Experimental and numerical investigations on several parameters of clamp-on ultrasonic flowmeter

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Abstract:

Clamp-on ultrasonic flowmeter based on differential transit time method is widely used due to absence of moving parts, which cause no pressure drop, simplicity in installation and low cost of maintenance. In comparison with other types of flowmeters, ultrasonic transit time has higher accuracy. The accuracy of ultrasonic flowmeters severely depends on characteristics of piezoelectric transducers, which transmit and receive signals. Numerous parameters that affect signals should be carefully considered, investigated and optimized in order to improve the transducer performance. In this paper effect of several parameters on amplitude of received signal voltage were investigated based on finite element analysis with COMSOL multiphysics software. These parameters were amplitude of transmitted voltage signal, shape of piezoelectric crystal, temperature, diameter of pipe, material of pipe, beam angle and excitation frequency. In addition, some experiments were conducted to verify simulation results on the amplitude of transmitted signal and material of pipe in practice. Results of experimental and numerical study have shown linear relation between transmitted voltage amplitude and received voltage amplitude. In addition, it was observed that circular crystal achieve 18 percent larger voltage amplitude and also optimum beam angle is 33 degree.

1. Introduction

Ultrasonic flowmeters are widely used for liquid flow measurement in industries such as petrochemical, oil, gas, food, water and wastewater because of high accuracy and installation convenience. Clamp-on types have advantage of no pressure drop in pipeline due to absence of moving part and contactless measurement. Accuracy is one of the most important factors especially in custody transfer applications. For achieving high accuracy, effect of different parameters on transmitted and received signal should be carefully considered in design, programming, manufacturing and optimizing process.

For investigating these parameters, several simulations have been conducted. Holm et. al. used computational fluid dynamics (CFD) to determine calibration factor for ultrasonic flow meter. The tests was performed in different Reynolds number from 100 to 100,000. Results were compared with analytical and experimental data. Also, they investigated the effect of change in the flow field [1]. Wang and Li simulate and apply a neural network to eliminate the influence of temperature in ultrasonic flowmeter [2].

The effect of fluid turbulence and consequently flow profile was investigated by Iooss et. al. with using ray tracing technique to simulate the acoustic propagation in moving inhomogeneous fluid [3]. Ma et. al. analyze the effect of the differential separation distance between transducers using numerical simulation. The result of their work shown that the distance between transducers significantly affect the flow measurements [4].

Zheng et. al. studied transducer protrusion and recess effects by using CFD. They accomplished their computations using FLUENT software. With analysis of experimental and computational results they conclude that measurement error of protruding transducers is smaller therefore it is a better arrangement type of transducer for ultrasonic flowmeters [5].

In this research, effective factors on ultrasonic flowmeter performance were determined. These factors (or parameters) are amplitude of transmitted voltage signal, shape of piezoelectric crystal, temperature, diameter of pipe, material of pipe, thickness of piezoelectric crystal, beam angle and frequency of signal which they have influence on the amplitude of received signal. Afterwards using COMSOL multiphysics software, these factors were evaluated. Furthermore, experimental tests were conducted to verify the effect of the amplitude of transmitted signal and material of pipe.

2. Numerical simulations

Simulation were conducted based on finite element analysis (FEA) using COMSOL software. It was assumed that there is laminar flow for liquid in pipe. Effect of various parameters on amplitude of receive voltage were investigated.

2.1. Dimensions and materials

Dimensions of sensor or transducer have shown in figure 1. Material of piezoelectric was assumed PZT 5H according to piezoelectric material used in experimental tests. Table 1 shows diameters and thickness of pipes used for both simulation and experimental study. Figure 2 shows 3D model that was used in COMSOL.

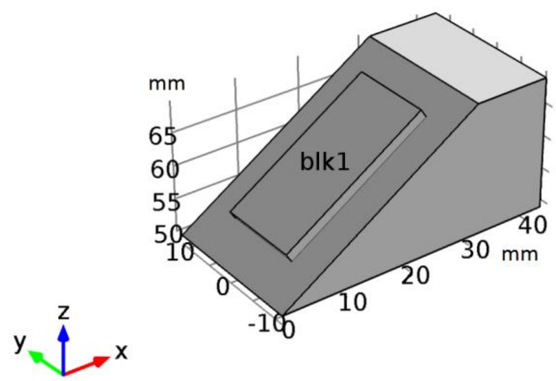

Figure 1. Geometry and dimensions of sensor and transducer

2.2. Effect of excitation amplitude voltage

In these series of simulations, effect of excitation amplitude voltage was investigated. Voltages of 4, 8, 12, 16 and 24 with 1280 KHz frequency signals on DN125 pipe were simulated. Figure 3 shows these signal which they all have about 2.34 microsecond excitation time.

One of the received signals for 12 Volt excitation signal have shown in Figure 4.

Table 1. Thickness of pipes in different diameters

DN	Outer Diameter-OD (in mm)	Wall thickness (in mm) SCH 40s/40/STD
65	2.875 (73.03)	0.203 (5.156)
80	3.500 (88.90)	0.216 (5.486)
90	4.000 (101.60)	0.226 (5.740)
100	4.500 (114.30)	0.237 (6.020)
115	5.000 (127.00)	0.247 (6.274)
125	5.563 (141.30)	0.258 (6.553)
150	6.625 (168.28)	0.280 (7.112)
200	8.625 (219.08)	0.322 (8.179)
250	10.75 (273.05)	0.365 (9.271)
300	12.75 (323.85)	0.375 (9.525)
350	14.00 (355.60)	0.375 (9.525)
400	16.00 (406.40)	0.375 (9.525)
450	18.00 (457.20)	0.375 (9.525)

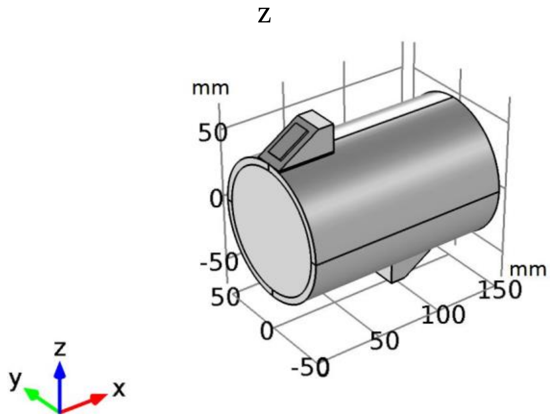

Figure 2. 3D model used in COMSOL

There is not any change in wavelength and other parameters of received signal due to change in amplitude of excitation signal except amplitude which has been increased with increasing amplitude of excitation signal.

Amplitude, or maximum received voltage, for all excitation signals shown in table 2. The ratio of maximum received voltage to excitation voltage is approximately constant which shows linear relation as in Figure 5.

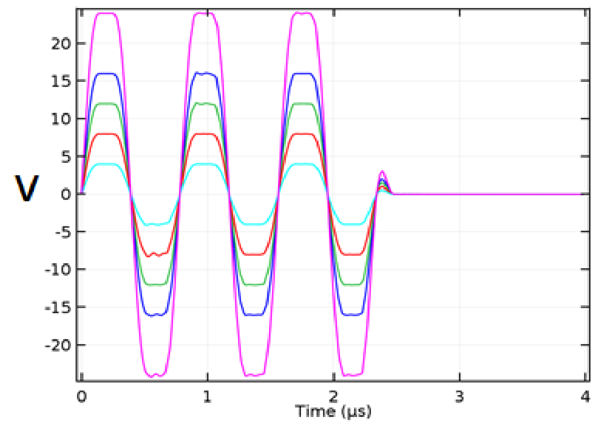

Figure 3. Piezoelectric excitation signals

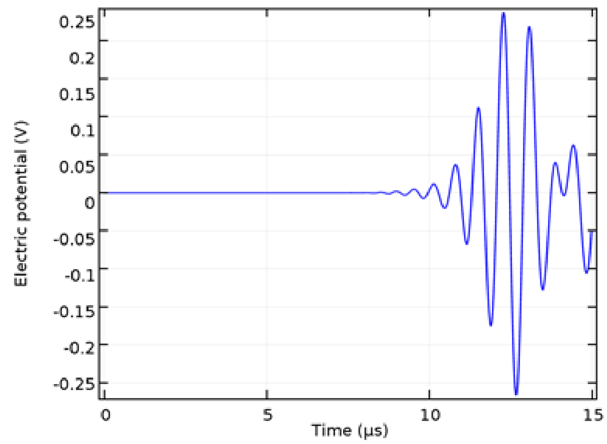

Figure 4. Received signal in sensor due to 12 Volt excitation signal

Table 2. Effect of change in excitation voltage on maximum received voltage

24	16	12	8	4	Excitation Voltage
0.548	0.354	0.263	0.173	0.095	Maximum received Voltage
0.0228	0.0222	0.0219	0.0217	0.0238	The ratio

2.3. Effect of piezoelectric crystal shape

Circular and rectangular shapes were investigated using numerical simulations. The area of both shape were equal. Excitation voltage, frequency, material and size of pipe were respectively 12 V, 1280 KHz, PVC and

DN90. Figure 6 and 7 shown received signals of these two shapes. Results illustrate that maximum received voltage is 18 percent bigger in circular shape.

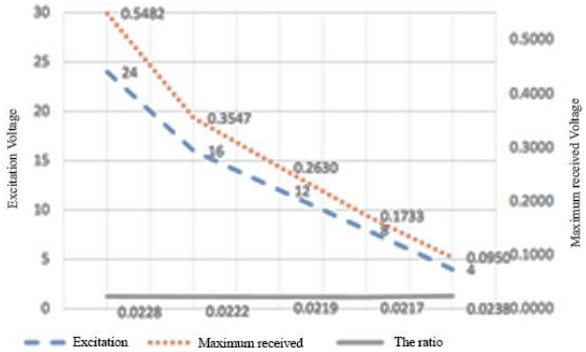

Figure 5. Relation between excitation and received Voltage

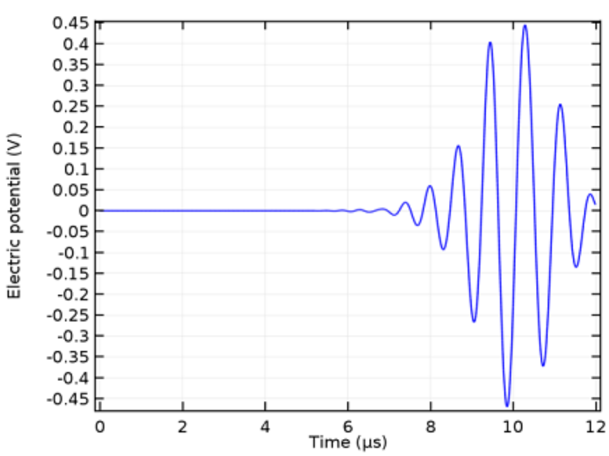

Figure 6. Received signal using circular shape

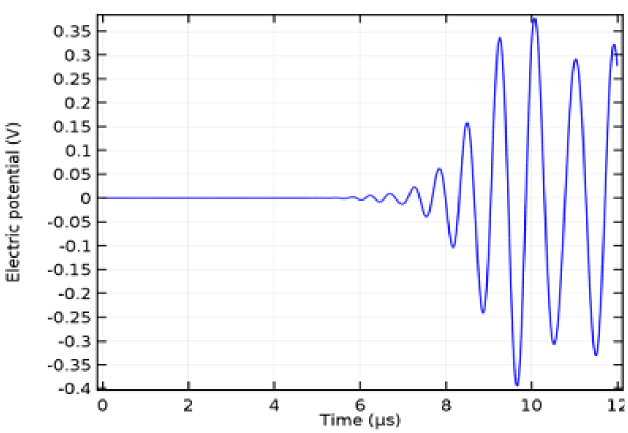

Figure 7. Received signal using rectangular shape

2.4. Effect of Temperature

In these simulation methane considered as fluid material. Size of pipe assumed DN90 with PVC material. Excitation voltage amplitude considered 50V with 320, 640 and 1280 kHz frequencies. Result have shown in figure 8. According to results, influence of temperature in 640 and 1280 kHz frequencies is very small. Although influence of temperature in 320 kHz frequency is relatively small but for accurate measurements it should be considered. The results shown why lower frequencies are used in gas measurements.

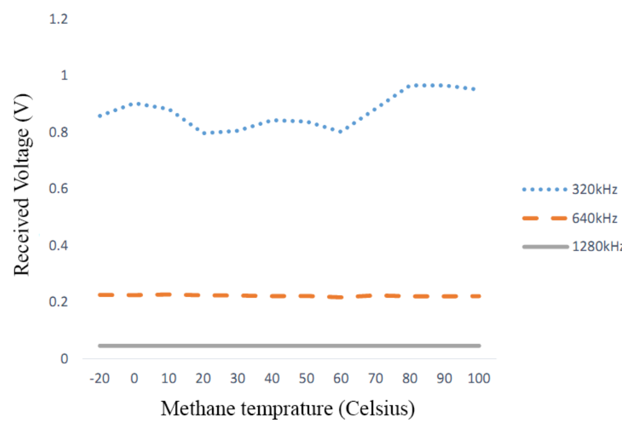

Figure 8. Effect of temperature

2.5. Effect of diameter of pipe

DN65, DN90 and DN125 pipe sizes were investigated. Frequency and voltage amplitude was considered 1280 kHz and 12 Volt, respectively. Excitation signal has shown in figure 9. Simulations were conducted for two opposite direction of flow with average speed of 0.5 m/s. Result for DN65 pipe size has shown in figure 10.

Figure 11 show maximum received voltage in different pipe sizes. As diameter of pipe increase, the maximum received voltage would decrease due to increase in wave path.

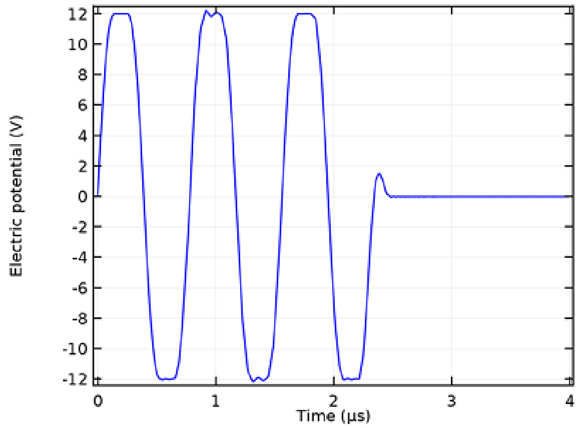

Figure 9. Excitation signal for investigating effect of pipe diameter

In figure 12 time difference between two direction of signal in pipe for different pipe sizes has plotted. As diameter of pipe increases, time difference increases too and lead to better precision.

40 percent increase in pipe diameter cause 50 percent decrease in maximum received voltage and 35 percent increase in time difference between two direction of waves.

2.6. Effect of pipe material

PVC, stainless steel and asbestos-cement pipes were investigated using FEA. Properties of pipes have listed in table 3. Table 4 contain results of these simulations. PVC pipes provide better condition for measurement while asbestos-cement pipes are worst due to high absorption of ultrasonic signal.

2.7. Effect of beam angle

Piezoelectric actuators was set for 25, 29, 33, 37, 40 and 50 degrees angles to investigate the effect of beam angle. Excitation Voltage, frequency and size of the pipe was assumed 12 V, 1280 kHz and DN90. Configuration of model for numerical simulation have shown

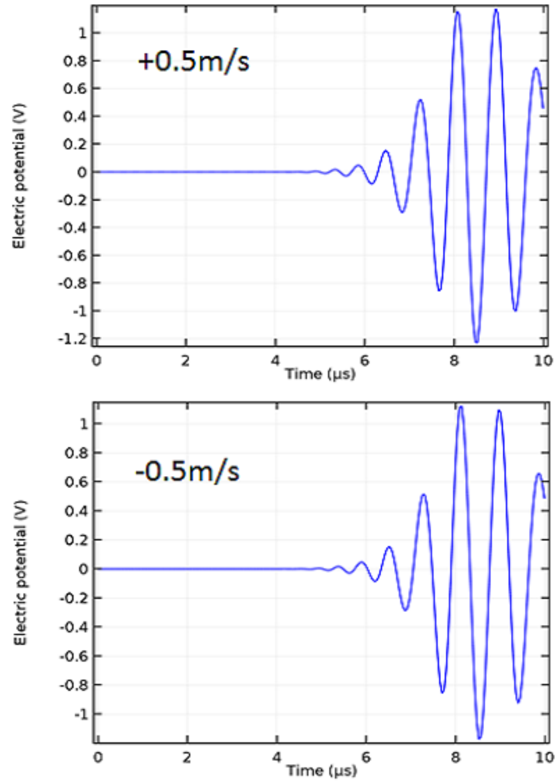

Figure 10. Received signal in dual opposite direction in DN65 pipe

In figure 13. The result for 50 degrees beam angle has shown in figure 14. Figure 15 shows how receive voltage varies in different beam angles.

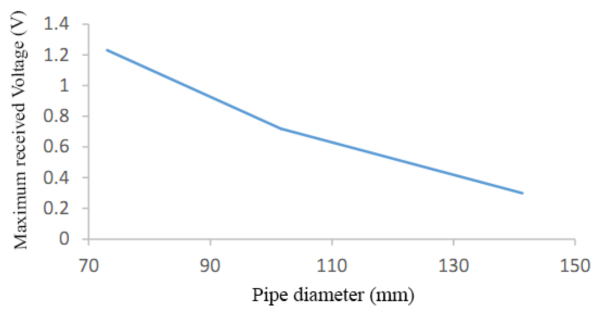

Figure 11. Effect of diameter on maximum received voltage

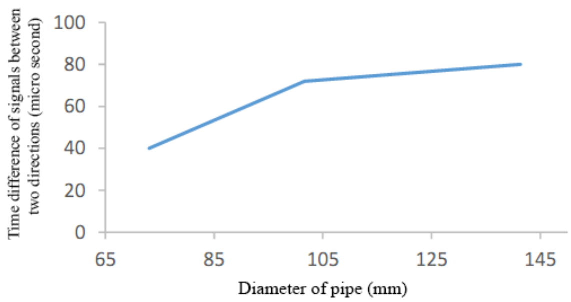

Figure 12. Effect of diameter on time difference between signals of opposite directions

Table 3. Properties of pipe materials

Material	Sound speed (m/s)	Modulus of elasticity (GPa)	Poisson Ratio	Density (kg/m^3)
PVC	2394	2.9	0.41	1350
Stainless steel	6100	210	0.3	7800
asbestos-cement	3400	25	0.33	2300

Table 4. Maximum amplitude of Voltage in piezoelectric sensor

Material	Reading time (μs)	Maximum received Voltage (V)
PVC	12	0.0755
Stainless steel	10.5	0.0570
asbestos-cement	11	0.0492

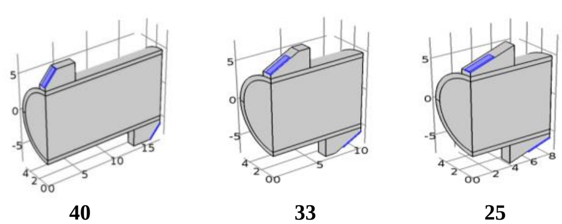

Figure 13. Model configuration for three different beam angles

In 33 degrees beam angle, the maximum amount of Voltage amplitude of signal was achieved. As beam angle increases, the distance that wave would travel through tube will decrease. So in high beam angles the wave that travel the tube would receive sooner than the wave that travel through liquid. This may lead to measurement error.

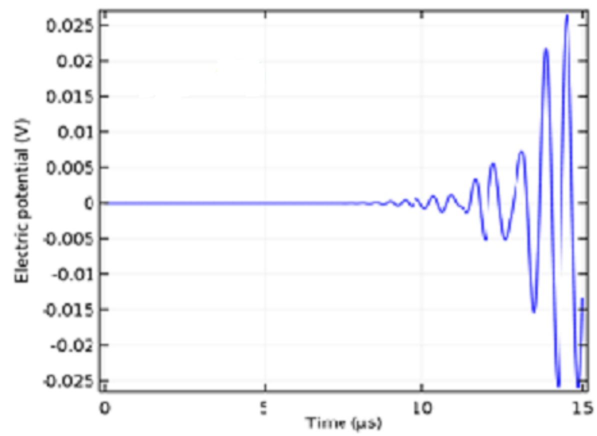

Figure 14. Received signal for 50 degrees beam angle

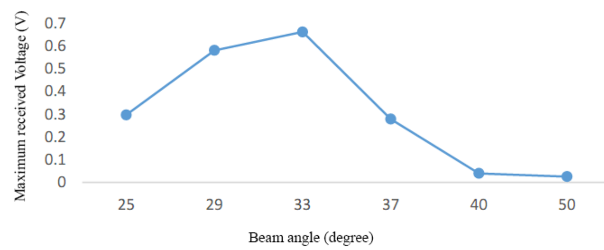

Figure 15. Effect of beam angle

2.8. Effect of frequency

Frequency range from 320 to 1500 kHz was considered. Figure 16 shows the results of simulations. Maximum received Voltage was about 1000 kHz frequency.

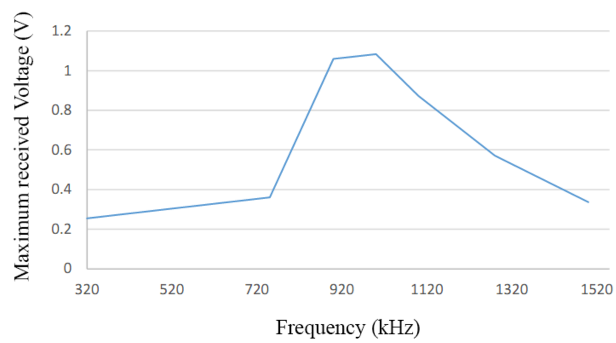

Figure 16. Effect of frequency

3. Experimental study

Frequencies 320, 640 and 1280 kHz were used in experimental tests. Sensor/transducer set for 1280 kHz frequency has shown in figure 17. Excitation signals have measured and shown using digital oscilloscope. Excitation signal in 640 kHz frequency with 64 V amplitude has depicted in figure 18.

Figure 17. Sensor/transducer set for 1280 kHz frequency

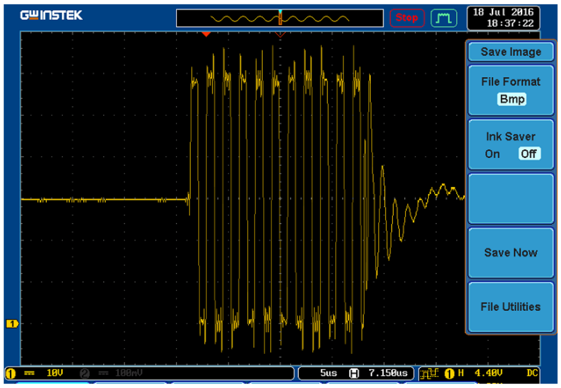

Figure 18. Excitation signal with 64 V amplitude

3.1. Effect of excitation amplitude voltages

On a PVC pipe using 1280 kHz frequency, excitation signals with amplitudes of 18, 24, 28, 32, 36 and 40 volts were applied. Maximum received voltages for each signal has listed in table 5. Figure 19 shows maximum received voltage as a function of excitation Voltage.

The results of experimental tests and numerical simulations show linear relation which verify the simulations.

Table 5. Maximum received Voltages in different excitation Voltages

Excitation Voltage	24	28	32	36	40
Maximum received Voltage	0.49	0.56	0.64	0.70	0.76

3.2. Effect of pipe material

PVC, stainless steel and asbestos-cement pipes were tested with 640 kHz frequency. Figure 20 shows the received signal from asbestos-cement pipe. S/N is low due to high absorption of asbestos-cement. Figure 21 shows the receive signal from PVC pipe which signal has high quality.

4. Conclusion

Several parameters of ultrasonic flowmeters were investigated. It was conclude that:

- Crystal shape: circular crystal shape lead to more amplitude of signal voltage than rectangular one.
- Excitation voltage: according to experimental and numerical simulations, there is a linear relationship and as excitation voltage increase, the receive voltage increase too.
- Crystal beam angle: 33 degrees was found as a best angle for crystal installation.

- Pipe diameter: As the pipe diameter increases, the receive voltage decreases and differential time
- between opposite direction of signals increases too.

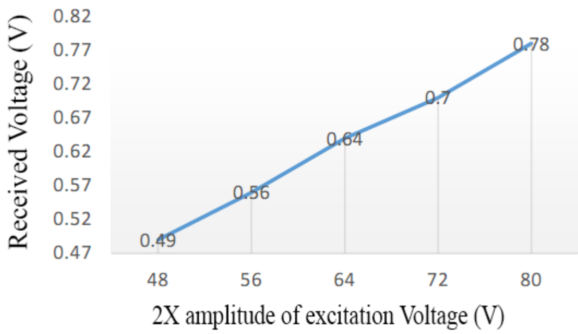

Figure 19. Sensor/transducer set for 1280 kHz frequency

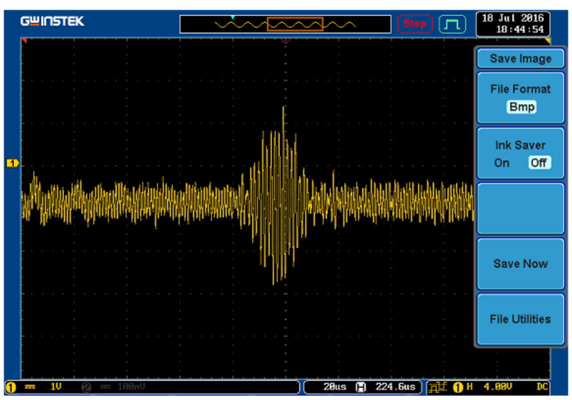

Figure 20. Received signal form asbestos-cement pipe

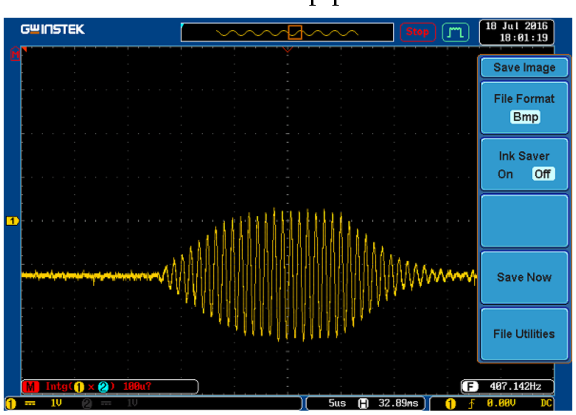

Figure 21. Received signal form PVC pipe

- Temperature: There is not a linear relationship but due to large effect of temperature, for achieving high accuracy, it should be considered in flow calculations.
- Frequency: 1000 kHz frequency was found best frequency that gives maximum amplitude of voltage in the specific range of frequencies.

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