

The Gap Discharge Transducer as a Sound Pulse Emitter in an Ultrasonic Gas Flow Meter

Kristoffer Karlsson, Jerker Delsing

*Luleå University of Technology, EISLAB
Department of Computer Science, Electrical and Space Engineering*

Abstract

In this paper the gap discharge transducer is used as a sound pulse emitter in an ultrasonic flow measurement setup to determine its capabilities to measure a gas flow. An industrial fan and a 3 m long pipe with diameter 62 cm was used to create a flow scenario. The gap discharge transducer was placed between two standard piezoelectric receivers to mimic an ultrasonic flow meter setup. A hot-wire anemometer was used as reference. The gap discharge transducer shows good potential as a sound pulse emitter in a flow measurement setup if more care is taken in aligning the system.

Keywords: Flow measurement, Gap discharge transducer, Ultrasonics

1. Introduction

Measurements of the flow of gases and liquids are being performed routinely everywhere in the world. Be it air in a ventilation or gasoline through a gas pump, flow measurements are an integral part of society. For most flow scenarios there are at least a couple of solutions how to perform the measurement with one or two of them being more advantageous depending on the situation. For example in some liquid flow measurements ultrasonic transducers are used to determine the flow through the time-of-flight method and in gas flows a venturi pipe might be used that determines the flow through differential pressure [1].

However, in some situations there are no definite choice of method and the decision then falls on the method that is “least bad”. One such scenario can be the exhaust pipes at a process plant. The environment is so harsh that available technology in many cases fail to function for even a short while. The best choice at this point has been concluded to be the venturi pipes but they rely on precise geometry to maintain good accuracy and with an environment filled with dust and dirt particles the geometry is sooner or later compromised and the pipe will need regular maintenance.

As a step towards a new measurement system for these harsh environments the gap discharge transducer has been tested and proven durable and a potent candidate as a sound pulse emitter [2, 3, 4]. In this paper the

gap discharge transducer is studied further by incorporating it as a sound pulse emitter in an ultrasonic flow measurement setup. The purpose is to test its ability to determine the flow of a gas in a laboratory environment as an initial step towards flow measurement in an actual environment.

1.1. The gap Discharge Transducer

The gap discharge transducer is basically two metal electrodes connected to a high voltage power supply. When the voltage between the electrodes is great enough to cause breakdown in the gap a spark is produced. Accompanying the bright light produced by the spark is also an intense sound pulse [5].

2. Theory

The method used takes advantage of the fact that a sound pulse travels with different speeds in different flows. By determining the time it takes a sound pulse to travel a certain distance it is possible to calculate the flow speed of the fluid from [1]

$$t = \frac{L}{c \pm V \cos(\theta)} \quad (1)$$

where t is the time, L the distance, c the speed of sound in the medium, V the flow of the medium, and θ the angle between the flow velocity and the sound pulse path. The plus/minus depends on if the pulse travels

with or against the flow. In some ultrasonic flow measurement devices it is common to place two transducer as in figure 1. In this setup the transducers alternate between the first transducer emitting a pulse while the second is receiving and the second emitting while the first is receiving. By doing this it is possible to determine the travel time for sound pulses both with and against the flow. From equation 1 it is then possible to solve for V without knowing c . By adding a possible calibration coefficient $k(Re)$ (eg. to be used to calibrate against changes in viscosity as in [6, 7]) the relationship can be expressed as:

$$V = k(Re) \frac{L}{2\cos(\theta)} \left(\frac{1}{t_1} - \frac{1}{t_2} \right), \quad (2)$$

where t_1 is the travel time when the pulse travels with the flow and t_2 when it travels against it.

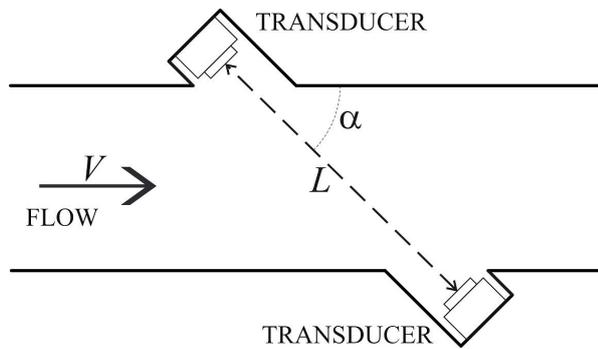


Figure 1: Setup of a flow measurement device used in some cases in ultrasonic flow measurements.

However, the gap discharge transducer is only used as a sound pulse emitter. Therefore the measurement setup must be changed. By placing the gap discharge transducer between two receivers, as in figure 2, it is still possible to use equation 2 to determine the flow.

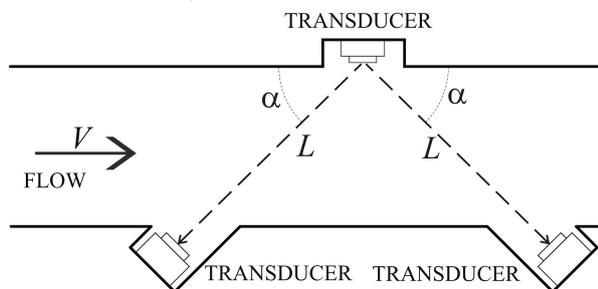


Figure 2: Alternative setup when using the gap discharge transducer as a sound pulse emitter.

3. Experiment and setup

The gap discharge transducer that was used can be seen in figure 3 and schematics of the electronic circuit with the key components can be seen in figure 4.

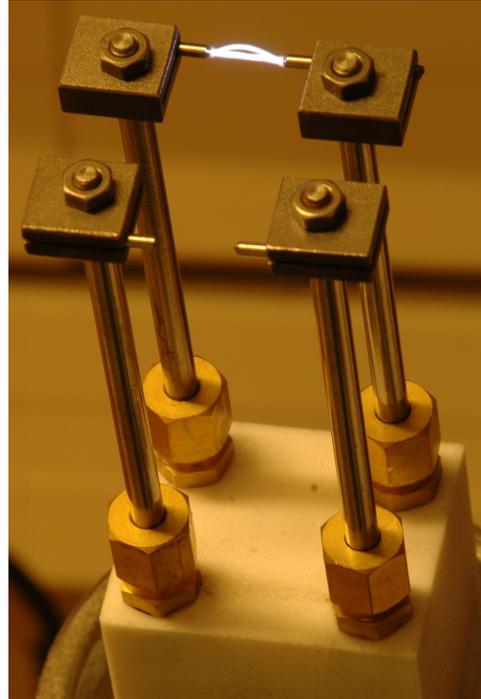


Figure 3: The gap discharge transducer used in the experiments with two pair of electrodes. Only one of the pairs is active during the measurements.

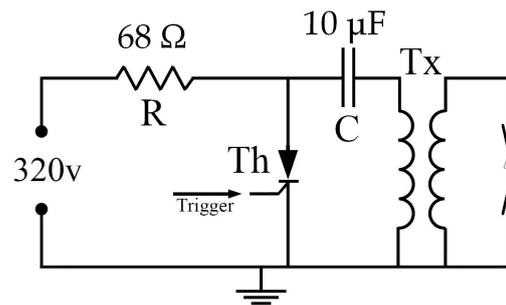


Figure 4: Schematics of the electronic circuit with the key components.

To create a basic flow measurement scenario an industrial fan that could be set to different speeds was used to generate the flow and a 3 m long pipe with 62 cm diameter was used to contain the flowing air. The gap discharge transducer was placed in the middle on one side and the two receivers on the opposite side on either

side of the transducer. Schematics of the setup can be found in figure 5. A hot-wire anemometer was used as a reference by measuring the flow speeds at three different positions from the pipe wall for each fan speed according to the “Log-linear” method in [8] for pitot tubes. The anemometer was placed directly opposite of the gap discharge transducer in the pipe.

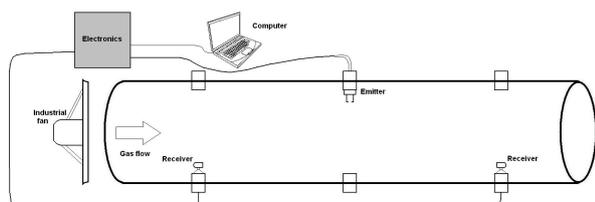


Figure 5: Schematics of the flow measurement setup used in the experiments.

The electronic circuit and computer software used for the transducer and receivers only allows for one receiver to be active at each time. Therefore they are set to alternate in such a way that one receiver was active for several transit time measurements before it was turned inactive and the other was turned active. For each set of transit times, while a receiver was active, the mean is taken and is considered to be one measurement. The gap discharge transducer was then allowed to generate at least 400 transit times, generating more than 200 time measurements at each receiver. The time measurements were stored on a computer for later analysis.

4. Results and discussion

To get a perspective on what type of flow that is expected in the pipe Reynold’s number can be calculated for the setup:

$$R = \frac{\rho V D}{\mu}, \quad (3)$$

where $\rho = 1.2 \text{ kg/m}^3$ is the air density at atmospheric pressure, V is the flow, D is the pipe diameter and $\mu = 18.4 \cdot 10^{-6} \text{ kg/m}\cdot\text{s}$ is the dynamic viscosity of air. A turbulent flow usually occurs at a Reynold’s number larger than 4000 [9] and by using this and solving for V yields

$$V \approx 0.1 \text{ m/s}, \quad (4)$$

to be the lowest flow required for a turbulent flow

Anemometer measurements versus fan value at four occasions are plotted in figure 6. The measurements have been shifted somewhat around the fan value to prevent the error bars from overlapping with each other.

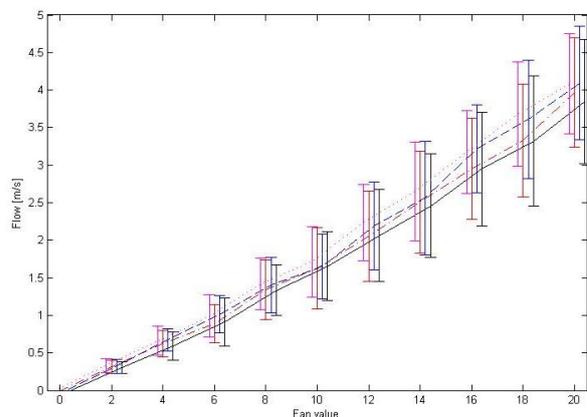


Figure 6: Plot of anemometer measurements from different measurement series. The measurements have been shifted somewhat around the fan value to prevent the error bars from overlapping.

4.1. Discrimination of outliers

A typical set of a 100 transit time measurements without any flow present can be seen in figure 7. In figure 8 is a plot of 100 transit times at zero flow where values diverging more than $\pm 20 \mu\text{s}$ from the median has been removed.

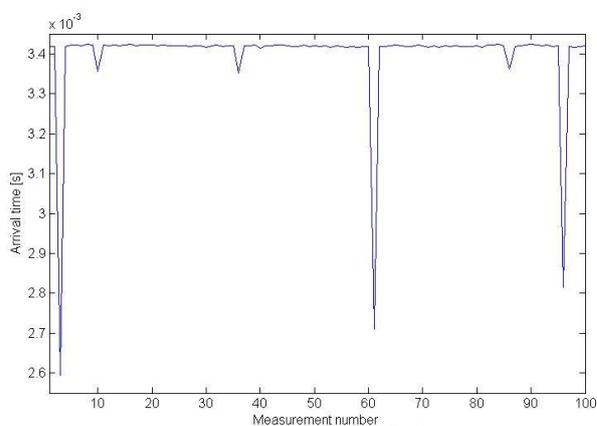


Figure 7: Plot of transit times to one receiver at zero flow.

The reason why the outliers in figure 7 are present is not investigated much further here, but we have considered a few hypotheses which are stated at the end of this section. In any case, the outliers have to be dealt with. The method for sorting out the outliers is motivated as follows: the travel time is

$$t = \frac{s}{c}, \quad (5)$$

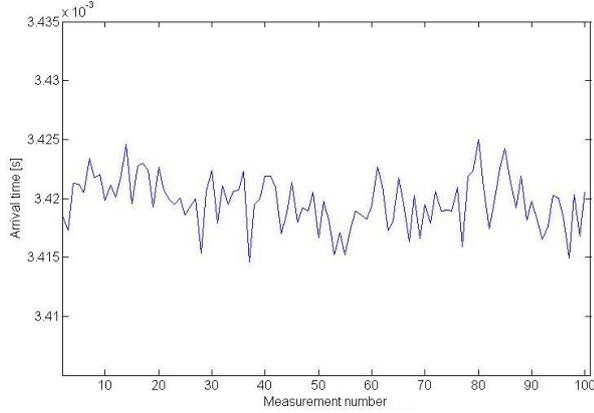


Figure 8: Plot of transit times diverging less than $\pm 20 \mu\text{s}$ from the median value at zero flow.

where s is the distance the sound pulse has to travel and c is the sound speed. According to error propagation analysis [10] the error in t (assuming there is no covariance between s and c) can be expressed as

$$\Delta t = \sqrt{\left(\frac{\delta t}{\delta s}\right)^2 \cdot (\Delta s)^2 + \left(\frac{\delta t}{\delta c}\right)^2 \cdot (\Delta c)^2}, \quad (6)$$

where Δt , Δs and Δc are the errors in t , s and c respectively. The error in s stems from the fact that the spark in general do not follow the closest path between the two electrodes. By visual inspection it was determined that the spark deviated at most 5 mm from the straight line path between the electrodes. The error in sound speed is assumed to depend on the fluctuations in the actual flow. By using the error bars in the anemometer measurements in figure 6 it was estimated that the flow variation was about ± 1 m/s. The sound speed was taken as 345 m/s, which is the approximate sound speed at room temperature [11], even though sound pulses from sparks are shock waves [12] and shock waves travel at supersonic speeds [13]. The standard $v = s/t$ results in a sound speed at about 390 m/s for zero flow, so the 345 m/s is used as a “worst case scenario” in estimating Δt . With this the estimated error becomes

$$\Delta t = \sqrt{\left(\frac{1}{c}\right)^2 \cdot (\Delta s)^2 + \left(\frac{s}{c^2}\right)^2 \cdot (\Delta c)^2} \approx 20 \mu\text{s}. \quad (7)$$

This error is then the error that can be expected due to the different distances the sound pulse has to travel and the fluctuations in the flow. It is used to sort out the outliers by removing values that deviates more than $20 \mu\text{s}$ from the median value.

4.1.1. False trigger hypotheses

Faulty triggers in the zero crossing technique used in these experiments to detect the signal have been investigated in [14] but where they arise from in this particular setup is debatable. Below are two different possibilities that have been discussed.

First thought was that a portion of the sound pulse enter and travel through the pipe wall which manages to trigger the receiver. This feels unlikely since the faulty triggers appear so seldom and at different arrival times. The receiver is set to expect a trigger no earlier than after 2 ms (and to wait at most 10 ms). Because the gap discharge transducer radiates almost spherically there is always a point where the sound pulse enter the pipe wall. Due to the high sound speed in (sheet) metal, compared to air, sound pulses traveling through the wall should start reaching the receiver well before 2 ms and then be present at all times until the sound pulse in air reaches the receiver. If sound pulses would go through the wall they should trigger the receiver almost directly at this point and not later since the sound strength should become smaller with time. The first sound pulse reaching the receiver after 2 ms should be the strongest and if this is not capable of triggering the receiver the later sound pulses should not be able to either. Hence, “faulty” arrival times due to sound through the pipe wall should appear close to 2 ms every time or not at all.

Another thought was that sound pulses from a previous spark is reflected in the pipe walls long enough to interfere with the next emitted pulse. This might be hard to discard completely since the pipe wall is not a smooth surface and reflections might find strange paths to the receiver. The simplest case is studied non the less. A sound pulse that reflects a total of two times (emitted from transducer, reflected in the lower wall, reflected in the upper wall, and then reach the receiver) would travel approximately 2.1 m. With a sound speed of 345 m/s this would give a transit time of about 6 ms. A direct transit time is in the order of 3.4 ms. The reflected sound pulse would then reach the receiver at about 2.6 ms into the next measurement. Consistent with the shortest transit time measured in figure 7 but if a sound speed of 390 m/s is used instead the pulse reaches the receiver before the expected time range. This would be more likely since the pulse from the spark is a shock wave and the pulse speed is expected to be greater than the regular sound speed. In any case, the reflection hypothesis can not be discarded completely but it still seems unlikely since there are so few measurements that causes false trigger events. Returning a little bit to the pipe wall hypothesis, if triggers were caused by reflections they

should trigger the receiver close to the 2 ms mark since obscure reflection angles would cause pulses to arrive “all the time” during the next measurement and the first ones to arrive should be the strongest and most capable to trigger the receiver.

4.2. Calibration

The only varying terms in equation 2 is t_1 and t_2 . Therefore, the entire $L/2\cos\theta$ is replaced as a single constant K

$$V = K\left(\frac{1}{t_1} - \frac{1}{t_2}\right), \quad (8)$$

which can be used to calibrate the system against the anemometer. For each measurement series (fan values 0 to 20) a K was determined at each fan value by

$$K = \frac{V_a}{\left(\frac{1}{t_1} - \frac{1}{t_2}\right)}, \quad (9)$$

where V_a was taken as the anemometer measurement at that fan value. A mean K was then determined for each measurement series and then a mean was taken from those as the final K value to be used. The K for each measurement series and the final mean value can be found in table 1.

| Measurement | K |
|-------------|--------|
| 1 | 0.5738 |
| 2 | 0.5789 |
| 3 | 0.5912 |
| 4 | 0.5852 |
| Mean: | 0.5823 |

Table 1: The different K values and the mean K value.

In figure 9 are two measurement plots calibrated against their respective anemometer measurements. The flow measurement with the gap discharge transducer is plotted against the anemometer measurement.

In figure 10 are the same measurement plots as in 9 but calibrated using the mean K value.

The difference between the gap discharge measurement and the anemometer reference measurement plotted against the anemometer measurement in figure 11.

The reason for different flows between measurement series can be explained by the fact that the alignment of the pipe and the fan had to be performed between each measurement occasion. Due to external circumstances the setup had to be taken away when the measurement was complete for the day and realigned the next time a measurement was performed.

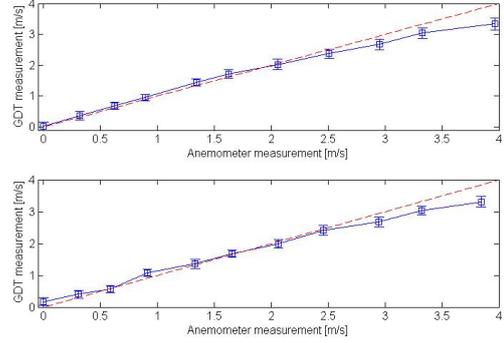


Figure 9: Plots of flow measurements using the gap discharge transducer (GDT) versus the anemometer measurement. The measurements are calibrated against their respective anemometer measurement. The error bars only account for the gap discharge transducer measurements and does not include the variations from the anemometer measurements.

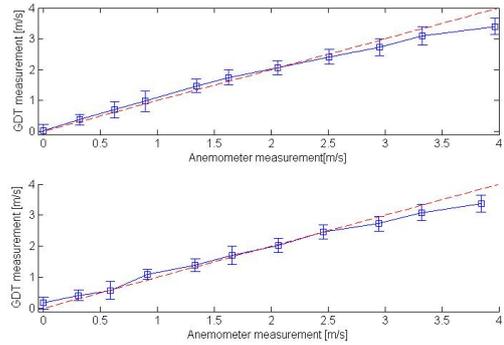


Figure 10: Plots of flow measurements using the gap discharge transducer (GDT) versus the anemometer measurement. The measurements are calibrated with the mean K value. The error bars only account for the gap discharge transducer measurements and does not include the variations from the anemometer measurements.

The anemometer measurements were performed at about 2, 8 and 20 cm from the wall for each fan speed. The measurements closest to the wall was the biggest contributor to the error since the flow is noticeably slower that close to the wall and fluctuates more. Especially at larger flows. Also the actual hole in the pipe wall where the anemometer was put in might have altered the flow profile a little.

The calibrated gap discharge transducer measurements align very well with the anemometer measurements at the lower flows and fairly good at the higher. The most obvious reason why they deviate is probably the alignment of the receivers. If the receivers are not placed at the same distance from the transducer the calculated flows will of course include errors. This er-

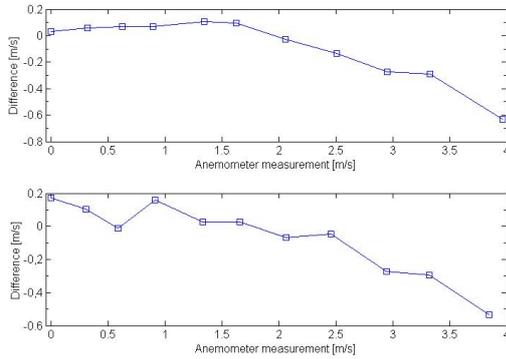


Figure 11: The difference between the gap discharge transducer measurement and the anemometer reference measurement. The results are plotted against the anemometer measurements.

ror might also become greater as the flow increases if, for example, the sound pulse has to travel up streams slightly longer than expected. Then the increasing flow will generate longer delays due to the misalignment and the error in the flow measurement becomes larger. Also the non-zero flow measurement at no flow indicates that there might be an error in the alignment.

A potential error in the K value is not investigated at this stage.

5. Conclusions

The use of gap discharge transmitter in an ultrasound flow metering set up has been investigated. The experimental results confirms theoretical considerations [3] that gap discharge transducers are feasible as sound transmitters for having pipe diameters larger than 0.5m.

6. Future work

To improve the flow measurements, apart from more precise alignment, a couple of areas have been identified to be of interest for further investigation.

The first is the sound path architecture. A more reliable measurement can be performed if a multipath solution is designed [15].

The second is to allow the system to receive a sound pulse at both receivers at the same time. This will minimize the risk of the flow changing between switching the active receiver during a measurement.

Future work also involves testing the gap discharge transducers in pipes with even larger diameters. Some in the order of 2 – 3 m.

However, the most important work for the future is constructing a setup that is able to function for extended intervals in a harsh environment. For this other receivers must be used that are as durable as the emitter. The piezoelectric receivers used in the current setup is fine in a laboratory environment but will suffer due to the environmental conditions in an actual test site after a while. Work is being conducted to find a suitable receiver but available technology do not seem to be able to withstand the environmental conditions that has been specified. Hence, considerations have also been made that developing a new kind of receiver might be the only option.

As for further flow measurements, a test site has been established in an exhaust chimney at LKAB in Kiruna. This chimney is considered to have a harsh environment due to high dust content but is still a suitable site for short term tests with standard equipment. Next step in this process should be to evaluate the system capabilities at that test site, with only hour long sessions at a time to prevent the piezoelectric receivers from being too contaminated. The results could then be compared against the already present venturi pipes that are installed to determine the capability of the system in an actual environment it is expected to work.

7. References

- [1] J. G. Webster (Ed.), The measurement, instrumentation and sensors handbook, CRC press LLC, 1999.
- [2] E. Martinson, J. Delsing, Environmental tests of gap discharge emitter for use in ultrasonic gas flow measurement, in: 7th ISFFM 2009, 2009.
- [3] E. Martinson, J. Delsing, Electric spark discharge as an ultrasonic generator in flow measurement situations, Flow Measurement and Instrumentation 21 (2010) 394–401.
- [4] J. Delsing, K. Karlsson, Low-pressure gap discharge ultrasonic gas flow meter, in: 15th International Flow Measurement Conference 2010, 2010.
- [5] W. M. Wright, N. W. Medendorp, Acoustic radiation from a finite line source with n-wave excitation, J. Acoust. Soc. Am. 43 (1968) 966–971.
- [6] J. Delsing, Viscosity effects in ring-around type flow meters, in: International conference on industrial flow measurement, onshore and offshore, 1987.
- [7] J. Delsing, On ultrasonic flow meters, Ph.D. thesis, Lund institute of technology (1988).
- [8] Air distribution and air diffusion - rules to methods of measuring air flow rate in air handling duct.
- [9] D. W. Spitzer, Flow measurement: practical guides for measurement and control, ISA, 2001.
- [10] H. W. Coleman, W. G. Steel, Experimentation and uncertainty analysis for engineers, Wiley, 1989.
- [11] G. W. C. Kaye, T. H. Laby, Table of physical and chemical constants, 16th Edition, Longman, 1995, ISBN 0-582-22629-5.
- [12] R. A. Freeman, J. D. Craggs, Shock waves from spark discharges, Brit. J. Appl. Phys. (J. Phys. D) 2 (1969) 421–427.

- [13] P. O. Krehl, Shock wave physics and detonation physics a stimulus for the emergence of numerous new branches in science and engineering, *Eur. Phys. J. H* 36 (2011) 85–152.
- [14] J. Delsing, Ultrasonic gas flow meter with corrections for large dynamic metering range, *Ultrasonics* 27 (1989) 349–356.
- [15] L. C. Lynnworth, *Ultrasonic measurements for process control: theory, techniques, applications*, Boston : Academic, cop, 1989.