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ACOUSTIC DESIGN OF A DUAL-PURPOSE SOUND TUBE ORGAN

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ABSTRACT

This paper presents the design and construction of a home-made sound tube demonstrator that doubles as a functional musical instrument. Developed as a pedagogical tool, the prototype aims to introduce children to fundamental musical concepts such as sound production, pitch, and scales. The design process involved validating the instrument's operation as both an open and closed tube, with special attention given to determining the precise tube lengths required for accurate tuning. The study addresses theoretical challenges, such as material selection and tuning techniques, alongside practical considerations to ensure the prototype is both accessible and durable. Acoustic measurements were conducted to validate the theoretical predictions and ensure accurate tuning of the instrument. To assess its educational impact, the demonstrator was tested in a public educational setting, where children engaged with it through guided activities. The results show that the tool helps inspire musical curiosity and makes learning more engaging through hands-on activities. This work highlights the potential of simple, low-cost instruments as educational resources, contributing to both acoustic design and music. The sound tube demonstrator exemplifies how functional hyper-instruments can bridge science and art, inspiring future generations to explore music and acoustics.

Keywords: *Sound tube organ, demonstrator, study, vibrations, education*

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1. INTRODUCTION

From an early age, children develop the ability to quickly identify, differentiate, and reproduce a wide range of sound sequences, including melodies [1]. This is further supported by studies [2–4], which demonstrate that children show a stronger attraction to a more melodic, song-like maternal speech compared to standard speech, showing toddlers to be naturally attracted to music. There is a substantial body of research affirming the importance of musical education in early childhood, highlighting its role in activating essential cognitive processes: music learning engages the mental operations required for young children to perceive and analyze auditory stimuli effectively [5]. It has been shown to enhance memory [6], improve attention and concentration [7], and serve as a powerful means of expression while stimulating imagination in children space [8]. Previous research has demonstrated that rhythmic abilities not only develop rapidly during early childhood but are also closely linked to the development of non-musical skills in cognitive and motor domains [9].

Music has numerous positive effects on a child's development, making it essential to integrate it into their education, with the majority of early childhood educators acknowledging how children prefer music-related activities over non-musical ones [5].

There are many musical instruments suitable for introducing children to the world of music, allowing them to learn in a simple and engaging way. To this end, percussion instruments such as bells, maracas, and triangles are commonly used to teach basic rhythmic patterns, while the recorder (flute) serves as a tool for developing breath control and learning simple melodies.

For this purpose, this work presents a musical instrument designed for children with no prior musical experience. The goal is to introduce them to basic musical concepts such as sound production, scale creation, and the distinction between low and high-pitched tones. For this purpose, a sound tube demonstrator is designed as a simplified pipe organ with eight tubes spanning the octave from C5 to C6. Its intuitive design ensures that anyone, regardless of their musical background, can easily use it to play and explore musical concepts interactively.

The novelty of this work lies in the integration of acoustic design and music education into a single, accessible instrument. The development process involved studying the fabrication of organ pipes, and selecting suitable materials and tuning system. Once constructed, the demonstrator's performance is evaluated by comparing its acoustic output with theoretical expectations. The effectiveness of the tool was demonstrated through an educational session with toddlers, during which various activities and new concepts were introduced and successfully understood by them.

This approach not only bridges the gap between theoretical and practical knowledge, but also provides an innovative tool that fosters creativity and learning in young children, making it a valuable contribution to music pedagogy and acoustic research.

This manuscript is organized as follows: Sec. 2 provides detailed information on the design and construction of the organ tube-like instrument, including the materials, tools required, and budget. Section 3 evaluates the instrument's performance and describes the educational activity conducted with children, demonstrating its effectiveness as a teaching tool. Finally, Section 4 presents the conclusions derived from this work.

2. DEMONSTRATION SYSTEM CONSTRUCTION

This section outlines the design details, materials, and tools used in construction, along with the budget considerations, as well as the challenges encountered during the process and the measures implemented to overcome them.

2.1 Materials and methods

The demonstrator is inspired by the mechanics of a pipe organ. This type of instrument produces sound by channeling pressurized air, or wind, through organ pipes, with each pipe generating a single pitch, typically controlled by one or more keyboards.

Unlike wind instruments powered by lung capacity, pipe organs require significantly higher air pressure and volume [10]. According to [11], an organ consists of several key components, all enclosed within a chest (resonance box), whose design varies based on historical period, craftsmanship, and register size.

- **Windchest with pipes:** The pipes are arranged by note and timbre. A rank consists of pipes that produce the same timbre across all notes. Each key corresponds to a note and can activate different ranks individually or in combination.
- **Wind system:** This includes the blower (air supply), reservoirs, regulators, and wind ducts that maintain stable airflow to the pipes.
- **Control system:** Comprising the keyboard, action mechanism (tracker, pneumatic, or electric), drawstops, and the pallet box, which connects keys to valves, allowing air to flow into the pipes.

Note that our demonstrator is designed as an educational tool to teach toddlers how sound is produced, using this simplified instrument as an example. Several adaptations have been made to achieve this goal:

- The pipes used in this demonstrator are indirect embouchure pipes. In this design, airflow passes through a narrow windway before striking the edge of the embouchure, ensuring sufficient pressure to produce sound. The demonstrator includes only one rank of eight tubes, covering the C5 to C6 scale. This limited size is intentional to suit toddlers' height and interaction ease. Note that not accidentals notes were considered to ease difficulty.
- The wind system replaces a traditional blower with a large balloon. This choice enhances usability for children while making the instrument visually engaging and intuitive to operate.
- The control system omits the keyboard, eliminating the need for a tracker action. Instead, airflow is managed manually via removable washers and a tap, which allow children to open specific pipes directly, fostering hands-on interaction.
- To enhance its educational value, the instrument does not include a resonance chest, leaving all components visible. This transparency helps young learners observe and understand the mechanisms behind sound production.

For the construction of the instrument, the following materials were considered:

- Polyvinyl chloride (PVC) was chosen for constructing the tubes of the instrument due to its affordability, ease of handling, availability in various diameters and rigidities, and the presence of pre-fabricated connection pieces further on the market.
- PVC was also used to create custom washers for sealing the tube bezels and fabricating the end caps of each tube with an eva sheet.
- The instrument is mounted on a handmade wooden plank with openings for each tube, enabling easy assembly and disassembly. This design keeps all components visible, enhancing its educational value.
- Recycled cork stoppers were repurposed to address windcap role.
- An adjustable tap was integrated to control the airflow through the tubes.
- A large balloon was employed as the air source to supply the instrument with consistent airflow.

The tools used to work with these materials included a PVC pipe cutter, a drill with a 8mm bit for creating the beveled hole, scissors for trimming the rest of the bevel, and sandpaper to smooth out imperfections and sharpen the beveled edge. Fig. 1 ilustrates the key components considered in the instrument functioning.

Figure 1. Instrument components, including a tube example (a), cork stopper (b), custom washer (c), tube end cap (d), and wind system with full assembly and tap (e).

When assembled, these parts are configured as depicted in Fig. 2, creating the complete instrument. This setup includes the custom wooden plank, which serves as an "open resonance chest" enabling both structural support and an educationally transparent view of the system.

Figure 2. Organ tube-like demonstrator constructed using the previously presented materials.

Tab. 1 presents a detailed breakdown of the budget required for the construction of the instrument.

Table 1. Detailed budget breakdown for components used in instrument construction

Component	Quantity	Unit price (€)
PVC tube 20mm (3m)	2	2.40
PVC tube 24mm (1m)	1	1.60
L connection	3	0.62
T connection	8	0.62
Nap	1	5.20
Eva rubber	1	0.90
Wood Plank	1	14.00
Balloon	1	2.00
	Total	35.32 €

The affordability of the selected materials and components highlights the accessibility of this solution, ensuring that the demonstrator can be easily reproduced and integrated by educators to introduce musical concepts to children in an engaging and practical manner.

2.2 Instrument Tuning

Pythagorean tuning, attributed to the sixth-century B.C. philosopher Pythagoras, was used as tuning system. It is based solely on the pure fifth (3:2 ratio) found in the harmonic series. This system prioritizes the purity of the fifths, over other intervals, such as seconds and thirds, which become noticeably compromised, which results in harmonically pleasing intervals [12].

To determine the intervals of each note relative to the tonic in Pythagorean tuning, successive additions of pure fifths are calculated within the limits of a single octave. Fig. 3 illustrates the final interval values derived from this method.

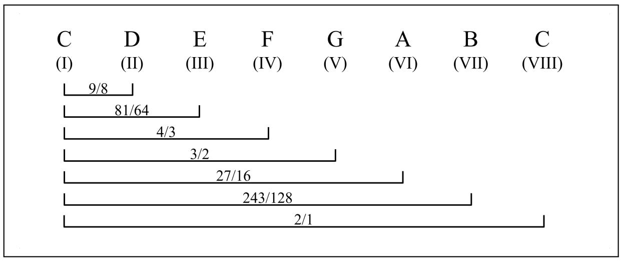

Figure 3. Intervals from each pitch to the tonic in the Pythagorean tuning system.

From this point, using these intervals to the tonic as a reference, the intervals between consecutive pitches are calculated and presented in Fig. 4.

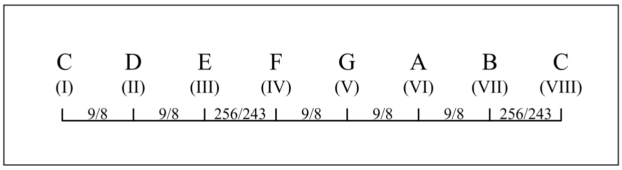

Figure 4. Intervals between consecutive pitches in the Pythagorean tuning system.

This figure illustrates how the Pythagorean scale is constructed using a single type of whole tone (9/8) and a single type of diatonic semitone (256/243).

First, the theoretical frequencies of the eight notes forming the demonstrator were calculated. The chosen system encompasses the octave from C5 to C6, with A5 (880 Hz) serving as the reference point, being the octave above the standard tuning note A4 (440 Hz). Using this reference, the frequency of each remaining tone is determined according to the following (1):

$$f_{\text{note}} = f_{\text{ref}} \cdot \left(\left(\frac{9}{8}\right)^{n_{\text{tones}}} \cdot \left(\frac{256}{243}\right)^{n_{\text{semitones}}} \right) \quad (1)$$

where f_{ref} corresponds to A5 frequency, and n_{tones} and $n_{\text{semitones}}$ represent the number of tones and semitones between the two notes. Note that if the new pitch is lower than A5, both n_{tones} and $n_{\text{semitones}}$ must be negative.

Tab. 2 presents the theoretical frequencies of the notes in the octave from C5 to C6, calculated using the expression outlined earlier.

Table 2. Theoretical frequencies calculated using the Pythagorean tuning system

Tune	Frequency (Hz)	Tune	Frequency (Hz)
C5	521.48	G5	782.22
D5	586.67	A5	880.00
E5	660.00	B5	990.00
F5	695.31	C6	1042.96

Now, tube design is assessed to obtain the target frequencies shown in the previous table. For this purpose, several assumptions are considered [13]:

- The tube diameter is sufficiently large to neglect the effects due to viscosity.
- The tube diameter is small compared to the tube length and the wavelength, λ, produced.
- The surfaces forming the tubes are rigid.

In pipe organs, sound is generated through longitudinal wave motion, where sound waves reflect at the tube ends. The air column is excited by the windway, transferring vibrational energy to the air. The point of excitation is neither a perfect node nor an antinode, leading to a slight inaccuracy in the frequency, which we aimed to adjust through design corrections.

In the tube's length, L, a half wavelength, λ, is produced [14]. The frequency of the harmonic can be calculated knowing the relationship between the frequency of the sound produced, the speed of propagation, and the wavelength using the following expression (2):

$$f_n = \frac{n \cdot c}{2L} \quad (2)$$

where f_n is the frequency of the $n-th$ harmonic, $c = 340m/s$ is the speed of sound in air, and L is the tube length.

Based on this expression, the first sound tube was constructed with a length of 12.7 cm to achieve a frequency of 880 Hz (A5 tune). The tube's length is measured from the end of the bevel to the open end (see Fig. 1.a). Fig. 5 displays the frequency response of the tube when excited.

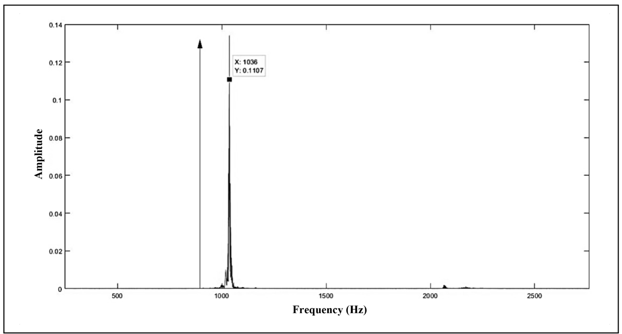

Figure 5. Spectrum obtained from a tube with $L = 12.72$ cm. An arrow is used to indicated the expected frequency of 880 Hz.

In this figure it can be observed the up-cited deviation from the theoretical expected frequency, with an obtained frequency of 1036 Hz when designing the tube to produce a sound of 880 Hz. Therefore, in practice it is observed how tube's length must be slightly lower than the theoretical value computed. This was already assesses in [15] where an approximation of the real length needed L_R is obtained by applying the following expression (3):

$$L_R = L - 3.3r \tag{3}$$

where L is the tube length and r stands for the intern ratio of the tube.

However, an adjustment to the formula is made based on the observed differences. This involves modifying the correction factor in the ratio according to the difference between the measured and expected values, as calculated by the following equations (4)(5):

$$L = \frac{c}{2 \cdot f} \tag{4}$$

$$L - L_R = c_{factor} \cdot r \tag{5}$$

where L is the tube length, L_R is the previously calculated real tube length, r represents the internal ratio of the tube, and c_{factor} is the new correction factor to be applied.

With this in mind, the new corrected tube length L'_R is computed as (6):

$$L'_R = L - 4.6 \cdot r \tag{6}$$

Following the calculations for all the desired frequencies, the resulting length values are presented in Tab. 3.

Table 3. New tube lengths obtained using the fixed equation previously presented.

Tune	Frequency (Hz)	Tube Length L'_R (cm)
C5	521.48	28.90
D5	586.67	25.30
E5	660.00	22.10
F5	695.31	20.80
G5	782.22	18.00
A5	880.00	15.60
B5	990.00	13.50
C6	1042.96	12.60

3. RESULTS AND EVALUATION

This section presents the actual measurements of each of the tubes, providing insight into the performance of the instrument and the details of the educational activity in which the demonstrator was tested with toddlers, illustrating its effectiveness as a pedagogical tool.

3.1 Instrument performance analysis

To test the instrument's alignment with theoretical values, three different types of measurements were considered: individual measurements for each pitch (tube), the intervals with the tonic, and the analysis of the closed tubes (lower octave). For the sound recordings and analysis, MATLAB software [16] was used, with a sampling frequency of 44100 Hz and a bit depth of 16 bits in a monochannel configuration. Each sound was recorded for approximately 5 seconds to ensure that all relevant details of each sound were captured effectively.

3.1.1 Individual tubes measures

The first set of measurements involved assessing each tube individually to examine their fundamental frequency in relation to their length. This approach aimed to validate the accuracy of the expression (6). Fig. 6 presents the spectrum obtained from the Fast Fourier Transform of the audio corresponding to the $C5$ tune.

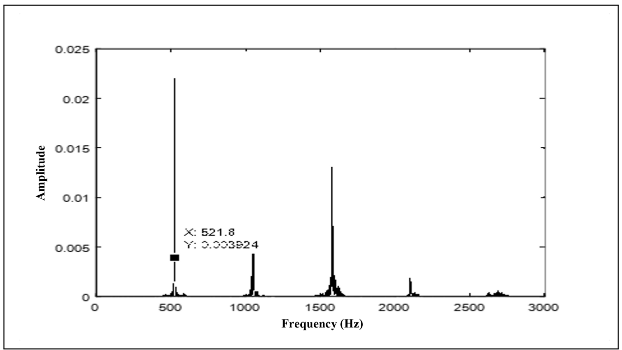

Figure 6. Spectrum obtained from a tube with $L = 28.90$ cm aiming to produce C5 tune ($f = 521.48$ Hz). The fundamental frequency is marked with a pointer.

This figure depicts that the fundamental frequency closely aligns with the theoretical frequency expected. Additionally, three harmonics are present at frequencies of 1044 Hz, 1571 Hz, and 2095 Hz, which correspond approximately to harmonics second to fourth harmonics ($2f$, $3f$ and $4f$). Their amplitudes are significantly lower than that of the fundamental frequency and diminishes as the frequency rises. At higher frequencies, the presence of harmonics becomes more difficult to discern, as expected from a wind instrument.

With this in mind, Tab. 4 presents a comparison between the obtained frequencies and the theoretical values, along with the absolute error in Hertz between them.

Table 4. Theoretical and obtained frequencies comparison, including the frequency error observed.

Tune	Expected frequency (Hz)	Obtained frequency (Hz)	Abs. Error (Hz)
C5	521.48	521.80	0.32
D5	586.67	585.90	0.77
E5	660.00	656.30	3.70
F5	695.31	695.60	0.29
G5	782.22	781.90	0.32
A5	880.00	881.00	1.00
B5	990.00	987.50	2.50
C6	1042.96	1042.00	0.69
		Mean Error	1.23

This table shows that the obtained results closely align with the expected frequencies, with a mean error below 1.25 Hz.

3.1.2 Intervals with tonic measures

The second set of measurements focused on analyzing each interval with the tonic. To present the results, graphs were created to display both the spectrum of the two sounds comprising the interval played simultaneously and each sound individually. This approach seeks to highlight the differences between a chord and the mere addition of two tones. An example is provided in Fig. 7, illustrating the major third interval formed between the notes C5 and E5.

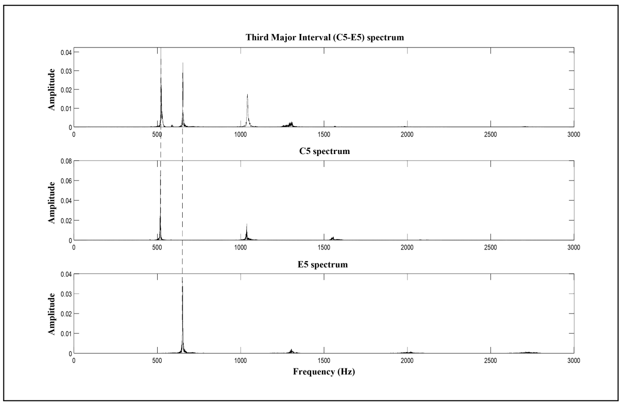

Figure 7. Frequency spectrums of C5 and E5 notes along with the spectrum of the interval formed between them.

The analysis confirms that the excited frequencies correspond to those of each individual tone in the interval. Additionally, alongside the fundamental frequencies, their respective harmonics are also excited. This behavior is consistent across all intervals, showing a similar trend to the findings in the previous section: as frequency increases, the number of generated harmonics decreases.

Furthermore, the spectral analysis reveals that the spectrum of an interval played as a chord is nearly identical to the sum of the spectra of its constituent tones. It was also observed that, depending on the interval, some harmonics of the individual tones may overlap in frequency, resulting in an additive effect. These findings highlight the predictable harmonic structure of the instrument and its intervals.

3.1.3 *Closed tubes measures*

Unlike open pipes, in a closed pipe, a node is formed at the closed end while an antinode occurs at the open end. Consequently, the wavelength in a closed pipe is twice that of an open pipe [14]. From the relationship between λ and f, the harmonics in a closed pipe are given by expression (7):

$$f_n = \frac{(2n-1) \cdot c}{4L} \tag{7}$$

where c is the speed of sound, L is the length of the pipe, and n represents the harmonic order. Note that only odd harmonics are present in closed pipes due to the boundary conditions at the ends.

However, since the tubes were specifically constructed to meet the design criteria for open pipes, the frequencies obtained through this method deviate significantly (mean value error of 4.85 Hz) from the ideal values, which should correspond to half the fundamental frequencies of the previous measurements (lower octave). Given the instrument's intended use as an educational tool, these deviations in frequency are considered acceptable. To achieve more conclusive results, the tube design would need to be adjusted to align with these new frequency requirements.

3.2 Educational activity

The ultimate purpose of constructing this demonstrator is its pedagogical use. It aims to help children understand how air is transformed into sound and how this sound depends on the size of the tubes. To evaluate its effectiveness, the demonstrator was presented at Colegio Enrique Tierno Galván in La Zubia (Granada) to a group of 5-year-old students.

The demonstration started by discussing musical instrument families—percussion, string, and wind—with examples like a tambourine, guitar, and recorder. Students then categorized other instruments and learned about the musical scale, writing and singing an octave from C5 to C6. Concepts like “low” (thick sound) and “high” (thin sound) were introduced.

The demonstrator was used to show how air turns into sound, starting with inflating a large balloon to capture toddler's attention. Playing the scale on the demonstrator, students observed that lower pitches came from larger tubes and higher pitches from smaller ones. They then took turns playing the demonstrator themselves, reinforcing the relationship between tube size and pitch.

The activity concluded with a recap of the concepts and another group performance of the scale. Fig. 8 shows three students interacting with the demonstrator.

Figure 8. Photograph taken during the musical instrument demonstration, showing students interacting with the demonstrator.

This activity was evaluated by the class tutor, who validated the tool's effectiveness and the achievement of its intended objectives. The demonstration proved its value as an educational resource for introducing young children to the physics of sound.

4. CONCLUSIONS AND DISCUSSION

This work presented a pipe organ demonstrator designed to illustrate sound production in open and closed pipes, enabling the study of vibration modes and the frequencies they produce. A comprehensive analysis of potential materials was undertaken, with PVC ultimately selected for its cost-effectiveness, availability, and recyclability, making the demonstrator an affordable tool for educational use.

The Pythagorean tuning system proved effective in demonstrating harmonic relationships in tuned intervals (2nd, 4th, 5th, and 8th) and inharmonicities in untuned intervals (3rd, 6th, and 7th). Adjustments were made to the tube length formula based on experimental data, improving the design's accuracy.

A thorough validation process was conducted to confirm the instrument's performance, with frequencies aligning closely with expectations for open pipes. While discrepancies in the closed-pipe configuration were observed, they were deemed acceptable for educational purposes, with a redesign necessary for precise implementation.

The demonstrator's effectiveness as a pedagogical tool was validated through a hands-on activity with 5-year-old students. Despite no prior musical knowledge, students successfully learned the musical scale and the relationship between pitch and pipe size. While the demonstrator could benefit from further refinement in certain areas, it has proven to be an effective and valuable tool for educators to introducing young learners to the basic principles of music and acoustics.

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