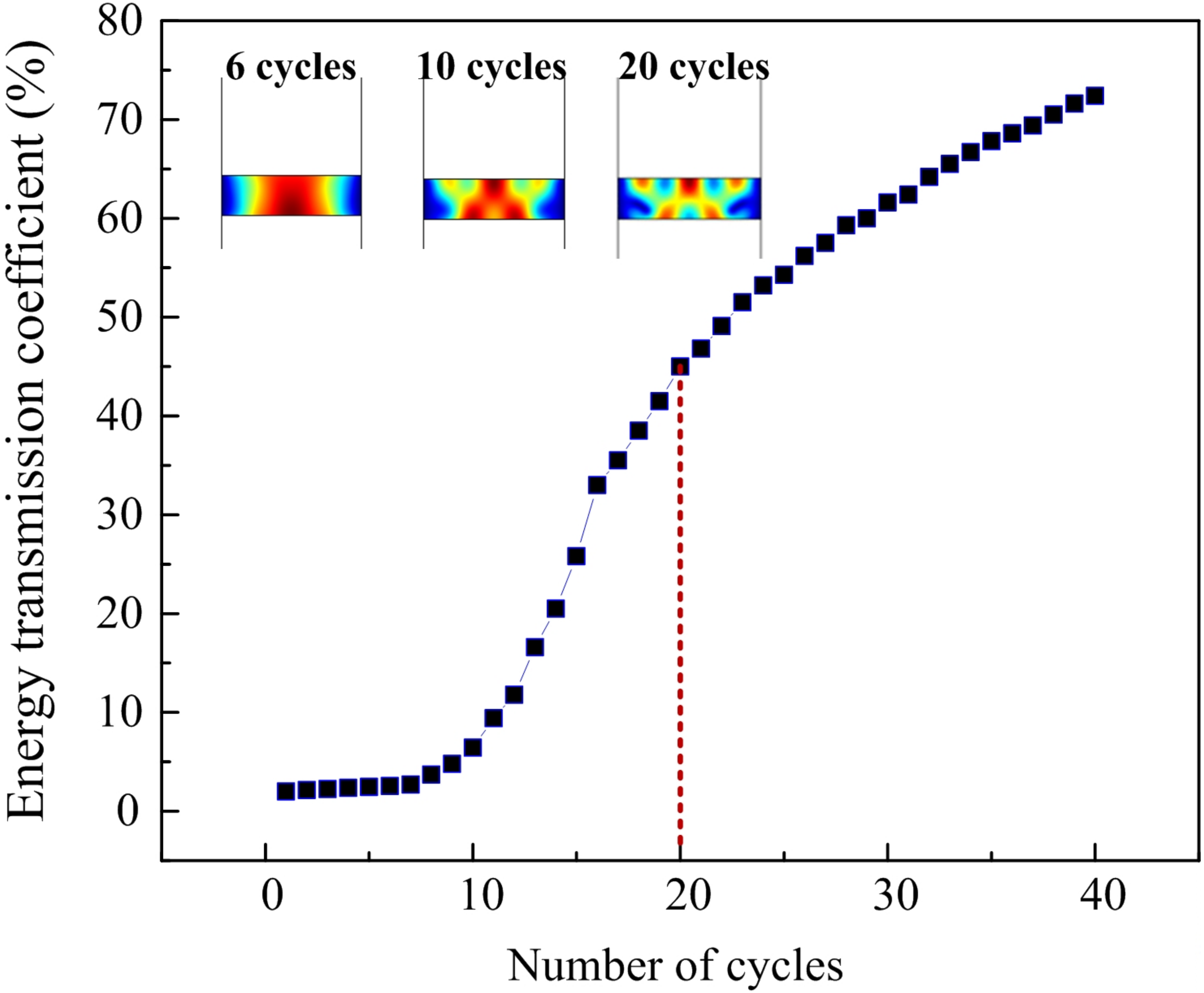
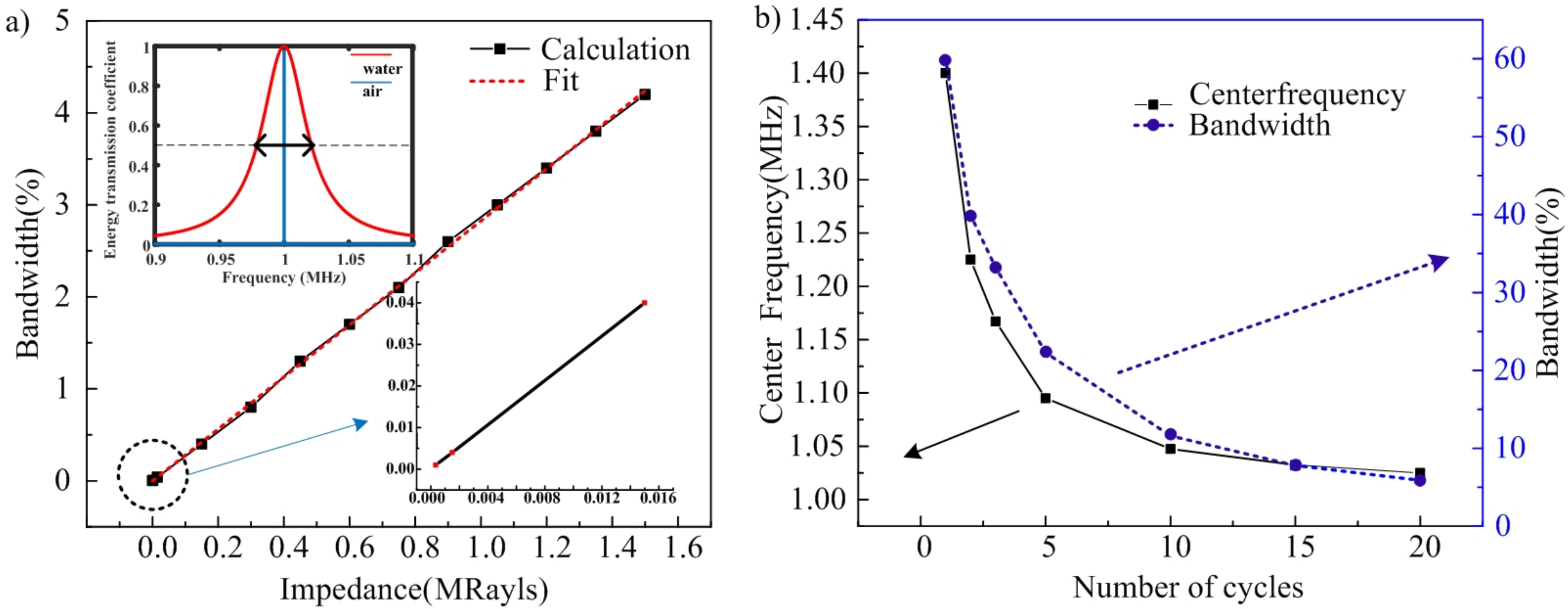
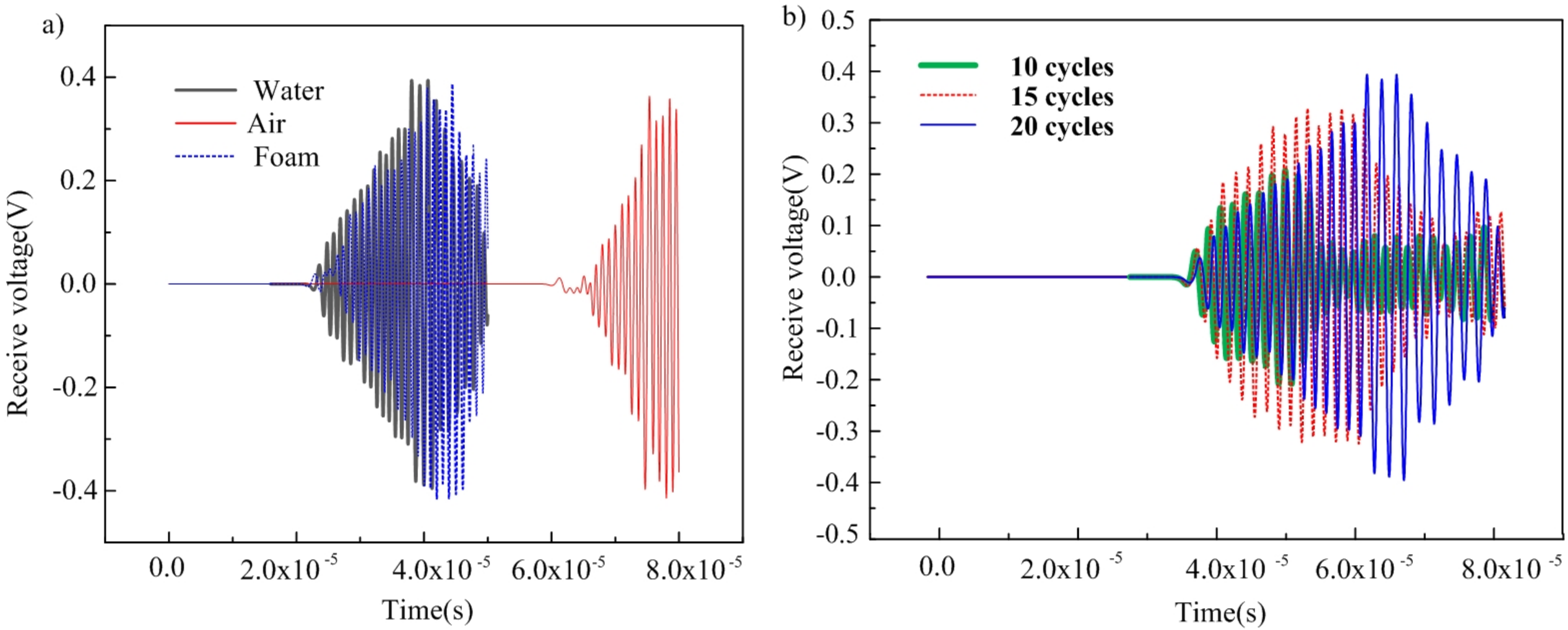

Steel plate
Air
Foam
Transducer
Transducer
Water


a)
Energy transmission coefficient
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
Frequency (MHz)
b)
0.5MHz
1MHz
1.5MHz
2MHz
2.5MHz
3MHz


6 cycles
10 cycles
20 cycles
Energy transmission coefficient (%)
Number of cycles
0
10
20
30
40
50
60
70
80


a)
b)
Bandwidth(%)
Impedance(MRayls)
Calculation
Fit
Energy transmission coefficient
Frequency (MHz)
water
air
Center Frequency(MHz)
Bandwidth(%)
Number of cycles
Centerfrequency
Bandwidth



a)
Water
Air
Foam
Receive voltage(V)
Time(s)
0.0
2.0x10 -5
4.0x10 -5
6.0x10 -5
8.0x10 -5
0.4
0.2
0.0
-0.2
-0.4
b)
10 cycles
15 cycles
20 cycles
Receive voltage(V)
Time(s)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5