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Development of a low-cost experimental platform with preliminary numerical analysis for the study of ultrasonic sound propagation speed

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Abstract: In recent years, universities have sought alternative methodologies to sustain the teaching–learning process, driven by the expansion of virtual classes and limited resources in many insti-tutions. In this context, this study investigates the influence of temperature and humidity on the speed of sound wave propagation (SSW) using a low-cost experimental setup complemented by numerical simulations. A hermetically sealed container was instrumented with sensors to meas-ure sound speed, temperature, and relative humidity, using an Arduino UNO development board. Four experimental conditions were analyzed, varying water presence and heating. In par-allel, a numerical model using harmonic acoustics is proposed. Experimental results showed an increase in sound speed with temperature, consistent with theoretical expectations, while the in-fluence of humidity was less pronounced due to near-saturation conditions. The presence of liq-uid water increased absolute humidity through evaporation, affecting measurements. However, measured SSW values were lower than theoretical predictions, likely due to sensor limitations and uncertainties under high humidity. Numerical results also diverged from experiments be-cause of simplified boundary conditions and the absence of thermal and humidity gradients. De-spite these limitations, the proposed approach indicates the feasibility of a replicable, low-cost system for educational and research applications, with potential improvements through en-hanced sensor calibration and multiphysics modeling.

Key words: Arduino, vibroacoustics, bench test, speed of propagation.

Desenvolvimento de uma plataforma experimental de baixo custo com análise numérica preliminar para o estudo da velocidade de propagação do som ultrassônico

Resumo: Nos últimos anos, as universidades têm buscado metodologias alternativas para sustentar o processo de ensino-aprendizagem, impulsionadas pela expansão das aulas virtuais e pelos recursos limitados em muitas instituições. Nesse contexto, este estudo investiga a influência da temperatura e da umidade na velocidade de propagação de ondas sonoras (VOS) utilizando uma configuração experimental de baixo custo complementada por simulações numéricas. Um recipiente hermeticamente fechado foi instrumentado com sensores para medir a velocidade do som, a temperatura e a umidade relativa, utilizando uma placa de desenvolvimento Arduino UNO. Quatro condições experimentais foram analisadas, variando a presença de água e o aquecimento. Paralelamente, um modelo numérico utilizando acústica harmônica é proposto. Os resultados experimentais mostraram um aumento na velocidade do som com a temperatura, consistente com as expectativas teóricas, enquanto a influência da umidade foi menos pronunciada devido às condições próximas à saturação. A presença de água líquida aumentou a umidade absoluta por meio da evaporação, afetando as medições. No entanto, os valores de VOS medidos foram menores do que as previsões teóricas, provavelmente devido às limitações e incertezas dos sensores em condições de alta umidade. Os resultados numéricos também divergiram dos experimentos devido às condições de contorno simplificadas e à ausência de gradientes térmicos e de umidade. Apesar dessas limitações, a abordagem proposta indica a viabilidade de um sistema replicável e de baixo custo para aplicações educacionais e de pesquisa, com potencial para melhorias por meio de calibração aprimorada de sensores e modelagem multifísica.

Palavras chave: Arduino, vibroacústica, teste em bancada, velocidade de propagação.

Introduction

The increasing integration of digital technologies into higher education has driven significant changes in educational methods, particularly following the widespread adoption of online and technology-mediated learning environments after the COVID-19 pandemic (Gaievska *et al.* 2024; Kharchenko *et al.* 2024). Recent studies indicate that technology-supported approaches have become central to teaching and learning processes, contributing to greater flexibility, student engagement, and pedagogical innovation, while also exposing financial and infrastructural limitations, especially in resource-constrained contexts (Maune 2025).

Within this framework, the demand for educational strategies that combine pedagogical effectiveness with economic feasibility has intensified (Dadzie *et al.* 2025). As a consequence, the development of low-cost educational tools emerges as a relevant response to support experimental and hands-on learning activities, enabling practical experimentation aligned with contemporary educational methodologies and facilitating broader access to laboratory-based learning experiences in science and engineering education classes, such as vibroacoustics.

The perception of sound is directly related to the way that vibrational waves are analyzed: In addition to the emitter and receiver, e.g., speaker and microphone, respectively, it is essential not only to use but also to understand the propagation medium of the sound wave. At the same time, the study of vibroacoustic dates to the XVIII century; however, recent works continue to explore this physical phenomenon given its complexity, even if the sensation of sound is something sui generis (Rayleigh 1984; Wittmann *et al.* 2022).

The vibroacoustic concepts are commonly discussed: For example, Firouz *et al.* (2024) have utilized parabolic equations and the RAMGEO model, focused on 100 and 500 Hz frequencies over a 10 km transmission range at six stations. Placing sound sources in the surface layer, thermocline layer, and near the seabed, the transmission loss analysis made by the authors shows the most significant impact from the seabed source position, followed by the thermocline and surface layers. In addition, this study also utilized the ROMS model, with the aid of ROMS 3D software, to develop mesoscale eddies with collected data.

Nevertheless, vibroacoustic helps in the understanding of daily phenomena in the most diverse areas and, consequently, its application also occurs in the most diverse solutions, from engineering to music (Couty *et al.* 2023; Kaselouris *et al.* 2023). For example, Sheykhi (2023) uses biomimetics to investigate the vibroacoustic performance of star-shaped honeycomb-core annular cellular structures. Working on top of the mass variation of the structure and the bending stiffness, the author manages to optimize the structure in order to obtain an increase in sound transmission loss of almost 500%.

The use of vibroacoustic concepts in most different applications also indicates that the study by new methods that present optimized results is constant in the area (Su *et al.* 2023). Corroborating the above, Citarella *et al.* (2022) presents the advances in vibroacoustic and aeroacoustics of marine, aerospace, and automotive systems. As noted in this section, vibroacoustic is widely used in transport vehicles, especially cars and planes. This is basically due to the safety required for these vehicles and their constant movement, resulting in dynamic requests during a large part of their operating life. To do so, a varied range of acoustic sensors is usually applied (Gunerkar & Jalan 2019; Patil *et al.* 2022).

In this context, several approaches to technical analysis are developed. While some works use multi-scale modeling to obtain structures with improved vibroacoustic performance (de Rosa *et al.* 2020), others use the wave chaos approach (Mohammed 2021). Also, some works use the statistical mode method (de Castro Braz & D'Andrade Souto 2023) and even machine learning methods (Cunha *et al.* 2022), one of the main tools of Industry 4.0. Amid so many methods of approaching these problems (Deng *et al.* 2022), it is also necessary to understand and develop models for interpretation and to obtain simulated results consistent with the physical system.

On the other hand, Boukadia (2021) studied the model order reduction, characterization, and optimization, while Xie *et al.* (2023) seek to develop a relatively fast algorithm for the models mentioned above. Still thinking about the type of medium and material used in the propagation of sound waves, the use of composite materials has also gained considerable space in studies about the optimization of an asset's vibroacoustic (Kushwaha & Bagha 2020). Summarizing, the propagation of sound waves varies according to system characteristics, such as temperature, pressure, and the type of propagation medium, and even the salinity influences this propagation if the studied environments contain aqueous solutions with dissolved salts (Shumeyko & Abramovich 2022).

In this sense, the present work aims to evaluate the influence of temperature and humidity variations on the apparent SSW in a hermetically sealed control volume. For this purpose, a low-cost bench test was developed using a microcontroller and sensors to monitor temperature, relative humidity, and ultrasonic wave propagation under different experimental conditions. Since the container is sealed, pressure variations may occur as a consequence of temperature changes; however, pressure is treated in this study as an associated limitation rather than as the main controlled variable. Lastly, this paper differs from others in the area by proposing a relatively simple and low-cost system for educational and experimental analysis, complemented by a preliminary numerical model intended to compare the acoustic behavior of the system under simplified conditions.

Sound propagation and environmental effects

The study of wave propagation is related to vibroacoustic, which unites and presents broadly based concepts on mechanical vibrations (Król *et al.* 2023). Nevertheless, for the purposes of the present study, the theoretical discussion is restricted to the variables directly involved in the proposed bench test: propagation medium, temperature, and humidity. This delimitation is necessary because the experimental system is not intended to reproduce complex vibroacoustic applications, but to provide a low-cost and replicable setup for observing variations in apparent sound wave propagation speed under laboratory conditions.

In this context, previous studies have shown that air temperature and relative humidity influence sound propagation (Tsuchiya & Kagawa 1992; Liptai *et al.* 2015) and, in the present work, these variables are relevant because the sealed container allows thermal variation and, in the tests involving liquid water, evaporation may alter the humidity conditions inside the control volume. As a consequence, the equations that describe sound wave propagation in fluids are well established in the literature and provide the theoretical basis for interpreting the experimental results of this study. Besides, variations for specific problems and methods to solve them are discussed till today (Chashechkin 2021) and, according to (Frey *et al.* 2000), the fundamental equation governing the propagation of sound waves in fluids, such as air or water, is defined in Equation 1.

$$\frac{\partial^2 p}{\partial t^2} = c^2 \nabla p \qquad \text{(Equation 1)}$$

In the equation above, p is the acoustic pressure; c is the speed of sound in the medium; ∇^2 is the Laplacian operator and t is time.

Still, according to Equation 1, the importance of characterizing the speed to explain the phenomenon is made explicit through the presence of the variable c. Also, as previously exposed, the speed at which sound waves propagate depends on the medium through which they are traveling and its characteristics, such as the temperature (Fukuoka *et al.* 2023). Simultaneously, there are primary equations to define that parameter according to each different medium and system configuration (Nowoświat 2022). While Equation 2 describes c for a wave propagating through the liquids, Equation 3 is for the phenomena occurring through air.

$$c = \sqrt{\frac{K}{\rho}} \qquad \text{(Equation 2)}$$

$$c = \sqrt{\frac{\gamma R T}{M}} \qquad \text{(Equation 3)}$$

In the equation above, γ is the adiabatic index; R is the universal gas constant; T is absolute temperature, M is the molar mass of the gas, K is the bulk modulus of the liquid, and ρ is the density of the liquid. In the bench test proposed in this work, the ultrasonic wave propagates mainly through the air column inside the container. Therefore, the gas-phase expression is the main reference for interpreting the experimental measurements, while the presence of liquid water is considered through its influence on evaporation, humidity, and boundary effects.

The speed of sound in the air also depends on temperature and, to a lesser extent, humidity (Hauko *et al.* 2022). To this extent, the empirical formula for the speed of sound in air as a function of temperature is shown in Equation 4:

$$c = 165.782 + 0.606T \qquad \text{(Equation 4)}$$

In the equation above, the constants were defined from experimental results. In addition, this relation is used as a theoretical reference for the expected trend between temperature and sound speed. Since the experimental system uses low-cost sensors and operates under high-humidity conditions in some tests, the comparison with theoretical values is interpreted qualitatively rather than as a high-precision validation.

Therefore, the theoretical basis adopted in this work supports the interpretation of temperature as the dominant variable affecting sound speed in air, while humidity is expected to have a secondary effect. This framework also justifies the experimental comparison between tests with and without liquid water inside the sealed container, since evaporation may alter the humidity conditions of the propagation medium.

Methodology

In order to achieve the proposed goals, this topic will address the methodology used in this work. It is also noteworthy that the solution proposed here can be divided into two large groups of distinct fronts: The first, related to the development and physical tests on a bench; and the second, related to the virtual simulation of the system. From the moment that the virtual system is correlated to the physical system, results in which the studied system is exposed to varied conditions that are more difficult to reproduce on the bench, e.g., higher temperatures, different fluids, and larger dimensions, can be done via simulation.

Bench test

Aiming for a low-cost reservoir that would allow the proposed tests, the control volume of the system used is presented in **Figure 1**. Storing up to 5300 mL and with dimensions of approximately 130 x 180 x 230 mm (DxLxH), the container in question is hermetically isolated in order to guarantee eventual tests with pressure control, which, in turn, justifies the installation of a pressure gauge on the top cover.

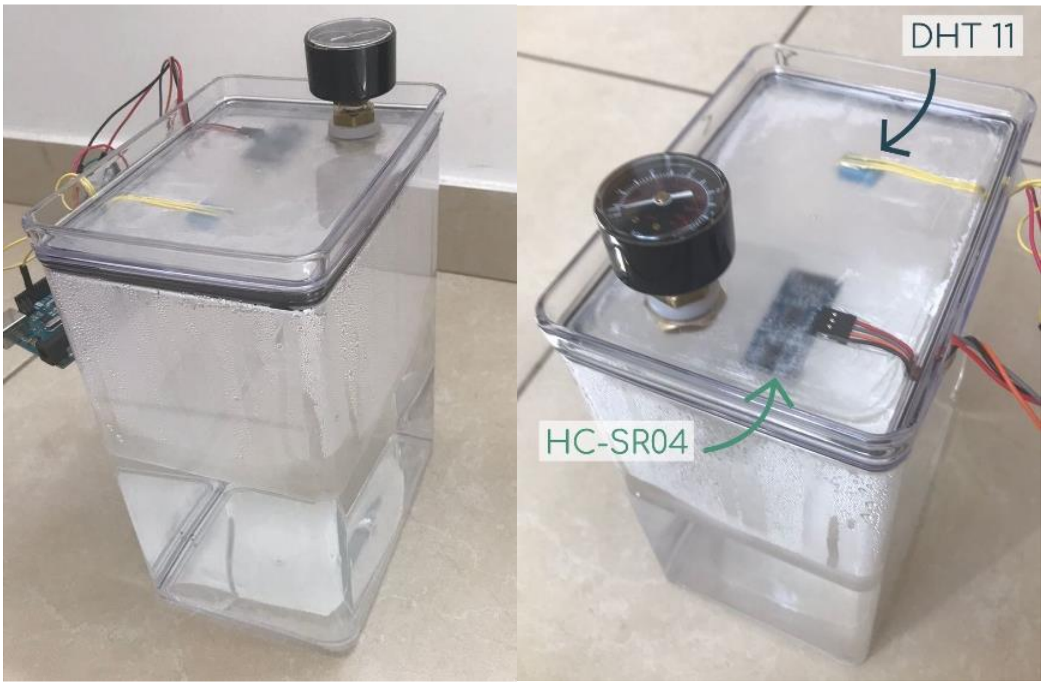

Figure 1. Bench test. Both HC-SR04 and DHT 11 are electronic components to deal with data from the system: While the latter is the temperature and humidity sensor, the former is responsible for emitting and receiving the ultrasound waves.

Schematically, **Figure 2** presents the electrical circuit for connecting the sensors to the microcontroller. It is also noteworthy that while an HC-SR04 sensor is capable of emitting and collecting sound waves, the DHT11 sensor was used to measure temperature and relative humidity inside the container. As only relative humidity was recorded, variations in absolute humidity were later inferred from the experimental conditions, particularly in the presence of liquid water.

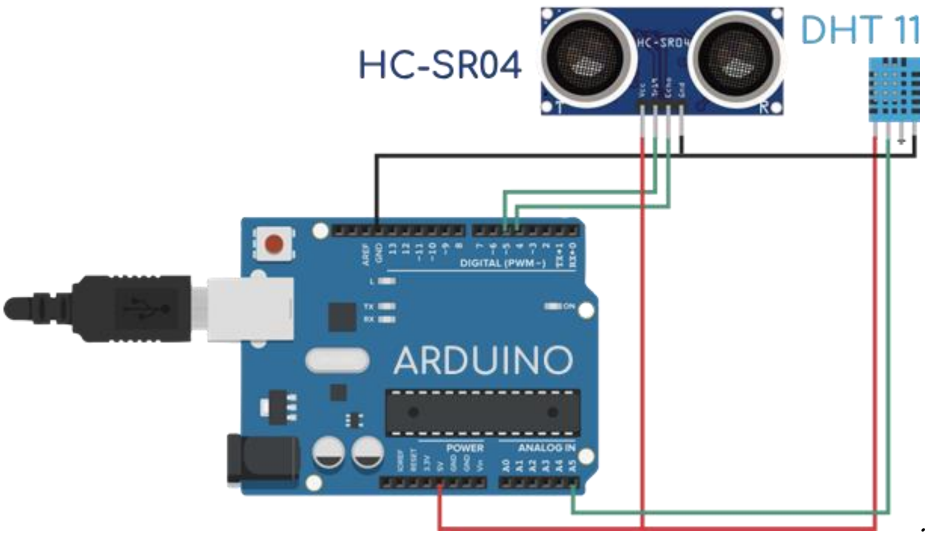

Figure 2. Schematic of connections made in the bench test.

In addition to the characteristics previously mentioned about the HC-SR04 sensor, it is noteworthy that it sends out an ultrasonic pulse of omnidirectional nature, i.e., the pulse is emitted in all directions from the sensor module. Besides, more information about the low-cost sensors presented above is widely available in the literature (Kamal *et al.* 2019; Margret Sharmila *et al.* 2019; Jenila *et al.* 2022), it should be noted that the measured values, as well as the display of this information to the user, were processed using an Arduino UNO development board, based on an ATmega328P microcontroller.

Frequently applied in simplified experimental systems of this type, this platform is programmed through the Arduino IDE, which uses a C/C++-based language with specific libraries and abstractions (Tupac-Yupanqui *et al.* 2022). However, it is anticipated that, according to the software and sensor settings, eight pulses are emitted at a frequency of 40 kHz and then are received at the other sensor's end after colliding with water, which in this case serves as a barrier to the propagation of sound waves. In addition the HC-SR04 sensor was selected due to its low cost, availability, simple integration with the Arduino platform, and operation compatible with the ultrasonic measurements proposed in this work. However, its use in high-humidity and high-temperature environments represents a limitation of the bench test. For this reason, the proposed system should be interpreted as a low-cost educational and exploratory setup rather than a high-precision acoustic measurement device.

Once the system is properly assembled, testing can begin. Nevertheless, it is key to clarify that the definition of the bench test parameters was made empirically based on previous tests and the lack of related works that use a methodology similar to the one proposed here. As the next steps of the work, the definition of system parameters, such as the control volume size for optimal obtaining of the expected results, should be worked on.

Proposed tests

Aiming at analyzing different scenarios, four tests were proposed, where **Figure 3** and the following list present the details related to them. The experimental conditions were defined to compare the effect of liquid water, external heating, and natural cooling on the measured sound wave propagation speed; while the tests were conducted until the monitored variables reached an approximately stable trend in the monitored variables or until the cooling process was completed.

- Test A: After heating 1500 mL of water to its boiling point, i.e., 98°C, the fluid was poured into the reservoir and it was immediately sealed. Thus, the test was designed to evaluate not only the progress in the SSW according to the increase in temperature and pressure but also with the increase in relative humidity. Since the reservoir has a capacity of 5300 mL and considering the thickness of the cover as well as the sensor, the height of the air column is approximately 110 mm. It should also be noted that this value is important for measuring the SSW, since the amount of liquid water serves, in fact, as a barrier to the propagation of sound;
- Test B: This time, 1500 mL of water at room temperature, i.e., 25°C, was poured into the empty and sealed reservoir. Placed on another metallic platform and opened with water so that the acrylic of the control volume is not damaged by direct contact with fire, the system was heated according to the limitations of the HC-SR04 sensor, which stops responding in situations considered high humidity and temperature (-15°C to +70 °C and < 90% RH);
- Test C: Not counting the pouring of water into the control volume this time, test C followed the same idea proposed in test B. This time, the maximum heating temperature was defined based on the moment when the variables analyzed in the system reached stability;

- Test D: After heating the air performed during test C, in test D the heat source was removed, and the SSW behavior was observed as the system cooled under the effect of natural convection alone.

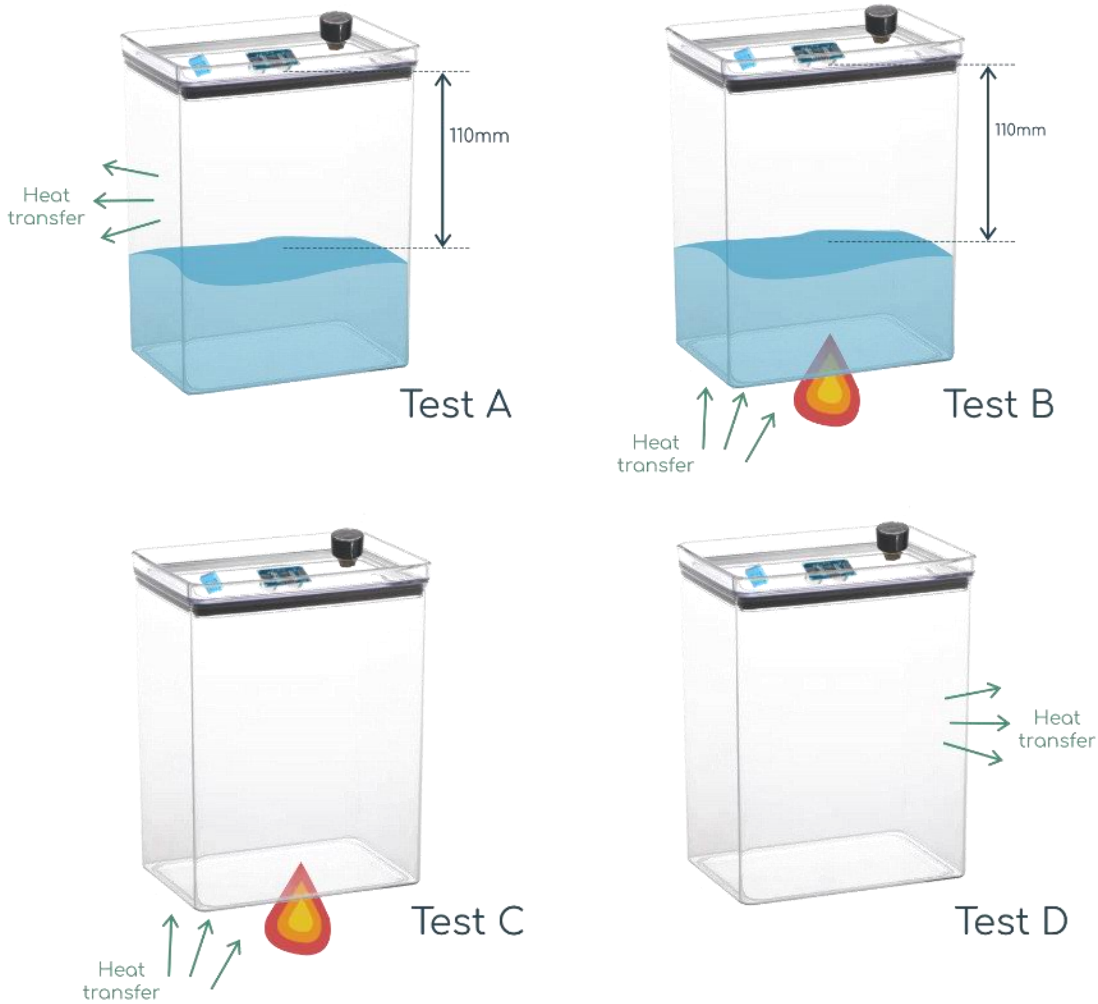

Figure 3. Schematic representation of the four experimental conditions, combining the presence or absence of liquid water with external heating or natural cooling.

It should be noted that during tests involving liquid water (A and B), evaporation occurred as the temperature increased, which raised the absolute humidity of the system even when relative humidity remained close to saturation. This behavior must be considered when interpreting the results. Additionally, each test was conducted until the monitored variables reached an approximately stable trend or, in the case of Test D, until the natural cooling process was completed. The total duration varied depending on the test, but was sufficient to capture the complete transient behavior.

Virtual simulation

After the development of the three-dimensional model of the control volume discussed above, the acoustic simulation was carried out in Ansys using the harmonic acoustics module based on the finite element method (**Figure 4**). Using the water as a barrier in the propagation of the sound wave through the air in the bench test, the simulation was developed considering the conditions presented in the above topic.

According to the **Figure 4**, the harmonic acoustics module was utilized with definitions for both acoustics and a structural region, including a mass source, fluid-solid interface, and radiation boundary. The emission of sound waves was set at 50 phases with a frequency varying up to 40 kHz, considering the ambient temperature. The choice of 40 kHz maximum frequency was based on the technical specifications of the HC-SR04 ultrasonic sensor and its balance between range and resolution (Hidayat *et al.* 2019).

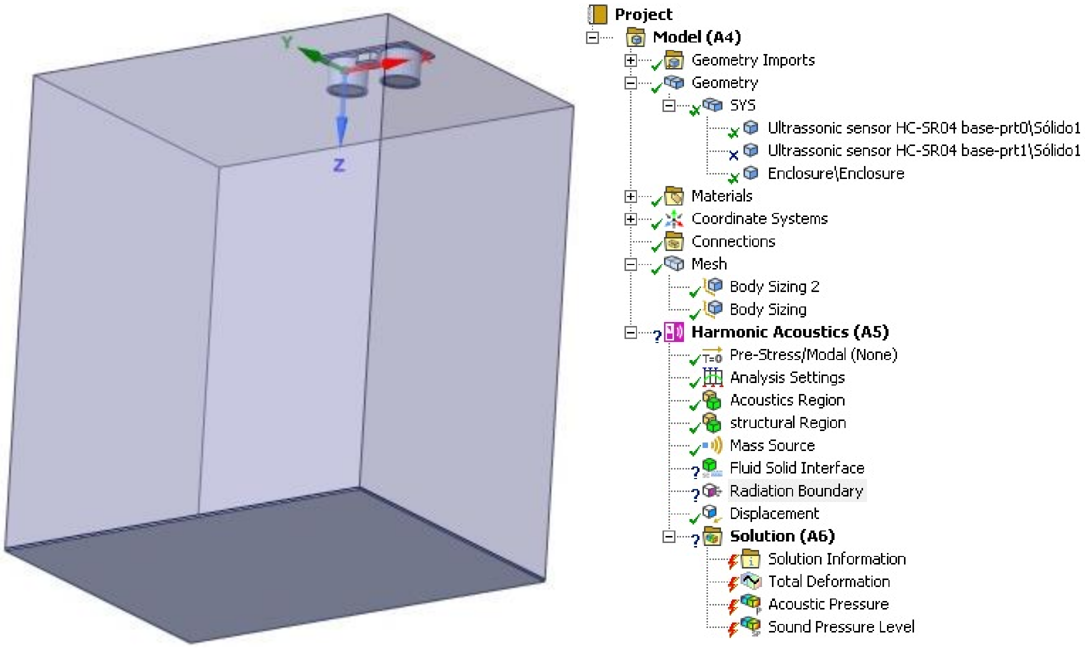

Figure 4. Modelled control volume and simulation configuration on Ansys.

Regarding the model configuration, the "Project" component encapsulates all configurations and analyses conducted within the model. Additionally, the geometry import and system component definitions are explored, encompassing the ultrasonic sensor's respective geometry and a control volume representing the simulation environment. As discussed in the bench test assembly, this sensor is responsible for both emitting and receiving sound waves (Mexias *et al.* 2024; Shi *et al.* 2024), while the control volume sets the boundaries within which the waves propagate. Modeling of the temperature sensor was unnecessary, as Ansys provides this variable as one of its results.

The definition of materials used in the simulation is crucial since the physical properties directly affect the SSW. Therefore, the system was assembled considering air as the propagation medium, simplifying the simulation execution. Calculations with varying control volume sizes were considered under the premise that water in the container would act as a barrier hindering sound propagation in this medium. Consequently, variations in air humidity were disregarded in the proposed premise.

Following this setup, mesh configuration (represented in body sizing) determines how the simulation space is discretized. A well-defined mesh, tailored to the studied problem, is essential for ensuring results align with the phenomenon under study (Sailesh *et al.* 2024). In terms of simulation setup, stress pre-loading or modal analysis was not included to focus exclusively on acoustic analysis, as depicted in the harmonic acoustics module in **Figure 4**. Additionally, radiation boundaries were defined to restrict how waves interact with simulation domain boundaries, preventing undesired reflections and limiting propagation strictly within the control volume.

Lastly, in terms of expected results, charts are defined similarly to standard finite element analyses. According to the figure above, results in terms of total deformation, acoustic pressure, and sound pressure level are standard outputs of the analysis. While total deformation aids in understanding the impact of sound waves on structures, acoustic pressure and sound pressure level provide direct measures of sound intensity in the environment (Rama Krishna *et al.* 2022;

Sanaka *et al.* 2023). Given the goal of measuring sound wave propagation speed, the first and last results were not analyzed.

After preparing the bench test and the virtual model, the tests were finally performed, and the main results are presented in the following section. Before, it is important to notice that the mesh was generated using the automatic body sizing available in Ansys. Thus, a full mesh independence analysis was not performed; therefore, the numerical results are interpreted qualitatively and not as validated quantitative predictions.

Results

As with the methodology, the results obtained are presented into two subtopics: The first, related to the bench test; the second, relative to the simulation.

Bench test

In **Figure 5**, speed and humidity curves are plotted against temperature variation. It is also noteworthy that the linear regression was drawn on top of the values obtained for the speed points.

The first observation, according to the figure above, is that humidity does not appear to have influenced the speed of sound propagation. Similarly, as expected, the SSW basically did not vary in test A, since the system conditions were kept unchanged. In contrast, in the scenario of test D (**Figure 5D**), where there was also no external heating source, the temperature drop resulted in a decrease in SSW. It is noteworthy in this latter case that readings should be from left to right, as the temperature decreased over time.

On the other hand, considering tests B and C (**Figures 5B** and **5C**, respectively), where there was significant heating of the system due to induced external heat, the slopes of the SSW lines are considerably higher than in the other tests. While the variation in humidity is more evident in test C than in B, especially due to the heterogeneous system with the presence of water, the difference in the SSW curves should also be observed from the perspective of the initial and final temperatures of each case. Nevertheless, the behavior of the curves is similar, reinforcing that humidity does not appear to have significantly influenced the results.

During each test, temperature, relative humidity, and ultrasonic time-of-flight data were recorded using the Arduino UNO development board. In this sense, the sound wave propagation speed was calculated from the measured distance between the ultrasonic sensor and the reflecting surface and the time interval between pulse emission and echo reception. In addition, no digital filtering or moving-average procedure was applied during data acquisition and the fluctuations observed in the experimental curves were preserved and are associated with sensor instability, echo detection variability, and the influence of high-humidity conditions.

Consequently, linear regression was applied to the experimental speed data as a trend-identification tool. The purpose of this procedure was not to eliminate measurement fluctuations, but to highlight the overall relationship between temperature variation and the measured apparent sound wave propagation speed. Since no formal calibration procedure beyond the manufacturers' specifications was performed, the experimental results are interpreted mainly in terms of qualitative trends rather than absolute precision.

Simulation

Meanwhile, **Figure 6** shows the results found with the aid of virtual simulation. The maximum acoustic particle velocity obtained in the simulation was 0.063 mm/s, while the minimum value was 0.037 mm/s. These values correspond to the local velocity field calculated by the harmonic acoustics model and should not be interpreted as the thermodynamic speed of sound in the medium. Therefore, the numerical model is discussed as a preliminary qualitative representation of the acoustic field rather than as a validated prediction of the experimental sound speed.

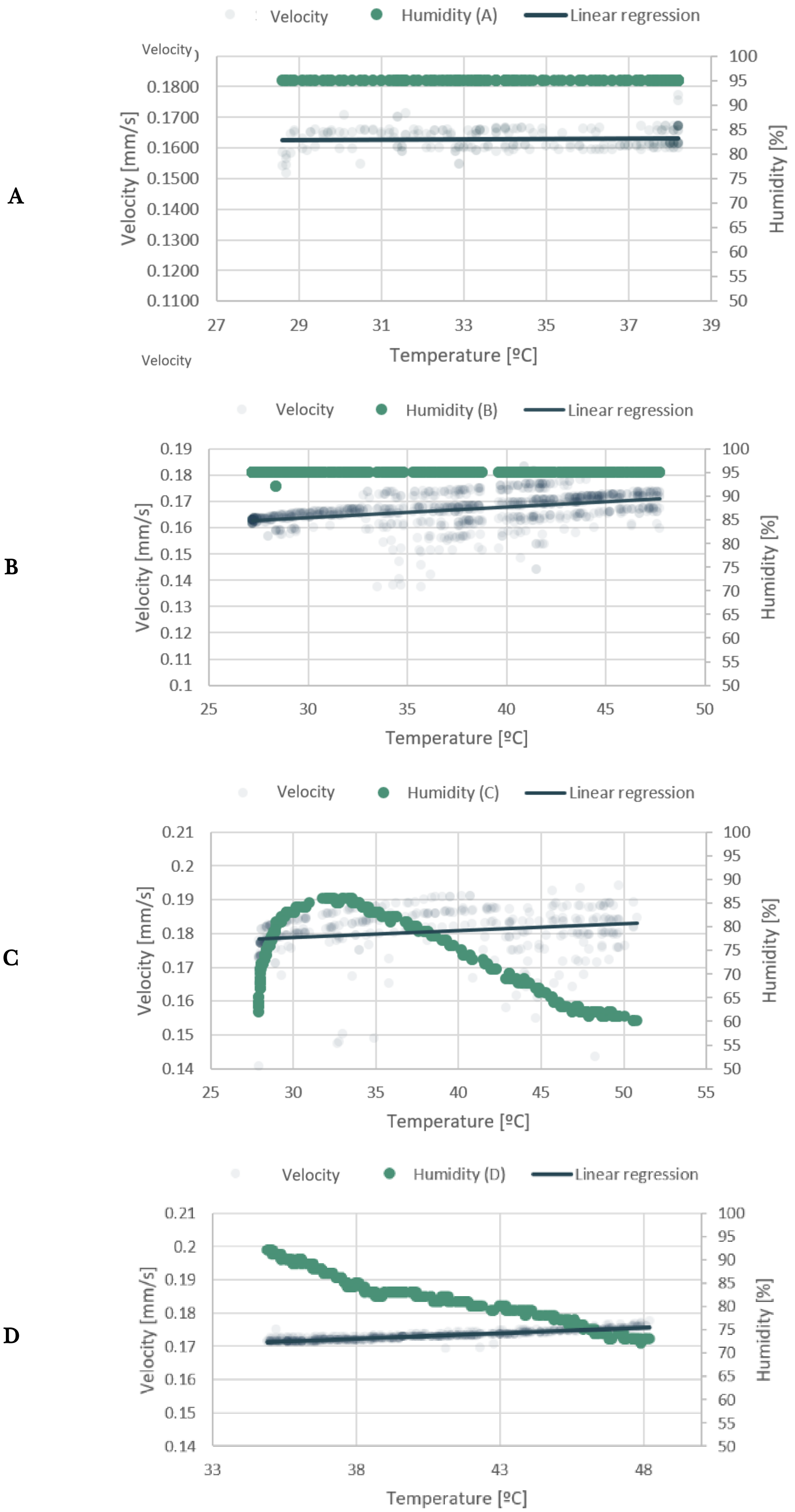

Figure 5. Apparent sound propagation speed and relative humidity as functions of temperature for Tests A–D. Solid lines represent linear regressions fitted to the experimental speed data.

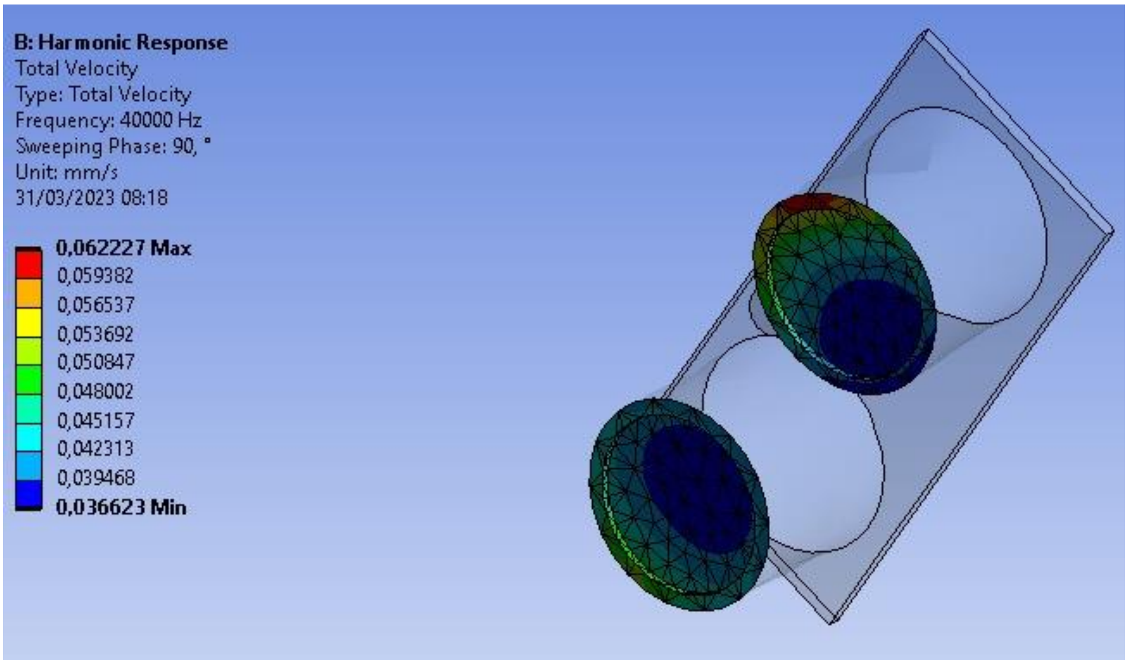

Figure 6. Acoustic particle velocity field obtained from the harmonic acoustic simulation at 40 kHz, illustrating the ultrasonic emission and reception regions.

Discussion

The experimental results indicated that temperature had a dominant effect on the measured sound speed, while the influence of humidity was comparatively negligible. This observation aligns with established acoustic theory, which predicts a square-root dependence of sound speed on absolute temperature. In addition, the experimental results should be interpreted mainly in terms of qualitative trends, since the bench test was developed with low-cost sensors and no formal calibration procedure beyond the manufacturers' specifications was applied.

Additionally, the experimental trends can be compared with previous investigations of environmental effects on acoustic propagation: Liptai *et al.* (2015) evaluated the influence of temperature and relative humidity on atmospheric sound propagation, whereas Hauko *et al.* (2022) investigated sound speed as a function of temperature in both dry and saturated humid air. In the present experiments, temperature showed the clearest association with the measured apparent sound speed, although this result should be interpreted within the limitations of the proposed setup. In contrast, the numerical model did not reproduce the same tendencies observed experimentally. The discrepancy between the numerical and experimental results is mainly related to the simplified numerical assumptions, including the absence of humidity gradients, thermal gradients, convection effects, pressure coupling, and detailed sensor geometry. Therefore, the present numerical model requires further refinement before being used for quantitative validation. Nevertheless, similar challenges have been reported in previous studies, where experimental complexity was not fully captured by simplified finite element models.

Although the present simulation did not correlate directly with the experimental data, the exercise highlights the importance of refining boundary conditions, incorporating multiphysics effects, and validating numerical models against controlled experimental setups. Therefore, the combination of experimental and virtual methods, despite their current divergence, remains valuable for guiding future developments. In this scenario, **Table 1** shows sources of uncertainty and limitations in the experimental and numerical approaches.

Conclusions

The results obtained indicated the variation of SSW under different conditions proposed for the system, thereby partially achieving the experimental objective of observing qualitative trends in the bench test. Throughout four distinct test scenarios, the temperature and humidity within a sealed container were systematically varied. However, the anticipated outcomes from the virtual simulation were not realized, primarily due to limitations in the development of the virtual model. Factors such as sensor emission considerations, intricacies of control volume curves, and the presence of water as a barrier to fluid propagation likely contributed to this discrepancy.

Table 1. Sources of uncertainty and limitations in the experimental and numerical approaches, including their expected impact on the results.

Source / Limitation	Type	Description	Impact on results
Sensor accuracy	Experimental	The precision of the ultrasonic sensor may decrease under high humidity and temperature conditions; temperature and humidity sensors also have limited resolution.	May increase fluctuations in the measured sound speed and reduce the reliability of absolute values.
Sensor selection	Experimental	The HC-SR04 was selected due to low cost and simple integration, but it is not specifically designed for operation in high-humidity environments.	Limits the use of the setup for high-precision measurements under saturated or near-saturated humidity conditions.
Calibration	Experimental	No formal calibration procedure was applied beyond the manufacturers' specifications.	Limits quantitative comparison with theoretical values and reinforces the qualitative interpretation of the results.
Data filtering	Experimental	No advanced signal filtering or moving-average procedure was applied during data acquisition.	May contribute to fluctuations in the experimental curves, especially when echo detection is unstable.
Environmental influence	Experimental	Evaporation of water during tests increased the absolute humidity inside the sealed container, although only relative humidity was recorded.	Makes it difficult to isolate the independent effect of humidity on sound speed.
Measurement repeatability	Experimental	Variations between repeated runs may occur due to manual assembly, sealing conditions, heating rate, and sensor positioning.	May affect the reproducibility of the measured trends between tests.
Pressure coupling	Experimental	Because the container was hermetically sealed, temperature variations may have caused internal pressure variations that were not fully analyzed.	May have influenced the measured sound speed and introduced an uncontrolled variable in the experiment.
Boundary effects	Experimental	The presence of liquid water, container walls, and internal geometry may have caused reflection, scattering, and attenuation of ultrasonic waves.	May alter echo detection and affect the apparent propagation speed measured by the sensor.
Mesh discretization	Numerical	The chosen mesh density affects numerical accuracy, and a full mesh independence analysis was not performed.	Reduces confidence in the quantitative accuracy of the simulated acoustic field.
Boundary conditions	Numerical	Simplified boundary conditions were adopted, neglecting thermal gradients, humidity variation, convection effects, and pressure coupling.	Reduces agreement between numerical and experimental results.
Sensor modeling	Numerical	The detailed interaction between acoustic waves and the actual ultrasonic sensor geometry was not fully represented.	Limits the ability of the model to reproduce the experimental emission and reception process.
Medium properties	Numerical	The numerical model considered simplified air properties and did not include variations in humidity, temperature, or pressure during the tests.	Prevents direct representation of the changing experimental conditions inside the sealed container.
Acoustic velocity interpretation	Numerical	The velocity field obtained in the harmonic acoustics model corresponds to acoustic particle velocity, not directly to the thermodynamic speed of sound.	Prevents direct quantitative comparison between simulated velocity values and experimentally measured sound speed.
Linear acoustics assumption	Numerical	Nonlinear propagation effects were not considered in the harmonic acoustics simulation.	May limit accuracy under conditions where wave interactions, reflections, or boundary effects become relevant.

The main conclusions drawn from this study are summarized as follows:

- SSW increases with rising system temperature: According to Equation 3 for gases, the speed of sound increases as temperature rises, attributable to heightened molecular motion in the gas phase, facilitating faster sound wave propagation. This relationship explains why sound travels faster in the air on warmer days compared to cooler ones (Wells *et al.* 2021).
- In systems where the fluid consists of both air and liquid water, identifying variations in SSW is less straightforward than in systems composed solely of air: The presence of liquid water complicates direct correlations between temperature and sound speed, as air and water exhibit different speed variations with temperature. Additionally, sound can scatter and reflect at interfaces between phases, diminishing the observable speed variation compared to homogeneous air systems (Dou *et al.* 2022).
- Air humidity appears to exert a lesser influence on sound wave propagation compared to temperature: While water vapor, being less dense than dry air, marginally increases sound speed, its effect is minimal compared to temperature's impact. Temperature's stronger influence stems from its direct effect on air molecule kinetic energy, significantly altering sound propagation speed (Yang & Zhu 2021; Xu *et al.* 2021).
- The virtual model's current considerations were insufficient to meet expected outcomes, necessitating further refinement and development.

It is also important to note that, because the container was hermetically sealed, any temperature variation inherently caused a change in internal pressure. Although these pressure data were not fully explored in the present work, they represent a relevant variable and should be explicitly reported and analysed in future studies.

While experimental results followed theoretical expectations regarding temperature effects, though qualitative and not necessarily quantitative analysis; numerical simulations did not achieve full correlation, primarily due to model simplifications. These discrepancies underscore the need for further refinements, including improved boundary definitions, more detailed representation of humidity and temperature effects, and enhanced mesh strategies.

Despite these limitations, this work highlights the potential of low-cost experimental platforms as educational tools for illustrating acoustic theory and supporting preliminary experimental investigations. In conclusion, this study recommends future tests involving controlled pressure variations within the system, as well as experiments focused on determining the optimal dimensions for the control volume. Additionally, exploring different sensor configurations, particularly the emitter and receiver of sound waves, would enhance understanding and accuracy in future studies. Meanwhile, for the virtual simulation, further refinements to the model should include more detailed simulations of sensor interactions, a precise representation of control volume dynamics, and consideration of additional physical phenomena, such as boundary effects and thermal gradients.

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Supplementary material

```
#include <Ultrasonic.h>
#include "DHT.h"
#define pinoTrigger 4
#define pinoEcho 5
#define DHTPIN A5


#define DHTTYPE DHT11 // DHT 11

Ultrasonic ultrasonic(pinoTrigger, pinoEcho);
DHT dht(DHTPIN, DHTTYPE);

 void setup()
{
  Serial.begin(9600);
  dht.begin();
  Serial.println("Tim, Vel, Temp, Hum");
}
 void loop()
{
  float distancia = 200; // mm

  // obtendo tempo de leitura
  float tempo = ultrasonic.timing(); // ms


  float h = dht.readHumidity();
  float t = dht.readTemperature();

  Serial.print(tempo/1000, 4); // s

  Serial.print(",");
  Serial.print(distancia/tempo, 4);
  Serial.print(",");
  Serial.print(t);
  Serial.print(",");
  Serial.println(h);

  delay(1000);
}
```