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Czech
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F3

Faculty of Electrical Engineering
Department of Microelectronics

Automated Calibration and Error Detection of Ultrasonic Clamp-On Flowmeters

Lukáš Kornel Gajdár

Supervisor: Ing. Pavel Burget, Ph.D.
Field of study: Electronics
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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

Příjmení: **Gajdár** Jméno: **Lukáš Kornel** Osobní číslo: **492371**

Fakulta/ústav: **Fakulta elektrotechnická**

Zadávající katedra/ústav: **Katedra mikroelektroniky**

Studijní program: **Elektronika a komunikace**

Specializace: **Elektronika**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Automatizovaná kalibrace a detekce chyb ultrazvukových příložných průtokoměrů

Název diplomové práce anglicky:

Automated Calibration and Error Detection of Ultrasonic Clamp-On Flowmeters

Jméno a pracoviště vedoucí(ho) diplomové práce:

Ing. Pavel Burget, Ph.D. Testbed CIIRC

Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) diplomové práce:

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

Datum převzetí zadání

Bc. Gajdár Lukáš Kornel

Podpis studenta

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Pokyny pro vypracování:

Ultrasonic clamp-on flowmeters are widely used in industrial applications due to their non-intrusive nature and ease of installation. However, accurate calibration is crucial for maintaining precision across different flow rates and temperatures. Furthermore, long-term operation introduces offsets and potential faults, necessitating periodic recalibration and error detection mechanisms. This thesis aims to develop a systematic approach to calibrating ultrasonic flowmeters and ensuring their reliability over extended periods.
Objectives:
1. Develop a Calibration Strategy. Research and evaluate existing calibration methods and identify the most efficient and accurate one for ultrasonic clamp-on flowmeters.
2. Automate Flowmeter Setup and Calibration. Design an automatic process for setting up the flowmeter, from flashing firmware to final validation. Implement a system that enables automatic calibration for different flow rates to minimize errors in the expected operating range. Develop a mechanism to calibrate flowmeters at different liquid temperatures to improve accuracy.
3. Ensure Continuous Calibration in Operation. Develop a methodology for periodic offset calibration to compensate for drift over long-term operation. Implement an automatic recalibration process to maintain accuracy without disrupting operation.
4. Error Detection and Fault Diagnosis. Identify potential fault states such as empty tubes, bubble interference, or sensor misalignment. Develop an algorithm to detect and classify these fault conditions in real-time. Implement a feedback mechanism to alert users and trigger corrective actions.
Expected Outcomes:
1. A validated, automated calibration process for ultrasonic clamp-on flowmeters.
2. A systematic approach for periodic recalibration during long-term operation.
3. A robust error detection mechanism capable of identifying common flowmeter faults.
4. A prototype system demonstrating the effectiveness of the developed methodologies.

Seznam doporučené literatury:

[1] Application of clamp-on ultrasonic flowmeter for industrial flow measurements.
https://www.sciencedirect.com/science/article/pii/0955598694900477
[2] The development of the ultrasonic flowmeter sensors for mass flow rate measurement: A comprehensive review. https://www.sciencedirect.com/science/article/pii/S0955598624000943
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[4] Ultrasonic Water Flow Measurement. https://www.ti.com/lit/ug/tidua10a/tidua10a.pdfث
[5] Self-Calibration of Ultrasonic Water Flow Meter.ث
https://www.researchgate.net/publication/338886029_Self-Calibration_of_Ultrasonic_Water_Flow_Meterث

FAKULTA ELEKTROTECHNICKÁ
FACULTY OF ELECTRICAL ENGINEERING
Technická 2
166 27 Praha 6

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ČESKÉ VYSOKÉ
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PROHLÁŠENÍ

Já, níže podepsaný

Příjmení, jméno studenta:	Gajdár Lukáš Kornel
Osobní číslo:	492371
Název programu:	Elektronika a komunikace

prohlašuji, že jsem diplomovou práci s názvem

Automatizovaná kalibrace a detekce chyb ultrazvukových příložných průtokoměrů

vypracoval samostatně a uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací a Rámocovými pravidly používání umělé inteligence na ČVUT pro studijní a pedagogické účely v Bc a NM studiu.

Prohlašuji, že jsem v průběhu příprav a psaní závěrečné práce použil nástroje umělé inteligence. Vygenerovaný obsah jsem ověřil. Stvrzuji, že jsem si vědom, že za obsah závěrečné práce plně zodpovídám.

V Praze dne 28.04.2025

Bc. Lukáš Kornel Gajdár
....
podpis

Acknowledgements

I would like to thank our Lord and savior Jesus Christ for guiding me on this difficult journey we call life.

Declaration

I declare that this work is all my own work and I have cited all sources I have used in the bibliography.

Prague, May 22, 2025

Prehlasujem, že som predloženú prácu vypracoval samostatne, a že som uviedol všetku použitú literatúru.

V Prahe, 22. května 2025

Abstract

Ultrasonic clamp-on flowmeters are valued for their non-intrusive design and ease of installation in industrial flow measurement. Their accuracy depends on precise calibration and robust error detection. This thesis develops an automated calibration system and real-time fault diagnosis for ultrasonic clamp-on flowmeters, addressing challenges such as manual calibration inefficiencies, temperature variations, and operational faults such as bubble interference or sensor misalignment. A transit-time method was used for the proposed ultrasonic flowmeter. This work lays the foundation for scalable, maintenance-efficient ultrasonic flowmeters suitable for industrial deployment and further development in smart metering systems.

Keywords: Ultrasonic, Transducer, Flowmeter, Clamp-On, Calibration, Flow rate

Supervisor: Ing. Pavel Burget, Ph.D.
Head of Testbed for Industry 4.0

Abstrakt

Ultrazvukové príložné prietokomery sú cenené pre ich neinvazívnosť a jednoduchosť inštalácie pre priemyselné merania prietoku. Ich presnosť závisí od precíznej kalibrácie a robustnej detekcie chýb. Táto práca rozvíja automatizovaný kalibračný proces a detekovanie chýb v reálnom čase pre príložné ultrazvukové prietokomery. Rieši pritom výzvy, ako sú neefektívnosť manuálnej kalibrácie, teplotné zmeny, problémy pri prevádzke ako rušenie bublinkami alebo nesprávne zarovnanie senzorov. Bola implementovaná metóda založená na čase prechodu. Táto práca kladie základ pre škálovateľné, ľahko udržovateľne ultrazvukové prietokomery pre priemyselné nasadenie a ďalší vývoj v inteligentných meracích systémoch.

Klíčová slova: Ultrazvukový, Transducer, Prietokomer, Neinvazívny, Kalibrácia, Prietok

Překlad názvu: Automatizovaná kalibrace a detekce chyb ultrazvukových příložných průtokoměrů

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Chapter 1

Introduction

Flow measurement is essential across industries such as water management, oil and gas, and manufacturing, ensuring operational efficiency, safety, and compliance with regulations. Ultrasonic clamp-on flowmeters have an inherent advantage due to their non-intrusive design, which allows easy installation on various pipe sizes without disrupting the flow. However, maintaining their accuracy is challenging due to time-consuming manual calibration processes and errors caused by factors like temperature changes, bubble interference, or sensor misalignment. This diploma thesis seeks to address these issues by developing ultrasonic clamp-on flowmeter with an automated calibration system and advanced error detection. Using the MSP430FR5043 microcontroller and integrating RS485 and NB-IoT communication protocols, the project aims to streamline setup, ensure consistent accuracy during operation, and detect faults in real time.

Figure 1.1: Example of ultrasonic clamp-on flowmeters [26]

1.1 Thesis Goals

- Develop ultrasonic clamp-on flowmeter.
- Research and develop an efficient calibration strategy for ultrasonic clamp-on flowmeters.
- Automate the setup and calibration process to reduce errors across various flow rates and temperatures.
- Implement continuous calibration to maintain accuracy during long-term operation without disruption.
- Create real-time error detection and fault diagnosis for issues like empty tubes or bubble interference.

Chapter 2

Theoretical Background

2.1 Fluid Dynamics

Fluid dynamics studies the behavior of fluids to help solve practical problems. The volumetric flow rate Q is the volume passing a cross-section A per unit of time, related to the flow velocity v. Mass flow rate $\dot{m}$ is calculated from volumetric flow rate and fluid density . From these calculations we can easily obtain volume and mass of a known liquid:

$$Q = A \quad v \tag{2.1}$$

$$\dot{m} = \quad Q \tag{2.2}$$

Figure 2.1: Volumetric flow rate [8]

Figure 2.1 shows an illustration of volumetric flow rate concept. The speed of sound c in a fluid is dependent on the bulk modulus K and density of the fluid (and varies with temperature and pressure), which affects transit-time calculations:

$$c = \sqrt{\frac{K}{\quad}} \tag{2.3}$$

Conservation of mechanical energy in the fluid is described by Bernoulli's equation [2]:

$$\text{const.} = \frac{1}{2} v^2 + p + w_p \qquad (2.4)$$

Where is density, v is flow velocity and p is the pressure. Potential energy density $w_p = gh$, where g is gravitational acceleration and h is the elevation (height) above the reference level. Equation 2.4 relates pressure and flow velocity at different elevation in the tube.

Laminar and turbulent flow regimes influence the velocity profile in a pipe. In laminar flow, which is characterized by low Reynolds number, the velocity is highest at the center and lowest at the walls has parabolic profile, whereas in turbulent flow characterized by high Reynolds number the profile flattens. A fully developed flow profile is assumed for accurate flow rate calculation from a single ultrasonic path. Flow disturbances such as bends or valves upstream can distort the profile, so industry guidelines often recommend straight pipe lengths (e.g., 10 20 diameters upstream) to re-establish a uniform profile before the meter for best accuracy [1].

Figure 2.2: Laminar vs. turbulent flow [11]

2.2 Fundamentals of Ultrasonic Wave Propagation

2.2.1 Mechanical Waves

There are three main types of mechanical waves: longitudinal, transverse (sheer) and surface. In liquids, acoustics waves are longitudinal, which means that particles of the fluid are moving in the direction of the wave. This means that the acoustic speed is the speed of particle oscillating around its equilibrium. Since there is no mass transfer during the propagation of acoustic waves, the excitations, i.e. the deflection of a fluid particle from its equilibrium position, are transmitted gradually from one fluid particle to another [2]. Transverse wave causes deflection of the material perpendicularly to the direction of the wave. In doing so the medium is being displaced. [32] Finally, surface waves are emerging on the interface between two materials.

The relationship between period of a wave T, frequency f, wavelength and speed is:

$$v = \frac{}{T} = f \tag{2.5}$$

2.2.2 Attenuation of Waves

Ultrasonic attenuation refers to the gradual decrease in the amplitude and intensity of a wave as it propagates through a material. This attenuation results from intrinsic material properties and wave interactions that diminish the wave's energy over distance. In an ideal, lossless medium, wave amplitude decreases only due to geometric spreading. However, real materials exhibit additional weakening caused by scattering and absorption, collectively termed attenuation [32].

Scattering occurs when the wave is reflected or redirected in various directions at heterogeneities within the material, reducing the energy traveling in the original propagation direction. Absorption involves the conversion of acoustic wave energy into other forms of energy, such as heat, within the medium. Together, these processes cause an exponential decay of the wave amplitude A with distance z, described by:

$$A = A_0 e^{z} \tag{2.6}$$

where A_0 is the initial amplitude at the reference location, and is the attenuation coefficient, typically expressed in nepers per unit length (Np/m). The neper is a dimensionless unit related to logarithmic attenuation.

Attenuation coefficients are often expressed in decibels per unit length (dB/m) due to the widespread use of the decibel scale in acoustics. The conversion between nepers and decibels is given by dividing (in Np/m) by approximately 0.1151 [32]. The decibel (dB) itself is a logarithmic unit quantifying ratios of powers or amplitudes, defined as [2]:

$$X\ (\mathrm{dB}) = 10 \log_{10} \frac{X_2}{X_1} \qquad (2.7)$$

where X is the difference in decibels between two measurements X_1 and X_2.

When measuring sound or ultrasonic wave intensities, power is proportional to the square of the wave amplitude or pressure. Because many transducers output voltages proportional to pressure, the relationship for intensity differences in decibels can be rewritten in terms of pressure or voltage ratios as:

$$I\ (\mathrm{dB}) = 10 \log_{10} \frac{P_2^2}{P_1^2} = 20 \log_{10} \frac{P_2}{P_1} = 20 \log_{10} \frac{V_2}{V_1} \qquad (2.8)$$

where $P_1; P_2$ are sound pressures, and $V_1; V_2$ are corresponding transducer voltages.

In ultrasonic flowmeters, attenuation affects the received signal amplitude and thus measurement accuracy. Attenuation depends on material properties, frequency, and path length. Understanding attenuation mechanisms and correctly applying decibel scales is essential for designing effective ultrasonic measurement systems and interpreting their outputs reliably.

2.2.3 Critical Angle

When searching for an angle of the ultrasonic transducer to the pipe, there are multiple important parameters to take into consideration, such as Snell's law (equation 2.9 and figure 2.3), signal attenuation, speed of ultrasound in the medium and length of signal path in the fluid. For best accuracy signal path in the fluid needs to be maximized while not attenuating the signal and introducing error from noise. Maximizing the signal path clashes with critical angle, which is the largest possible angle of incidence which still results in refracted ray. Our incident ray has to be chosen to avoid hitting critical angle or total internal reflection. The angle of refracted ray will be given by speed of ultrasound in the medium or in other words by the ratio of refractive indices.

$$\frac{\sin}{\sin} = \frac{v_1}{v_2} \tag{2.9}$$

Figure 2.3: Snell's law[2]

We can choose the first angle between transducer and pipe, and then calculate the remaining refracted angles based on equation 2.10.

$$= \mathrm{asin}(\sin \quad \frac{v_1}{v_2}) \tag{2.10}$$

To calculate the critical angle we substitute the refracted angle as 90.

$$_{\mathrm{critical}} = \mathrm{asin}(\sin(90\ )\frac{v_1}{v_2}) = \mathrm{asin}(\frac{v_1}{v_2}) \tag{2.11}$$

2.2.4 Acoustic Impedance

Acoustic impedance Z of any material is the product of volumetric mass density and the speed of sound in the medium v. To help one choose, the optimal transducers to pipe angle, equations 2.13 for reflected energy R and transmitted energy T can be used. Transmitted energy refers to the percentage of energy transmitted trough interface of two mediums and reflected energy back from this interface.

$$Z = \quad v \tag{2.12}$$

Ultrasonic wave propagation across material interfaces also affects transit-time measurement. Each interface (transducer to wedge, wedge to pipe, pipe to fluid) can reflect a portion of acoustic energy. The acoustic impedance Z of a material is $Z = \rho v$. A large impedance mismatch between materials causes strong reflections. At normal incidence, the fraction of energy reflected is given by:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 \qquad T = 1 - R \tag{2.13}$$

Equations 2.13 are only true if the ultrasonic transducer was perpendicular to the tube. For other angles the full equation is 2.14. Equation 2.14 gives the energy reflection coefficient of a longitudinal ultrasonic wave.

$$R = \left(\frac{Z_2 \cos\theta_i - Z_1 \cos\theta_t}{Z_2 \cos\theta_i + Z_1 \cos\theta_t}\right)^2 \tag{2.14}$$

where R and T are the reflected and transmitted energy fractions for an acoustic wave moving from medium 1 to 2. For oblique incidence, the effective impedance changes with angle, but the principle is similar. In clamp-on systems, couplant (like grease or silicone) is used between the transducer and pipe to minimize any air gap, because air's Z is extremely low (nearly all energy would reflect at an air gap). Still, only a portion of the ultrasonic energy enters the fluid. Higher-frequency ultrasound (e.g. 1–5 MHz) yields better time resolution but is attenuated more by the pipe wall and fluid, limiting range. Lower frequencies (e.g. 100–500 kHz) penetrate further with lower attenuation but produce smaller ΔT (coarser time resolution). Thus, transducer frequency and angle are chosen based on pipe material, diameter, and required accuracy. Precise alignment of transducers is also critical, any misalignment changes the effective path and angle, leading to error (see section 2.6.3).

2.2.5 Mode Conversion

The phenomenon affecting signal integrity is mode conversion, where an incident ultrasonic wave changes from one type of wave mode to another upon encountering an interface between materials with differing mechanical properties.

When an ultrasonic longitudinal wave travels in a solid medium and hits an interface at an angle other than perpendicular, part of its energy can convert into a shear (transverse) wave. This conversion occurs because the particle motion associated with the wave can shift direction, initiating shear deformation in the material. The degree of mode conversion depends on the acoustic impedances, wave speeds of the materials, and the angle of incidence [33].

Mode conversion can be relevant in clamp-on ultrasonic flowmeters, where transducers are attached externally to pipe walls. The acoustic wave must traverse multiple interfaces: from the transducer through the coupling material, the pipe wall, the fluid inside, and back. Each interface presents an opportunity for mode conversion due to differences in density and elastic properties, affecting the amplitude, velocity, and mode composition of the received signal.

The elastic modulus and material strain-stress relationship govern how ultrasonic waves propagate within and between materials. At each interface, part of the incident wave reflects back, and part refracts forward, often splitting into longitudinal and shear modes. The refraction and reflection angles are governed by Snell's law 2.15, which applies to both wave types and can be seen on figure 2.4:

Figure 2.4: An incident longitudinal wave (L1) is reflected and transmitted at an interface of two solids as a longitudinal wave (L1' and L2), but also partially as a transverse wave (S1 and S2).[33]

$$\frac{\sin \theta_{L1}}{V_{L1}} = \frac{\sin \theta_{L2}}{V_{L2}} = \frac{\sin \theta_{S1}}{V_{S1}} = \frac{\sin \theta_{S2}}{V_{S2}}; \tag{2.15}$$

where V_L and V_S denote longitudinal and shear wave velocities respectively in the different media, and θ represents the corresponding angles relative to the interface normal.

Because shear waves travel significantly slower than longitudinal waves, they are refracted less at interfaces. This velocity difference leads to distinct critical angles, beyond which certain wave modes no longer propagate into the next medium but instead become surface-bound waves. The first critical angle relates to longitudinal waves, beyond this angle, the refracted longitudinal wave travels along the interface, creating a creeping wave that quickly attenuates and contributes little useful signal. The second critical angle relates to shear waves and marks the onset of shear creeping waves or surface waves, which also attenuate rapidly [2].

In clamp-on flowmeters, these effects mean that only specific incident angles allow efficient transmission of ultrasonic energy into the fluid via longitudinal waves. Mode conversion can reduce signal strength and complicate interpretation, as both longitudinal and shear waves may arrive at the receiver, sometimes overlapping in time. To minimize these complications, many ultrasonic flowmeters use shear wave transducers or carefully optimize transducer angles and frequencies to favor a particular wave mode that provides a clearer signal.

Understanding mode conversion also informs the design of custom transducer housings and the selection of coupling materials. For example, materials with acoustic impedances close to the pipe wall reduce reflections and mode conversions, improving signal-to-noise ratio. Additionally, controlling the incident angle can suppress unwanted shear modes, enhancing measurement stability.

2.3 Piezoelectric Element in Transducers

2.3.1 Piezoelectric Element Physics

An ultrasonic transducer employs a piezoelectric material that converts an electrical signal into a mechanical force and vice versa [4]. A commonly used material is lead zirconate titanate (PZT), valued for its strong piezoelectric properties. Other materials, such as ceramics and quartz, which are not naturally piezoelectric, are rendered piezoelectric during manufacturing by exposure to a high electric field at elevated temperatures. Additionally, polymer piezoelectric materials like Polyvinylidene Fluoride (PVDF) are utilized for their flexibility and ability to be formed into larger sizes, offering advantages in specific applications [12].

The piezoelectric effect refers to the ability of certain materials with an asymmetrical crystal structure to produce an electric charge or voltage when subjected to mechanical stress or pressure. This occurs due to the "direct piezoelectric effect," where electric dipole moments form within the material [16]. Electric dipole moments are shown in figure 2.5. and the vector of dipole moments p_i is:

$$\hat{P} = \sum_{i}^{P_1} \tilde{p}_i = 0 \tag{2.16}$$

Figure 2.5: Polarization of lattice [16]

Conversely, the "inverse piezoelectric effect" involves the mechanical deformation of the crystal when a voltage is applied. Typically, sensors rely on the direct effect to transform mechanical energy into electrical energy. In the longitudinal effect shown in figure 2.6, the generated charge is expressed as [23]:

$$Q = d_{mn} F_x \tag{2.17}$$

where d_{mn} is the piezoelectric coefficient and F_x is the applied force. For the transverse effect, the charge depends on the element's dimensions:

$$Q = d_{mn} F_x \frac{b}{a} \tag{2.18}$$

where b and a are the dimensions of the element [16].

When a voltage impulse excites the piezoelectric element via its electrodes, electric charges accumulate near the top and bottom electrodes, generating stress that propagates as an acoustic wave. Assuming thin electrodes and matched acoustic impedances of external media, the stress at the top electrode consists of an initial impulse followed by a second impulse after a propagation delay. The stress and its frequency response are given by [17]:

Figure 2.6: Principle of longitudinal piezoelectric effect [16]

$$S(t) = \frac{hC_0}{2A} \quad (t) \qquad t \quad \frac{d}{c} \tag{2.19}$$

$$|S(f)| = \frac{hC_0}{A} \sin \quad \frac{f}{2f_0} \tag{2.20}$$

where C_0 is the clamped capacitance, h is the piezoelectric constant, c is the speed of sound in the element, A is the cross-sectional area, d is the thickness, and $f_0 = \frac{c}{2d}$ is the fundamental resonant frequency [4]. The piezoelectric element functions as an acoustic resonator, with resonant frequencies at odd multiples of f_0.

2.3.2 Equivalent Circuit Model

Piezoelectric elements can be modeled using equivalent electrical circuits to analyze their behavior. The KLM model, developed by Krimholtz, Leedom, and Matthaei, is particularly effective for transducers with a dominant thickness-expander mode, prevalent in medical ultrasound applications [13].

Figure 2.7: KLM equivalent circuit model for a piezoelectric element [13]

The KLM model separates the acoustic and electrical components via a transformer, as illustrated in Figure 2.7. It features two acoustic ports V_1 and V_2. One leading to the matching layer and load medium, and the other to the backing layer and one electrical port V_3. The acoustic transmission line represents the propagation and resonance within the piezoelectric element, characterized by its thickness d, speed of sound c, and acoustic impedance Z.

In the electrical domain, the model includes the clamped capacitance C_0 and a negative capacitance-like component C^0, which accounts for acoustoelectric feedback. The transformer's turns ratio is defined as [13]:

$$= k_T \frac{}{\omega_0 C_0 Z_C}^{\frac{1}{2}} \operatorname{sinc} \frac{\omega}{2\omega_0} \tag{2.21}$$

and the negative capacitance is:

$$C^0 = \frac{C_0}{k_T^2 \operatorname{sinc} \frac{\omega}{\omega_0}} \tag{2.22}$$

where k_T is the electromechanical coupling constant, and ${}_0$ is the angular resonant frequency [4].

The electrical input impedance $Z_T(\omega)$ for a loaded transducer is:

$$Z_T(\omega) = \frac{1}{j\omega C_0} + Z = \frac{1}{j\omega C_0} + R + jX \qquad (2.23)$$

with the real and imaginary components:

$$R = \frac{k_T^2}{\omega_0 C_0}\left(\frac{\omega_0}{\omega}\right)^2 \left(1 - \cos\frac{\omega}{\omega_0}\right)^2 \qquad (2.24)$$

$$X = \frac{2k_T^2}{\omega_0 C_0}\left(\frac{\omega_0}{\omega}\right)^2 \sin\frac{\omega}{\omega_0}\left(1 - \frac{1}{2}\cos\frac{\omega}{\omega_0}\right) \qquad (2.25)$$

At resonance, Z becomes purely real, simplifying the impedance. However, due to non-ideal conditions, a matching network, such as a series inductor, may be introduced at the electrical port to compensate for capacitive input impedance, minimizing power loss [4].

2.4 Ultrasonic Flow Measurement Principles

Ultrasonic flowmeters measure fluid velocity by sending acoustic waves through the fluid and detecting their propagation characteristics. They offer high accuracy and reproducibility without intruding into the flow, making them widely used for clean liquids in industrial applications. Clamp-on ultrasonic sensors are mounted externally on the pipe, using the pipe wall as a part of the acoustic path, whereas inline sensors contact the fluid directly. Two fundamental ultrasonic measurement methods are commonly used: the transit-time (time of flight) method and the Doppler method.

2.4.1 Transit-time Method

The transit-time method, sometimes called Time of Flight, calculates flow velocity by measuring the time difference of ultrasonic signals traveling upstream and downstream through the fluid. In this setup, the flowmeter uses two ultrasonic transducers that are sending and receiving ultrasonic signal. Their position compared to pipe is seen in figure 2.8.One transducer sends a pulse that propagates downstream (in the direction of flow) and the other sends a pulse upstream (against the flow). If the time it takes for the signal to travel from Transducer 1 to 2 (T_{12}) and vice versa (T_{21}) is the same, there is no fluid flow. If there is a difference, we can calculate the flow velocity and determine whether the fluid is flowing upstream or downstream.

Figure 2.8: Simplified signal path in ultrasonic flowmeter on left and more detailed cross section of the pipe on the right [9] [19]

Simplified signal path in figure 2.8 shows tube diameter D and signal path length L. For a path length L through the fluid, the transit times are:

$$\begin{aligned} T_{12} &= \frac{L}{c + v\cos\theta} \\ T_{21} &= \frac{L}{c - v\cos\theta} \end{aligned} \tag{2.26}$$

where c is the speed of sound in the fluid and v is the flow velocity (with $v\cos\theta$ the component of v along the ultrasonic path). From these, the average flow velocity can be derived as:

$$v = \frac{L}{2\cos\theta}\,\frac{T_{21} - T_{12}}{T_{12}\,T_{21}} \tag{2.27}$$

Calculating the volumetric flow rate, we can use 2.1 (with $A = \pi D^2/4$ for pipe diameter D) to express:

$$Q = \frac{\pi D^2}{4}\,\frac{L}{2\cos\theta}\,\frac{\Delta T}{T_{12}\,T_{21}} = \underbrace{\frac{\pi D^3}{4\sin 2\theta}}_{\text{Area}}\,\underbrace{\frac{\Delta T}{T_{12}\,T_{21}}}_{\text{Flow velocity}} \tag{2.28}$$

where $\Delta T = T_{21} - T_{12}$. In the equation above, the first term represents the cross-sectional area factor and the second term represents the effect of the measured transit-time difference on flow velocity.

2.4.2 Doppler Method

Ultrasonic flowmeters based on the Doppler method use the principle of frequency shift due to motion (the Doppler effect). For the flowmeter to function reliably, fluid needs to have an evenly distributed particles of impurities through it. This means that the speed of fluid is measured indirectly by measuring the speed of impurities. Ultrasonic signal is continuously transmitted by emitting transducer, reflected from particles in the fluid and the shifted signal is then received by receiving transducer. The Doppler effect causes the emitted frequency f_e to be shifted compared to frequency at zero flow f_0. The particles are moving at velocity v, the speed of sound in the medium is c and [θ] is the angle between the flow direction and ultrasonic signal path coming from the transducer. [7]

Figure 2.9: Doppler effect in ultrasonic flowmeter [7]

If the particles move at velocity v and the ultrasonic beam is at angle θ to the flow direction, the frequency perceived by a particle is:

$$f_1 = \frac{c + v\cos\theta}{c} f_0 \tag{2.29}$$

its reflected wave then experiences a second Doppler shift upon reception:

$$f_2 = \frac{c}{c - v\cos\theta} f_1 \tag{2.30}$$

Substituting f_1 from 2.29 into 2.30 yields:

$$f_2 = \frac{c + v\cos\theta}{c - v\cos\theta} f_0 \tag{2.31}$$

The frequency difference (Doppler shift) $\Delta f = f_2 - f_0$ can be rearranged to solve for v:

$$\Delta f = f_0 \frac{2v\cos\theta}{c - v\cos\theta} \quad ; \qquad v = \frac{\Delta f\, c}{(2f_0 + \Delta f)\cos\theta} \tag{2.12}$$

For $v \ll c$, this simplifies to $\Delta f \approx \frac{2f_0 v\cos\theta}{c}$, so $v \approx \frac{\Delta f\, c}{2f_0\cos\theta}$. The Doppler method requires that some fraction of ultrasonic energy be scattered back to the receiver; thus it only works in fluids with entrained reflectors. It is commonly used in applications like wastewater or blood flow, where transit-time methods cannot operate due to lack of a clear acoustic path [27]. Doppler flow measurements tend to be less accurate than transit-time for clean fluids, because the measured velocity depends on particle distribution and one must calibrate for the effective scattering cross section [1]. In contrast, transit-time measures the fluid flow directly (via sound speed and ΔT) and is generally preferred for high-accuracy requirements. [2]

The volumetric flow rate Q for a pipe with diameter D is obtained by substituting to the equation 2.1:

$$Q = A \cdot v = \left(\frac{\pi D^2}{4}\right) \cdot \frac{\Delta f\, c}{(2f_0 + \Delta f)\cos\theta} \qquad (2.32)$$

2.4.3 Clamp-on vs. Inline Flowmeters

Figure 2.10: Clamp-on vs. inline flowmeters realization [5] [24]

Clamp-on

Clamp-on flowmeters are mounted externally on the pipe, eliminating the need to cut into the pipe or interrupt flow during installation. This makes them highly flexible for retrofitting existing systems or for temporary measurements, as they can be easily moved or removed. However, the ultrasonic signals must pass through the pipe wall, which can cause attenuation depending on the pipe material, transducer/pipe interface (e.g. silicone coupling layer), and fluid properties. Great care must be taken when considering these parameters and choosing the best transducer to pipe angle. Moreover, precise transducer alignment is critical to ensure accuracy. Lastly, user error like insufficient acoustic coupling (grease) between transducer, silicone, and pipe can introduce error or render the device non-functioning.

Inline

Inline flowmeters are installed directly within the pipe, placing transducers in direct contact with the fluid. This configuration provides stronger signal quality, as there is no pipe wall to interfere, making them ideal for high-pressure, high-temperature, or permanent installations where accuracy is paramount. The downside is the need for pipe modification, which increases installation complexity, cost, and downtime, making them less flexible for applications requiring frequent adjustments. For inline flowmeters, the pipe section must be cut precisely to install the meter, ensuring proper alignment with the flow direction to minimize turbulence.

Table 2.1 provides a comparison of clamp-on and inline ultrasonic flowmeters.

Feature	Clamp-On	Inline
Installation	Non-intrusive, external	Intrusive, inside pipe
Signal Quality	Moderate (pipe wall attenuation)	High (direct fluid contact)
Applications	Retrofitting, temporary setups	High-pressure, permanent setups
Complexity/Cost	Low (no pipe modification)	High (requires pipe cutting)
Coupling Issue	Poor signal if not enough acoustic grease	Not applicable

Table 2.1: Comparison of Clamp-On and Inline Ultrasonic Flowmeters

Figure 2.10 shows clamp-on vs. inline flowmeter realizations . In general, clamp-on devices trade some signal strength and accuracy for easier installation, while inline devices achieve high signal fidelity at the cost of modifying the pipeline.

2.4.4 Mounting Configurations

Figure 2.11 shows the most common mounting configurations of transducer around the pipe. For metal tubes where corrosion can be an issue, Z method is preferred, since it will have smallest signal attenuation from these three configurations [3]. In plastic pipes such as PCV pipe it is sometimes not feasible to use V and W method, because the placing of transducers is technically impossible due to the critical angle. If maximizing length of ultrasonic signal path in fluid is required (to increase T), V and W methods are superior. The transducers must be securely mounted at the correct angle and distance from each other to align with the flow path and avoid signal loss.

Figure 2.11: Mouting positions: Z method (top), V method (middle) and W method (bottom) [3]

2.4.5 Comparison Between Transit-time and Doppler Methods

The transit-time method was chosen for the purposes of this thesis (clean water flow measurement). It provides better accuracy for clean fluids without impurities, which are more easily obtained for testing purposes. It measures the fluid flow directly without relying on on-homogeneous particles. Another factor is easier implementation for clamp-on flowmeter solutions. The flowmeter can be more easily adjusted for different types of pipes. In summary, for a clean-liquid clamp-on application, a transit-time ultrasonic measurement is more suitable, whereas Doppler is better suited for cases where the fluid contains significant entrained solids or bubbles.

2.5 Calibration Techniques for Flowmeters

2.5.1 Standard Calibration Methods

Flowmeter calibration ensures accurate measurements, with gravimetric and volumetric methods serving as primary standards [15].

Gravimetric Calibration

Gravimetric calibration measures the mass of fluid collected over a period, calculating the mass flow rate Q_m as:

$$Q_m = \frac{M}{t} \tag{2.33}$$

where M is the mass (kg), and t is time (s). The volumetric flow rate Q_v is:

$$Q_v = \frac{Q_m}{} \tag{2.34}$$

where is fluid density (kg/m^3). This method is accurate but labor-intensive, requiring precise weighing and timing.

Volumetric Calibration

Volumetric calibration measures the volume collected, calculating Q_v:

$$Q_v = \frac{V}{t} \tag{2.35}$$

where V is volume (m^3). It requires precise volume measurement and is sensitive to temperature-induced volume changes [21]. Reference flowmeter sometimes called golden flowmeter is connected to the tube as close as possible to the flowmeter that is being calibrated. This golden flowmeter needs to be as accurate as possible and during the calibration process, the flow of liquid should be even without big and sudden changes. Typically, calibration is performed at multiple flow points across the meter's range to characterize its response. Any systematic deviation (meter factor) can then be adjusted so that the flowmeter's readings match the reference across the range.

2.5.2 Factors Affecting Calibration Cccuracy

Calibration accuracy is influenced by temperature, fluid properties, and pipe conditions.

Temperature

Temperature affects the speed of sound c, critical for transit-time flowmeters. For water [14]:

$$c = 1404.3 + 4.7T - 0.04T^2 \quad \text{m/s} \tag{2.36}$$

where T is temperature (°C). This impacts flow velocity which is often times in literature approximated for $v \ll c$:

$$v \approx \frac{c^2 \Delta t}{2L \cos\theta} \tag{2.37}$$

where Δt is transit-time difference, L is path length, and θ is transducer angle.

Fluid Properties

Density ρ and viscosity μ affect the flow profile via the Reynolds number:

$$\mathrm{Re} = \frac{\rho v D}{\mu} \tag{2.38}$$

where v is velocity, and D is pipe diameter. Deviations from assumed profiles cause errors.

Pipe Conditions

Pipe material, diameter, and roughness impact signal transmission and flow profile, particularly in clamp-on setups. For example, a pipe with significant internal scale or roughness can disturb the velocity profile and attenuate the ultrasound, making the calibration on a clean reference pipe slightly off when applied in this situation. Additionally, if a flowmeter is calibrated on one pipe material (e.g., PVC) and then used on a different material (e.g., steel) of the same diameter, the acoustic transmission and timing might shift slightly due to different speed of sound in the wall, introducing calibration bias. In some cases even the same material, but from a different manufacturer, can introduce bias [22].

2.5.3 Automation in Calibration Process

Automated calibration enhances efficiency and consistency. It makes the manufacturing process faster, less labor-intensive and more reliable.

Automated Zero-Flow Calibration

Each ultrasonic flowmeter is unique when it comes to Zero Flow Drift (ZFD). This offset is usually just couple dozens of picoseconds and is caused by difference in transducers, silicone which cannot be poured and degassed to be exactly the same and different amount of acoustic grease. Even if we control the temperature, fluid and pipe conditions, the aging of the silicone will introduce some ZFD. Especially in its first week after curing, when it shrinks by about 1%. Afterwards the shelf life of silicone is over 30 years. [25] Adjusts for offsets at zero flow:

$$t_{cal} = \quad t \qquad t_0 \tag{2.39}$$

The flowmeter periodically measures $t_0 = t_{up} \quad t_{down}$ under no-flow conditions, averaging multiple samples to reduce noise [6].

Temperature Compensation

Temperature compensation is used to adjust c in real-time during calibration process and during operation. For example, increase in [c], speed of sound in water from equation 2.36 is 1482 m/s at 20 C to 1528 m/s at 40 C as 3% change in c, which will significantly change calculation of speed of flow velocity. θ for this example was chosen to be standard 45. When we substitute into equation 2.37 we get:

$$v_{new} = \frac{(1.03c)^2 \Delta t}{2L \cos\theta} = 1.063 \tag{2.40}$$

This corresponds to a 6.3% increase in v, and thus in volumetric flow rate Q. Since we want to achieve best accuracy we can use equation 2.26 to calculate ΔT:

$$\Delta T = T_{21} - T_{12} = \frac{L}{c - v\cos\theta} - \frac{L}{c + v\cos\theta} \tag{2.41}$$

$$\Delta T = \frac{2Lv\cos\theta}{c^2 - (v\cos\theta)^2} \tag{2.42}$$

From equation 2.42 we rearrange the equation to solve for v:

$$v = \frac{-L + \sqrt{L^2 + \Delta T^2 c^2}}{\Delta T \cos\theta} \tag{2.43}$$

For values above we get:

$$v_{new} = \frac{-0.05 + \sqrt{(0.05)^2 + (3.219 \times 10^{-8})^2 (1528)^2}}{(3.219 \times 10^{-8}) \, 0.707} \tag{2.44}$$

$$v_{new} \approx 1.062 \mathrm{m/s} \tag{2.45}$$

The difference between the exact value and approximation is quite small, 6.3% vs 6,2%, but for final calculations exact equations will be used.

Self-Diagnostic Features

Bubbles in the fluid scatter and attenuate the ultrasonic waves, reducing the amplitude of the received signal and introducing noise in the transit-time measurements, potentially leading to erroneous flow velocity calculations. By monitoring the signal amplitude and transit-time consistency the system identifies anomalies indicative of bubble interference when the signal strength drops below a predefined threshold or when ΔT fluctuates unexpectedly. The firmware implements an algorithm to compare real-time measurements against baseline values, triggering corrective actions such as temporarily pausing measurements or alerting the user via RS485/NB-IoT communication. Similarly, a drift in the measured Δt_0 (zero-flow offset) or in effective could indicate transducer misalignment or coupling degradation, prompting a recalibration or user check. These automated diagnostics help maintain long-term accuracy without frequent manual checks.

2.6 Error Sources in Ultrasonic Flowmeters

Ultrasonic clamp-on flowmeters are susceptible to various error sources that can compromise measurement accuracy. This section examines inherent hardware limitations, temperature variations, bubble interference, misalignment of transducers, and other common issues, providing real-world equations and data to quantify their impacts.

2.6.1 Inherent Hardware Limitations

Hardware limitations arise from the physical and electronic constraints of the flowmeter's components, including transducers, timing circuits, and the microcontroller. Let's take a differential time-of-flight (dToF) accuracy of 12.5 ps, enabling precise measurements [29]. For a setup with $c = 1482$ m/s, $L = 0.01$ m, $\theta = 45^\circ$, the minimum detectable $\Delta T = 12.5 \times 10^{-12}$ s corresponds to a flow velocity:

$$v = \frac{L + \sqrt{L^2 + \Delta T^2 c^2}}{\Delta T \cos\theta} \approx 1.9 \times 10^{-3}\ \text{m/s} \tag{2.46}$$

For a 25 mm pipe ($A \approx 4.91 \times 10^{-4}$ m^2), the minimum flow rate is $Q_{min} \approx 0.093$ l/s, this is theoretical accuracy of the microcontroller which is highly dependent on outside factors, manufacturer claims accuracy of less than 1 l/h[29]. Transducer frequencies (100 kHz 5 MHz) affect resolution and attenuation, with higher frequencies limited by pipe materials [22].

2.6.2 Bubble Interference

Bubbles scatter and absorb ultrasonic waves, reducing signal amplitude and introducing noise. A study found that a bubble volume fraction exceeding 1% renders the transit-time method nearly unusable, with errors exceeding 10% [34].

2.6.3 Misalignment of Transducers

Misalignment alters the effective angle , causing errors in v. For = 45 misaligned to 50 :

$$\frac{v^0}{v} = \frac{\cos 45}{\cos 50} \quad 1{:}1 \tag{2.47}$$

This 10% error underscores the need for precise alignment. Robust design of the case of the flowmeter, regular checks and diagnostics can mitigate this issue.

2.6.4 Sample Rate Error

Sample rate error arises from the frequency at which T is measured, affecting the capture of dynamic flow changes. Consider a flow rate fluctuating by 10% (1 l/s to 1.1 l/s) over 0.5 seconds.

- 1 Hz (1 sample/s) : Misses the spike, measuring 1 l/s instead of the average 1.05 l/s, yielding a 5% error.
- 2 Hz (2 samples/s) : Captures the spike and base, but for a 0.2-second spike, the error is 2:5%.
- 16 Hz (16 samples/s) : Captures the spike accurately, reducing error to $<$ 0:3%.

Higher sampling rate is not suitable for battery power applications, therefore dynamic sampling rate adjustment based on T variance can balance accuracy and power.

2.6.5 Other Common Issues

- Pipe Wall Effects : Materials like steel attenuate signals with rust exacerbating errors (the ultrasound may be weakened or mode-converted). If the pipe wall is very thick relative to the wavelength, multiple modes can propagate, complicating the received signal.

- Fluid Properties : Changes in viscosity or density can alter how a liquid flows. For instance, a thicker liquid may have a more uniform velocity across the pipe, which might not match the flow pattern expected during calibration, leading to inaccurate measurements [1].

- Flow Profile Distortions : Turbulence from pipe bends or valves leads to asymmetric or unsteady velocity distributions. To minimize this, transducers should be installed with some straight pipe length upstream and downstream. In critical installations, computational fluid dynamics or empirical tests can be used to determine if a shorter run (with a correction factor) can be tolerated [1].

- Electronic Noise : Electromagnetic interference introduces noise in T, requiring robust shielding and filtering. For instance, variable frequency drives (VFDs) and other electrical equipment can inject noise; using differential signal paths and shielded cables helps reject common-mode interference.

Error Source	Impact on Accuracy	Mitigation Strategy
Hardware Limitations	Limits low flow detection	Optimize transducers, enhance processing
Temperature Variations	Dependent on calibration	Temperature compensation
Bubble Interference	>10% error at >1% bubble fraction	Signal monitoring, bubble removal
Transducer Misalignment	~10% error for 5° misalignment	Precise alignment, diagnostics
Sample Rate Error	Dependent on sample rate and flow volatility	Dynamic sampling rate adjustment
Pipe Wall Effects	Variable signal attenuation	Select compatible materials
Fluid Properties	Variable error	Adjust for viscosity/-density
Flow Profile Distortions	Variable error	Use flow conditioners
Electronic Noise	Noise in T	Improve shielding

Table 2.2: Error Sources and Impacts in Ultrasonic Flowmeters

2.7 Ultrasonic Signal Processing and Measurement

Precise detection of the tiny time differences T requires advanced signal processing. Modern transit-time flowmeters often use specialized time-to-digital converters (TDCs) and correlation techniques. The MSP430FR5043 microcontroller includes a timing module that can measure upstream and downstream transit times with picosecond resolution. In essence, the microcontroller captures the received ultrasonic waveforms and determines the time of flight by identifying a specific point on the signal. For example, the first threshold crossing or the peak of cross-correlation with a reference signal.

There are two common approaches: a simple threshold/zero-crossing detection and a cross-correlation method [3]. The zero-crossing technique has low computational cost but can be vulnerable to noise and amplitude drift. For instance, if the signal amplitude changes (due to temperature or slight misalignment), the threshold crossing point may shift in time , leading to error [29] [28]. Cross-correlation, on the other hand, compares the incoming signal with a stored reference (often the averaged waveform at zero flow or a modeled pulse) to find the time shift that yields the highest correlation. This method is more computationally intensive, but it is highly robust against noise and distortions. It effectively uses the entire waveform shape, not just a single point, to determine transit time.

In practice, the MSP430FR5043 uses a combination of these strategies. Texas Instruments' design guides indicate that the internal processing can achieve on the order of 80 ps peak-to-peak timing jitter and about 25 ps drift at zero flow conditions [29], by leveraging high-frequency sampling and averaging. The microcontroller's analog front-end amplifies and filters the received echoes (bandpass filtering around the transducer frequency to improve SNR), then a digital processing algorithm (integrated in the Ultrasonic Sensing Solution library [30]) computes T. The result is that even extremely small time differences corresponding to very low flow rates can be measured reliably. Overall, sophisticated signal processing ensures that the theoretical resolution of the ultrasonic method is practically realized, and that noise, interference, and other nonidealities are adequately suppressed to maintain accuracy.

Chapter 3

Implementation

3.1 Hardware Design

Hardware design passed through multiple phases. First development board EVM430-FR6043 was used to test out the basic functionality, transducer combination, pipes, silicone selection and manufacture, acoustic grease and detectable flow rates.

3.1.1 Evaluation Board Setup

The development kit is primarily for gas metering. Therefore, it was necessary to re-solder some components on it to make it suitable for water metering [29]. Afterwards the devkit was connected to PC using windows program from Texas Instruments (TI) called Ultrasonic Sensing Design Center. After setting up parameters like frequency, gap between pulse start and ADC capture, number of pulses, upstream and downstream gap, sampling frequency and gain, the transducers were connected and put inside a 3D printed fixture opposite each other in water. The purpose of this was to test if signal is being received and how to set parameters to get good looking ADC capture of the signal. On the right in figure 3.1 there are basic settings to get the flowmeter to start working. Right side of the same figure shows pulse capture when the transducers faced directly each other and the only medium between them was water.

Figure 3.1: Left flowmeter parameters in GUI right pulse capture. Right capture of waveform.

Afterwards based on suggestion from TI, industrial lubricant was used as a coupler directly between the transducers and pipe, leaving out the silicone part [31]. While it works adequately, the problems are unnecessarily high consumption of the lubricant, mess created by the lubricant and cleaning after removing the flowmeter. Therefore, the next step was to test out silicone interface which will be discussed in more depth in section 3.1.4. Furthermore, everything was tested on enclosed pipe with standing water, with transducers facing each other directly - meaning they were placed perpendicular to the pipe. This was done to maximize the signal strength and to minimize losses from reflections and eliminate echoes, which could have been the results from choosing incorrect angles. Once the basic functionality was tested, the accuracy of the system was checked. This consisted of checking ToF its mean and . After setting the Gain control so that the maximum amplitude of the waveform is under 1000, to avoid overflow and rounding errors inside the MCU, the ToF was captured. Figure 3.2 shows the physical setup used to test the transducers. Figure 3.3 shows the results and we can see that the standard deviation is just 21.65 ps. There is a slight offset (mean of -12.96 ps) which is caused by hardware and physical limitations discussed in theoretical background.

3.1.2 Angles

One of the most important parameters when designing ultrasonic clamp-on flowmeter is choosing the right angle between transducers and the tube. The testing was done on two tubes with parameters shown in table 3.1. The values for this table were obtained by experiment. The density for pipes was calculated from $= \frac{m}{V}$. The speed of sound in the plastic pipes was calculated by using oscilloscope (Rhode & Schwartz RTB2004) at reference temperature

Figure 3.2: Test setup of transducers in water

of the water 22 C, measured by DS18B20 thermometer. Using the difference between the start of excitation pulse from the upstream flowmeter and start of the received signal, the approximate speed of sound in water and pipe material could be calculated. The speed is a rough approximation, but is sufficient for calculating the angles necessary for creating the ultrasonic flowmeter. The speed of sound in the MDP plastic will be for the purposes of this thesis the same as speed of sound in the water based on result of equation 3.1 . Time difference when Coldmaster MDP pipe was present and when it was not was:

$$t = t_2 \quad t_1 = 49{:}88us \quad 49{:}14us = 0{:}26us \tag{3.1}$$

Where t_2 is time with pipe present and t_1 is time with just water present. For the second pipe with diameter of 25mm we get:

$$t = t_2 \quad t_1 = 58{:}8us \quad 57{:}1us = 1{:}7us \tag{3.2}$$

Here, the difference is not negligible. To calculate the speed of sound through this medium, following equations were made:

Figure 3.3: Capture of ToF for two transducers with no pipe in between them

$$
\begin{aligned}
t_{\text{water only}} &= 58.8\,\mu s = 58.8 \times 10^{-6}\,s \\
v_{\text{water}} &= \frac{0.0856}{58.8 \times 10^{-6}} \approx 1456\,m/s \\
d_{\text{pipe}} &= 2 \times \frac{25-18}{2} = 7.0\,mm = 0.007\,m \\
d_{\text{water}} &= 0.0856 - 0.007 = 0.0786\,m \\
t_{\text{with pipe}} &= 57.1 \times 10^{-6}\,s \\
t_{\text{water}} &= \frac{0.0786}{1456} \approx 5.398 \times 10^{-5}\,s \\
t_{\text{pipe}} &= 57.1 \times 10^{-6} - 5.398 \times 10^{-5} = 3.12 \times 10^{-6}\,s \\
c_{\text{pipe}} &= \frac{0.007}{3.12 \times 10^{-6}} \approx 2244\,m/s
\end{aligned}
\tag{3.3}
$$

Calculated speed of sound in PP-RCT plastic tube is 2244 m/s, which is in the bulpark of what is to be expected for plastic materials (2000-2600 m/s) [22].

Property	Coldmaster MDP	FV PP-RCT HOT
Internal Diameter (mm)	9.5	18
External Diameter (mm)	12.7	25
Material	MDP	PP-RCT
Speed of Sound (m/s)	1490	2244
Density (kg/m^3)	940	986
Application	Beverages	Hot water in buildings

Table 3.1: Comparison of two tube types and their physical properties at 22 °C

With values from 3.1 and with equations 2.14, 2.12 and 2.11 we can calculate refraction angles of the signal, which allows us to position the ultrasonic transducers around the pipe so that we maximize transmitted power and the ultrasonic path in the fluid inside of the pipe. For this purpose short python script was created that calculates the critical angles between interfaces. From it we get following table for critical angles:

Interface	Coldmaster MDP	FV PP-RCT HOT
Silicone → PVC	42.16	26.46
PVC → Water	No critical angle	No critical angle
Water → PVC	No critical angle	41.61
PVC → Silicone	No critical angle	No critical angle

Table 3.2: Critical Angles at Material Interfaces for pipe Configurations

Figure 3.4 simulates approximately what will be the signal energy loss on medium interfaces, eg. going from silicone to plastic tube.

Figure 3.4: Simulation of total signal energy transmission vs. incident angle. Top graph shows smaller tube and bottom graph the larger.

Signal attenuation in pipe was empirically tested while testing the speed of sound in the pipe and water, from setup 3.2. The pipe was perpendicular to the transducers as to minimize losses and to avoid calculating angles without data about propagation speed of ultrasonic sound wave in the particular plastic pipe. From figure 3.6 we get amplitudes of $V_{pp1} = 1.02V$ and $V_{pp2} = 0.41V$.

This shows that for pipe at the best possible angle, when the total signal energy transmission was simulated to be 94%, the signal amplitude was lowered by almost 60%. This is caused by several factors. One is that power P and voltage V are related as:

$$P \propto V^2 \tag{3.4}$$

which means a relatively small drop in voltage corresponds to a much larger drop in transmitted power. In this case, the ratio of received to original voltage is:

$$\frac{V_{pp2}}{V_{pp1}} = \frac{0.41}{1.02} \approx 0.402 \tag{3.5}$$

and the corresponding power ratio is:

$$\frac{P_2}{P_1} = \left(\frac{V_{pp2}}{V_{pp1}}\right)^2 \approx 0.402^2 \approx 0.162 \tag{3.6}$$

This implies that only around 16.2% of the original power was received. Despite the simulated energy transmission being 94%, real-world losses such as signal attenuation in the plastic, partial decoupling at material interfaces and beam spreading due to curvature of the pipe wall increase the power loss substantially. The effect of curvature of the wall will be smaller in larger pipes, since the local surface of the wall more closely approximates a flat interface, reducing beam refraction, angular deviation, and associated signal dispersion across the interface. For the larger pipe the amplitudes were $V_{pp1} = 1.097V$ and $V_{pp2} = 0.5V$, which shows that the material in the larger pipe has smaller attenuation properties compared to the 12.7 mm pipe.

Figure 3.5: Capture of ToF for two transducers with the 25mm pipe in between them

The signal attenuation is still acceptable as seen in figure 3.5, we are getting similar standard deviation of ToF of about 22 ps. To get this value, some changes in the flowmeter settings such as adjusting the gap between start of the pulse and ADC capture, because the transducers are further apart in this fixture (85.6 mm compared to 72.8 mm in figure 3.3) and adjusting gain had to be made.

Figure 3.6: Transmitting and receiving ultrasonic signal. Top without pipe. Bottom with pipe present

3.1.3 Custom PCB Design

Once the basic functionality of the system was validated using development boards and modular components, a custom PCB was designed to integrate all necessary functions into a compact, energy-efficient solution. The main goals of the custom design were to:

- Minimize the physical size to fit inside the flowmeter housing.
- Reduce overall power consumption for battery or solar-powered use.
- Optimize the bill of materials (BOM) to lower production cost.
- Provide robust communication interfaces (RS485 and NB-IoT).

The final PCB's integrates the ultrasonic time-of-flight measurement engine, microcontroller, power regulation, transducer drivers, and communication modules.

PCB for RS485

The wired version of the flowmeter must meet the following requirements:

- Operate from a wide input voltage range of 10-24 V.
- Maintain low power consumption to ensure efficient operation and reduce thermal load.
- Include RS485 communication interface for robust and noise-immune serial data transmission.
- Provide basic protection features, including reverse polarity protection on power input pins.

Based on these requirements, the PCB was designed and tested, 3.7. For power, ultra low linear regulator (TPS70950DRVR) was used that is capable to take in from 10-24 V and has ultra-low IQ of just 1 A. After this regulator there is another linear regulator that has high-PSRR to get smooth voltage on input for the correct operation on the USS module (UltraSonic Sensing). Datasheet specifies that the voltage transitions remain within 0.05 V= s [29]. The final design can be seen on figure 3.7:

On the back of the PCB are pads that will be used for automated flashing and calibration 3.7.