The Aerophone Kit:
A Toolkit for Pneumatic Musical Instrument Design

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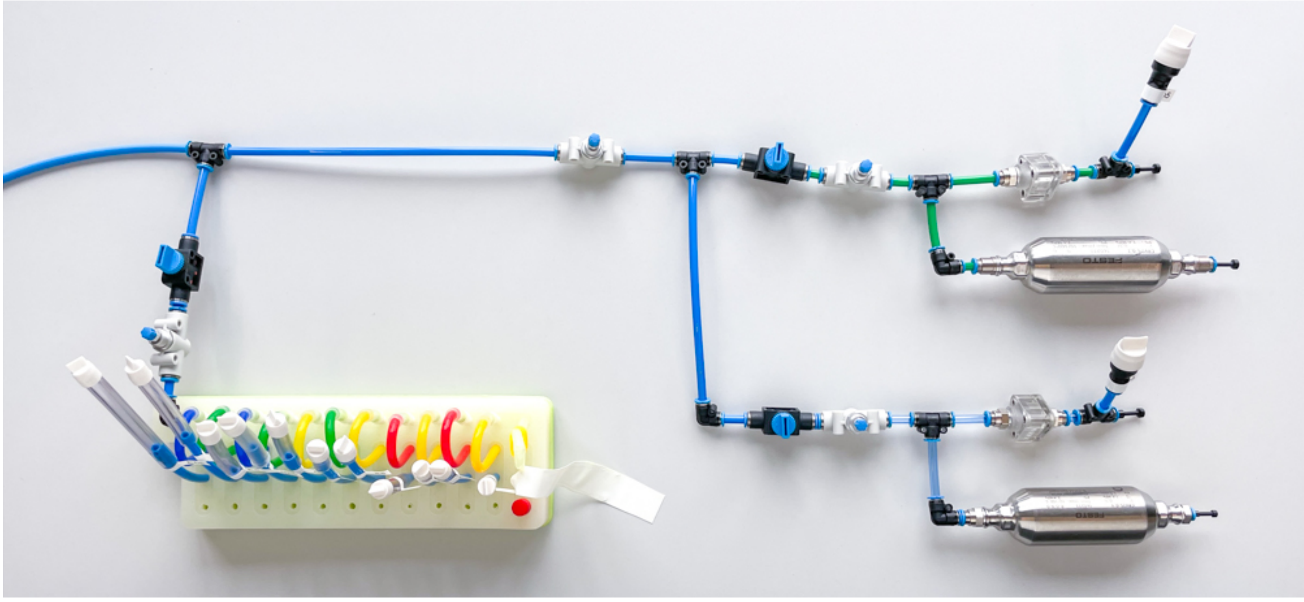

Figure 1: The automated pneumatic circuit with keyboard (left) and oscillators (right).

Abstract

We present the *Aerophone Kit*, a modular toolkit for designing pneumatic musical instruments that operate through air-pressure circuits without electronic or digital components. The system emerged from laboratory observations in which pneumatic circuits developed for soft robotics research produced rhythmic and tonal sounds. The *Aerophone Kit* consists of modular elements that can be configured to create bespoke musical instruments, including pneumatic keyboards and autonomous pneumatic oscillators. The toolkit enables tactile musical interaction through the direct manipulation of air pressure. This paper presents the system architecture, the acoustic characterization of whistle-based sound generation, and two prototype configurations that illustrate melodic and autonomous sound behaviors. We further report on a structured user study with ten participants (five musicians and five non-musicians), examining learnability, control, and exploratory engagement through hands-on interaction. Findings are reported following inductive thematic analysis of interviews and interaction observations, supported by survey responses. Together, these findings suggest that pneumatic logic offers a viable and musically expressive approach to instrument design, contributing a material-centered perspective to the ongoing NIME discourse on embodied musical interaction.

Keywords

Pneumatic, Modular, Toolkit, Fluidic Logic, Embodied Interaction, Soft Robotics, Musical Instrument Design

1 Introduction

Scientific research laboratories can become rich environments for sound exploration. The acoustic byproducts of experimental systems may reveal sonic behaviors that were not originally intended as musical output. However, they can form the basis for new musical interactions.

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During the development of a soft robotics oscillator, we observed that popping pneumatic domes produced rhythmic patterns similar to drumbeats, while one-way valves generated whistle-like tones. These observations formed the conceptual starting point for the *Aerophone Kit*. Rather than relying on electronic or digital components, the *Aerophone Kit* operates entirely through air-pressure circuits and pneumatic logic. The system treats airflow not only as a means of actuation and control, but also as a sound-producing material. The *Aerophone Kit* combines pneumatically programmable loops [13] with modular building blocks to support the design of a range of instruments, including pneumatic melodic interfaces and autonomous oscillators.

This paper presents the design principles, technical implementation, and acoustic characterization of the *Aerophone Kit*, alongside two initial prototypes that demonstrate melodic and autonomous sound behaviors: the pneumatic keyboard and pneumatic oscillators (Fig. 1). These prototypes represent an early stage within a broader design space, serving as reference implementations rather than an exhaustive set of modules.

We further report on a structured user study in which musicians and non-musicians engaged with pneumatic sound generation using the toolkit, investigating learnability, control, and exploratory interaction. Together, these contributions provide an overview of the system's capabilities and offer insight into how pneumatic logic circuits can support embodied musical interaction and expression.

Our core contributions to the NIME community are as follows:

1. **Conceptual**: A fully pneumatic approach to musical instrument design based on fluidic logic circuits, emphasizing physical causality and material behavior.
2. **Technical**: A modular pneumatic toolkit composed of interoperable physical components analogous to electronic synthesizer modules.
3. **Empirical**: A qualitative study of how musicians and non-musicians engage with pneumatic sound generation through hands-on configuration and interaction.

2 Related Work

Automated and Programmable Instruments. Before the adoption of electronic and digital technologies, automated musical instruments relied on ingenious mechanical systems for sound production and control [8]. Well-known examples include the music box, in which a pinned barrel excites metal tines to produce melodies [2], as well as the barrel organ and the player piano, which use pinned barrels or perforated paper rolls as mechanical memory [18]. Yet another example is the hydraulophone, an acoustic musical instrument that produces sound using pressurized water jets, often described as an underwater pipe organ [11]. While these instruments are often pneumatically powered, their control logic is fundamentally mechanical rather than pneumatic.

The introduction of clockwork mechanisms enabled timed musical output, as seen in musical clocks and church carillons that play pre-programmed tunes at specific moments [8]. With the advent of analog and later digital electronics, new forms of programmable instruments emerged, including sequencers and drum machines that could repeat and vary musical patterns [14]. These systems increasingly framed musical control in terms of symbolic representations and discrete parameters, such as note values, timing grids, and numerical control settings, rather than through continuous physical processes [10].

The *Aerophone Kit* belongs to this lineage of automated instruments but relies on pneumatic logic rather than mechanical, electronic, or digital control. Instead of encoding musical structure in fixed mechanical memory or digital sequences, it allows musical behavior to emerge from airflow, pressure dynamics, and circuit configuration.

Pneumatic and Fluidic Instruments. Within the HCI community, pneumatic and fluidic systems have long been explored as alternatives to electronic interfaces, offering different interaction modalities and material properties. A number of toolkits and platforms have been proposed to support the design of pneumatic interfaces, actuators, and sensors [4, 6, 7, 16, 17, 20–22]. Of particular relevance is the Fluidic Computation Kit [9], which demonstrates how logic gates and computational circuits can be realized entirely through fluidic components, including one-way valves, flow restrictors, and air reservoirs.

Pneumatic interfaces are also closely related to research on shape-changing and deformable interfaces, where compliance and material responsiveness play a central role in user experience. Such systems can adapt to the user's body, provide rich haptic feedback, and support expressive interaction beyond rigid mechanical controls. In musical contexts, these qualities have been explored in interfaces such as Airpinch, a pneumatic touch fader providing haptic feedback through fingertip air pressure [5], and the Pneumatic Practice Pad, a drum interface with dynamically adjustable stiffness [15].

While prior work has explored pneumatic actuation, haptic feedback, and interaction, comparatively little research has examined pneumatic logic as a modular and programmable framework for sound generation and musical structure itself. The *Aerophone Kit* builds on this underexplored area by treating pneumatic circuits not only as actuators, but also as sound-generating and sound-shaping frameworks. By combining pneumatic logic with musical sound production, the *Aerophone Kit* positions pneumatic interaction as a central musical material rather than solely as a control modality.

3 The *Aerophone Kit*

3.1 System Architecture

The *Aerophone Kit* consists of a set of modular pneumatic components, including oscillating valves [19], air reservoirs[1], flow control valves[2], whistles, and connector elements[3] (Fig. 2). These components can be freely combined to build a wide variety of pneumatic circuits, each exhibiting distinct sound behaviors. The modular architecture allows musicians and instrument designers to iteratively assemble, modify, and reconfigure circuits without predefined signal paths or control hierarchies.

Sound generation in the *Aerophone Kit* is primarily achieved through whistle modules that span two octaves (24 semitones). These whistles can be precisely tuned through variations in tube geometry and valve characteristics, supporting both conventional and microtonal pitch systems. Additional pneumatic elements, such as air reservoirs and resistive tubing, shape the temporal and dynamic behavior of the system by influencing pressure variation and airflow.

The pneumatic circuit used in the *Aerophone Kit* can be understood through an analogy to electrical circuits, where air pressure

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[1] Festo: CRVZS-0.1

[2] Festo: GR-QS-6

[3] Festo: QS-6, QSL-6

Figure 2: Overview of the main modular pneumatic components used in the *Aerophone Kit*. Lrtb: flow control valve, oscillator, T and L connectors, whistle, air reservoir, flow control valve, plug, flag.

corresponds to voltage and airflow corresponds to electrical current [12]. In this analogy, the pump that supplies positive pressure functions as the positive terminal of a voltage source, while ambient atmospheric pressure serves as the ground. Air expelled from the circuit returns to the environment and is drawn back into the inlet port of the pump.

It is worth noting that, although we use the fluidic-electronic analogy here to explain and predict our air circuits, it bears some conceptual limitations. For example, our fluidic capacitors allow air to flow through, whereas their electronic counterparts do not allow current to pass through in direct current circuits. Similarly, we do not take into account the compressibility of air or the influence of turbulence, which do not have an equivalent physical analog in electronics under standard operating conditions. Nevertheless, electronic and pneumatic terminology may occasionally be used interchangeably throughout the paper. An overview of the terminology mapping is provided in Table 1.

Electrical Term	Pneumatic Term
Voltage	Pressure
Current	Airflow
Voltage source	Pump
Capacitor	Air reservoir
Resistor	Flow restrictor
Diode	One-way valve
Ground	Ambient atmospheric pressure

Table 1: Mapping between electrical terms and their pneumatic equivalents as used in the *Aerophone Kit*.

Within this framework, flow control valves act as variable resistors, narrow tubing functions as fixed resistive elements, and air reservoirs behave similarly to capacitors by storing and releasing pressure, thereby smoothing pressure fluctuations over time. One-way valves, here implemented through the use of sleeved duckbill valves[4], operate analogously to diodes by permitting airflow only in a single direction. Notably, these silicone one-way valves also act as sound-producing elements. As air passes through them, the valve membranes vibrate, generating whistle-like tones that form the basis of the whistle modules used throughout the system.

Certain configurations of air reservoirs, flow restrictors, and one-way valves can produce periodic pressure oscillations within the circuit. In addition to these oscillatory behaviors, the *Aerophone Kit* includes custom-made pneumatic flags: thin, flexible elements placed within the airflow path. When air flows through the flag membranes, it begins to flap due to the interplay between gravity pulling the flag material downwards and the air pushing it upwards. This flapping introduces continuous, flow-dependent variations in pressure and airflow, resulting in modulation effects such as vibrato-like changes in pitch or amplitude through dynamic changes in the fluidic resistance of the component. These behaviors arise directly from the physical interaction between airflow and material properties rather than from explicit control signals. Further details on programmable pneumatic logic circuits can be found in [13].

Plugs are used to seal open ports in the circuit, preventing unintended pressure loss and enabling controlled airflow routing. Through selective sealing, users can sustain individual tones or activate multiple whistles simultaneously.

3.2 Acoustic Properties

This section examines the acoustic properties of the *Aerophone Kit*, focusing on whistle-based sound generation and the influence of the produced signals on pneumatic operating conditions. Rather than aiming for exhaustive physical modeling, we characterize the system to support consistent tuning, informed design, and potential musical applications.

3.2.1 Physics of the whistle. The whistle is the primary sound-producing element in the *Aerophone Kit*. It consists of a cylindrical tube, in some configurations composed of two interconnected segments with different inner diameters, and a silicone one-way valve mounted on top (Fig. 3b). When air flows through the valve, the valve membranes vibrate, producing a sustained tone.

Acoustically, the whistle functions similarly to a double-reed instrument, with the two valve membranes acting as reeds, approximated as a closed cylindrical pipe: the valve opening behaves as a closed end, while the lower end of the tube remains open. We define the length of the tube as l, with l_1 corresponding to the tube with diameter d_1 and l_2 corresponding to the tube with diameter d_2. The width of the silicone one-way valve is defined as x. Two whistle variants were evaluated: one consisting of a single tube diameter and one consisting of two tube diameters connected in series. Based on empirical observation and experimental characterization, we identify four primary parameters that influence the pitch of the whistle (Fig. 3b): tube length (l), tube diameter (d), valve material stiffness (shore hardness), and the effective tension of the vibrating valve membranes.

Following these observations, we propose a simplified model describing the fundamental frequency produced by the whistle. In this model, pitch is primarily determined by the effective resonant length of the air column, modulated by the vibrational behavior of the silicone valve membranes. The sound generation mechanism results from two concurrent physical principles.

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[4] Sourced from Minivalve at www.minivalve.com

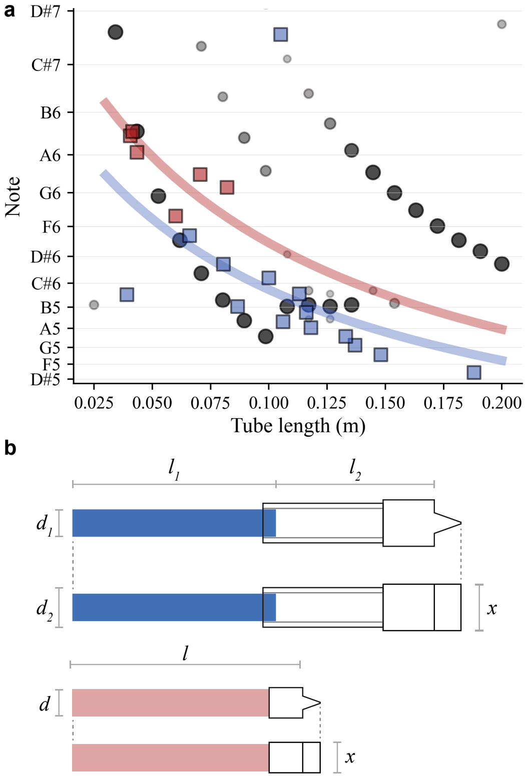

Figure 3: a) Experimental (squares) and fit (solid lines) for the different whistles. The black dots are the results of the pneumatic numerical simulations, and refer to the multiple resonant frequencies for the same tube length. b) Schematic representation of the two types of whistle used in the *Aerophone Kit*. Top: whistle consisting of two different inner tube diameters (d_1, d_2). Bottom: whistle consisting of a single inner tube diameter (d). The size of the silicone one-way valve is defined by its width (x).

First, the length of the tube provides characteristic resonant frequencies through a mechanism similar to that of open pipes (i.e., flutes). The diameter and length of the tube determine the fluidic capacitance. This capacitance dictates the ranges of airflow that, in the absence of the duckbill valve, generate certain frequencies in the output.

Secondly, the elastic behavior of the silicone membrane provides a time-varying fluidic resistance. When considered together, the stiffness of the silicone in the duckbill valve, the input flow, and the fluidic capacitance of the tube all introduce a characteristic time scale that is compatible with the sound waves generated by the whistle elements we study. We perform a numerical integration over the modeled system and compare the simulation results with the experimental data in Figure 3.

As the mixing and emergence of time scales (i.e., sound frequencies) are strongly non-linear, we rely on numerical simulations to interpret and predict the behavior of the system within our experimental conditions. Thus, the model serves as a guide for tuning and design rather than as a complete physical description of the coupled airflow and membrane dynamics.

3.2.2 Pitch, Amplitude, and Timbre Variability. Beyond static geometric and material parameters, the acoustic behavior of the whistle is significantly influenced by operating conditions, particularly air pressure and airflow rate. Increasing airflow generally raises the energy driving membrane vibration, which can result in a higher amplitude and, in many cases, a perceptible increase in pitch. At moderate flow rates, the whistle produces a stable tone with a clear fundamental frequency. As flow increases further, additional harmonics emerge, and the sound may transition toward a brighter or noisier timbre. At higher pressures, the system can exhibit increased instability, including pitch fluctuations, delayed onset, or transitions between oscillatory and sustained regimes. These transitions tend to occur gradually, enabling users to shape pitch, amplitude, and timbre continuously through physical interaction with airflow and pressure conditions.

3.2.3 Temporal Variability. The temporal behavior of the *Aerophone Kit* reflects the physical dynamics of pneumatic circuits. Pressure propagation delays, air reservoir volumes, and valve material properties introduce timing variations that influence onset, sustain, and rhythmic stability. Rather than producing perfectly periodic behavior, the system often exhibits temporal fluctuations. At lower pressures and moderate flow rates, whistle tones tend to be temporally stable, producing sustained sounds with relatively consistent amplitude. As pressure and flow increase, small pressure variations may accumulate over time, resulting in gradual tempo drift or evolving rhythmic patterns. Wear and creeping of the cut in the duckbill valve can introduce slow, long-term changes in timing and timbre, causing the sonic output to evolve during extended use. Rather than being treated as imperfections, these variations form an integral part of the musical behavior of the *Aerophone Kit*, supporting expressive and organic modes of interaction.

3.3 Initial Prototypes

Designing meaningful musical instruments based on this system requires further research and extended interaction time. However, to demonstrate how the *Aerophone Kit* works, we developed and explored two preliminary prototypes that can be combined into one configuration (Fig. 4). These prototypes are not intended as exhaustive designs, but as illustrative examples that highlight different aspects of pneumatic sound generation and interaction. The same configurations were used during the user study to provide a consistent basis for exploration and evaluation.

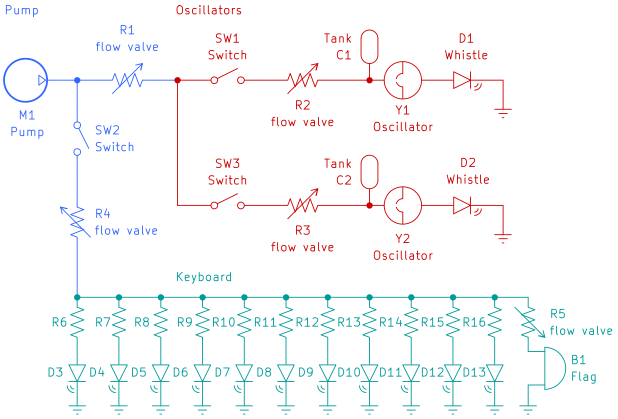

Figure 4: A schematic overview of the two main prototypes built with the *Aerophone Kit*: a pneumatic keyboard with oscillators, all powered through a single pump.

3.3.1 Pneumatic Keyboard. The pneumatic keyboard design was based on a modular, breadboard-like approach commonly found in electronics. The open holes in the keyboard allow users to place the whistles in any order they like, as well as double up whistles or insert plugs to create drone sounds (Fig. 5). The long, rectangular shape of the keyboard was inspired by piano-like key layouts, with the open holes functioning as piano keys. By choosing a modular, breadboard approach, keyboards can also be daisy-chained to create a wider keyboard or different keyboard layouts. The keyboard configuration supports melodic interaction by allowing users to directly control airflow to tuned whistle modules. It consists of a set of air channels connected to individual whistles, each of which can be opened or closed by the user through physical interaction, such as (partially) covering or uncovering openings with their fingertips. The keyboard supports two octaves of tuned whistles and can be reconfigured to accommodate alternative and microtonal tunings by rearranging tube lengths or whistle assignments.

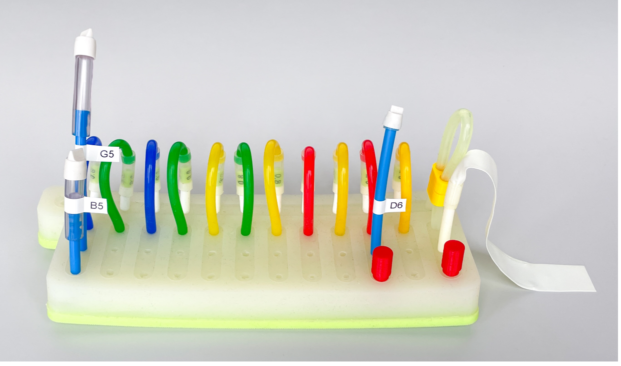

Figure 5: The pneumatic keyboard showing two modes for creating sustained sounds. Left: two whistles (G5 and B5) placed in the same column. Right: whistle (D6) and plug placed in the same column.

3.3.2 Pneumatic Oscillator. The pneumatic oscillator generates autonomous sound through recurrent pressure build-up and release within the circuit. Combinations of air reservoirs, flow restrictors, and one-way valves produce periodic pressure fluctuations, resulting in rhythmic sound patterns. Under specific configurations, the same circuit can transition from discrete rhythmic output to a sustained airflow state, producing continuous tones instead of pulses. This transition arises from the interaction between pressure accumulation, valve response, and airflow conditions rather than from an explicit mode switch. Small adjustments in component values or airflow routing can therefore lead to qualitatively different sonic behaviors within the same pneumatic logic structure. The pneumatic oscillator and keyboard configurations can be combined within a single circuit, allowing sustained or melodic tones to be layered with autonomous rhythmic patterns. Because the system operates from a shared airflow source, changes in one part of the circuit can influence pitch stability, amplitude, and temporal behavior elsewhere. Limited airflow capacity means that extensive openings of flow paths may reduce pressure stability, highlighting the interconnected nature of the pneumatic network. Together, these prototype configurations illustrate how the system supports both direct user interaction and autonomous sound generation, forming the basis for the structured user study described in the following section.

4 Study

We conducted a structured user study to investigate how musicians and non-musicians engage with pneumatic sound generation using the *Aerophone Kit*. The study examined how participants explored relationships between physical configuration and sonic outcomes, including their interaction processes and perceived control. The aim was to generate empirical insights into the usability and expressive potential of pneumatic instruments while informing future design iterations through observed interaction patterns and participant feedback.

4.1 Participants

Ten participants (four female and six male) took part in the study, subdivided into five musicians and five non-musicians. Participants self-identified their musical backgrounds prior to the study. All participants were students or staff at a technical university in Northwestern Europe and were recruited through convenience sampling. All participants provided written informed consent prior to participation.

4.2 Procedure

Sessions were conducted individually and lasted approximately 45 minutes. Participants were seated at a desk on which the components of the toolkit were laid out. A camera recorded participants' hands and interactions with the system. A standardized protocol was used to ensure consistent conditions across sessions. Participants were encouraged to think aloud throughout the study and were informed that they could freely explore the system without concern about damaging the components. During the user study, the system was powered by an electrical air compressor to ensure a stable and continuous air supply across sessions.

Each session consisted of four phases:

1. **Introduction (10 minutes).** Participants were introduced to the *Aerophone Kit* and guided through a structured tutorial, during which they assembled basic configurations and explored the effects of airflow control elements. This phase familiarized participants with the main components of the *Aerophone Kit*, including whistles, flow control valves, switches, and oscillating circuits.
2. **Challenges (10 minutes).** Participants completed two structured tasks: (1) creating different sound combinations using the pneumatic keyboard by rearranging whistle configurations, and (2) generating rhythmic patterns using the pneumatic oscillator circuits. These tasks were designed to evaluate participants' understanding of sound generation and control within the system.
3. **Free Play (10 minutes).** Participants were invited to explore the *Aerophone Kit* without specific goals, allowing for open-ended interaction and experimentation with sound, configurations, and behavior.
4. **Evaluation (15 minutes).** Participants completed a post-test survey followed by a semi-structured interview. The survey used 7-point Likert-scale questions to assess perceived enjoyment, intuitiveness, predictability, and ease of use. To capture first impressions, the survey was limited to two minutes. The interview explored participants' experiences with the system, including sound qualities, interaction strategies, and component combinations.

4.3 Data Collection and Analysis

Data collected during the study included video recordings of participants' interactions with the *Aerophone Kit*, think-aloud verbalizations, audio recordings of semi-structured interviews, written survey responses, and researcher observations. Interviews were transcribed using edited transcription, removing repetitions and interruptions while preserving meaning.

Qualitative data were analyzed using inductive thematic analysis [1] and coding with Taguette[5]. To improve inter-rater reliability, the guidelines provided by [3] were followed. An initial coding scheme was developed by researchers 1 and 2 in consultation while coding the first two transcripts. This coding scheme was refined through iterative reviews of the data. Both researchers then independently coded the remaining dataset based on the agreed-upon scheme. Researcher 3 subsequently reviewed all coded transcripts and consolidated any remaining disagreements.

5 Preliminary Results

This section reports findings from the user study, combining observations from the tutorial, challenges, and free play phases with post-test survey responses and interview data. Results are organized around three recurring themes that emerged during the thematic analysis of interview transcripts: (1) *experiential qualities*, describing how participants engaged with the system; (2) *sound exploration*, reflecting how participants produced and shaped sound using the pneumatic keyboard and oscillators; and (3) *system understanding*, documenting how participants interpreted, evaluated, and made sense of the system's behavior.

All participants were able to produce sound during the tutorial phase, and most successfully completed the guided exercises. This suggests that initial engagement with the system was accessible for both musicians and non-musicians. During the challenges and free play, participants explored different melodic configurations by rearranging whistle components and adjusting airflow resistance. Musicians tended to arrange the whistles in more conventional ways (e.g., from low to high note), whereas non-musicians favored the tube's shape and color.

Although the pneumatic keyboard was generally perceived as intuitive, generating rhythms using oscillators proved to be more challenging. Most participants reported difficulty predicting rhythmic outcomes or controlling oscillator interactions, indicating that temporal behavior required a deeper understanding of the system. Post-test survey results reflect this ambivalence: while the pneumatic keyboard was rated as enjoyable and easy to learn, predictability and rhythmic control with the pneumatic oscillators received comparatively lower scores (Fig. 6).

5.1 Experiential Qualities

Most participants (P1–8, P10) noted their enjoyment when interacting with the *Aerophone Kit*, particularly with the pneumatic keyboard. At the same time, several practical limitations were highlighted. The noise produced by the air compressor was mentioned as distracting (P1–2, P9), and some participants noted the need to pay attention to the available air pressure while configuring the system (P1, P3). Two participants (P2, P9) reported that they found it difficult to musically integrate the oscillators into the *Aerophone Kit* circuit. Others (P3–4, P6–8, P10) described difficulties in learning to use the oscillators, even when the components were technically operational. Three participants (P1–2, P9) specifically highlighted the tangibility of the components. They mentioned how this increased their enjoyment while making it easier to understand how the system operates (P1).

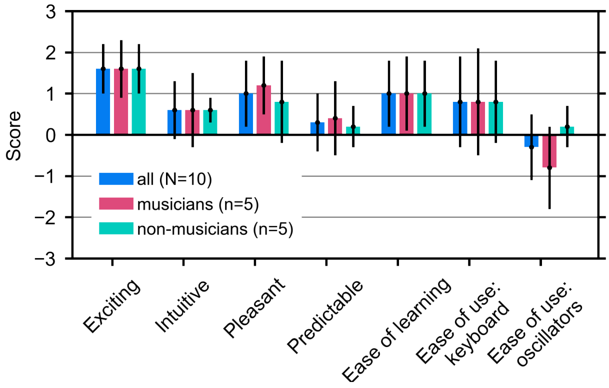

Figure 6: The survey results. The responses on the 7-point Likert scale are transformed to a -3 to +3 scale to more clearly visualize positive and negative outcomes. The error bars indicate the 95% confidence interval.

In terms of aesthetics and design, participants frequently noted the system's playful look (P3, P5–6, P8). They also indicated that the keyboard and oscillator parts of the system looked discrepant (P3–4, P6, P10), with some mentioning that the oscillator part looked more 'technical' (P5), 'industrial' (P2), 'unfriendly' (P8), and followed the 'brutalism' style (P6). Interestingly, some participants (P6, P8) were curious about the colors of the flow restriction valves on the keyboard, which had been randomly chosen.

Finally, the freedom offered by *Aerophone Kit* was appreciated by five participants, mainly because it increased exploration and creativity (P5, P7, P9, P10) and allowed new component configurations that suited the user's needs (P1, P2, P5).

5.2 Sound Exploration

Participants explored sound through system configuration, active listening, and iterative adjustment, such as manipulating flow restriction valves and adjusting the pneumatic flag to investigate how airflow routing affected pitch stability, amplitude, and tempo.

The first notable aspect is how they arranged the whistles. Most ordered them from low to high pitch, while some (P1, P5, P8) organized them to match a melody in mind, prioritizing spatial distance over tonal relationships. Other participants focused less on discrete melodies and more on sustained or evolving sounds. They used plugs to maintain airflow to selected whistles, creating drone-like tones. In some cases, participants (P3, P9) redirected whistles toward nearby objects to dampen the sound or removed them entirely to keep only the raw popping.

To illustrate the modular flexibility of the system, we highlight an unconventional configuration introduced by P9, who connected the output of the pneumatic oscillator to the keyboard input (Fig. 7). Repurposing it from a primary sound source to a modulation tool enabled further sonic explorations, including rhythmic chords and slowly evolving sounds.

Descriptions of the sound qualities of *Aerophone Kit* varied greatly among participants. The oscillators were generally found to be sharper and harsher sounding (P3, P6), while the keyboard whistles were often described as "too high pitched" (P3, P4, P6, P8), "piping" (P9), "annoying" (P8, P9), or "toy-like" (P5). P3, P6, and P10 suggested adding lower notes to the *Aerophone Kit*.

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[5] https://app.taguette.org/

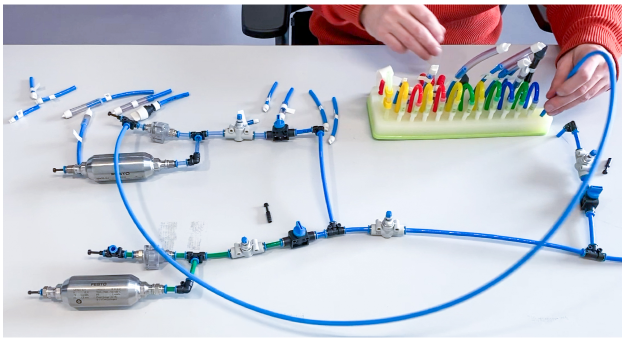

Figure 7: Pneumatic oscillator in P9's setup used as an airflow modulation unit for the keyboard circuit.

Participants noted some limitations of the system, such as "I can only use this stuff to play an okay song." (P7), and "The short [scale] you have right now, I don't think it's enough to play like big pieces, like children's songs, for example, you can play." (P6).

5.3 System Understanding

Beyond producing sound, participants developed interpretations of how the *Aerophone Kit* worked as a physical instrument, often emphasizing its material character. For example, P1 noted, "I like the physicality of it," and remarked that "the physical part adds, makes it easier to understand what's happening." Others described the system as "unpredictable" (P2) due to its non-deterministic pneumatic behavior.

Many participants found the keyboard easier to learn than the oscillators. P7 described the interaction as "quite fun, but a bit difficult," and P3 noted that it was "very difficult to make it sound nice," particularly when working with the oscillators. This is likely due to the fact that the oscillators are sensitive to slight changes in airflow. This, combined with the interconnectedness of the system, means that increasing the airflow to the keyboard could easily disrupt a previously established oscillator rhythm.

While interacting with the system, participants often referred to other instruments, such as a keyboard/piano (P1–2, P8), wind instruments (P1, P4, P8, P9), guitar (P3, P4), melodic percussion (P2, P6), sequencer (P1, P9), or instrument categories like electronic and digital instruments (P1–3). This analogy was often based on the way in which the pneumatic keyboard was played (like a keyboard, piano, or even xylophone), but also on the way it sounds (like a high-pitched keyboard, synthesizer, organ, or small wind instrument). The oscillators were often linked to sequencers or drums. P3 described this experience as follows: "the workflow was very fun and very much reminded me of like a modular synthesizer system [...] but it also hindered me in some ways because some things don't work as I expect them to from the pre-knowledge of having a modular synthesizer." These insights show that participants' previously established mental models may influence their understanding of the system and the way they interact with it.

Participants also responded differently to the system's temporal and pitch variability. Some initially described these fluctuations as unpredictable or difficult to manage. P3, for instance, remarked, "I found it difficult to really create something," while P10 noted that it was "still difficult to get them in a certain pattern." Several participants recognized the system's coupled nature. Changes in airflow or resistance in one part of the circuit affected behavior elsewhere. For example, opening the keyboard while the oscillator was running altered rhythmic stability because of the shared pressure distribution. P3 observed,"So things I do on the keyboard affect the LFO," and later referred to "the interconnectedness" of the system. These reflections indicate that participants gradually understood the circuit not as a set of isolated modules, but as an interconnected pneumatic network.

6 Discussion

The findings of this study highlight how pneumatic logic can function as a viable and musically expressive foundation for instrument design. Participants were able to engage with sound generation through physical configuration and interaction, developing an understanding of how airflow, pressure, and material properties shape sonic outcomes. Rather than relying on abstract parameter control, musical behavior in the *Aerophone Kit* emerged from the dynamics of the physical system itself.

A central observation concerns the role of variability in pneumatic sound generation. Temporal fluctuations, pitch instability, and gradual changes in timbre are frequently perceived as expressive qualities rather than limitations. These behaviors contrast with the stability and repeatability often emphasized in digital musical instruments, suggesting a type of interaction that is grounded in physical responsiveness and material agency.

The results also indicate that participants learned to interact with the system through embodied exploration. In this context, understanding is developed not through symbolic instruction or parameter mapping, but through hands-on manipulation of components and observation of the resulting sonic changes. The modular structure of the *Aerophone Kit* further supports this process by allowing participants to iteratively reconfigure circuits and directly experience the consequences of their design choices.

Differences between musicians and non-musicians suggest that prior musical experience influences how pneumatic variability is interpreted and used. Musicians more readily adapt interaction strategies to accommodate or exploit temporal and pitch fluctuations, while non-musicians often focus on exploratory configuration and discovery. Despite these differences, both groups were able to produce coherent and meaningful sonic outcomes, indicating that the system supports a broad range of musical backgrounds.

6.1 Limitations & Future Work

This study has several limitations. First, participants were recruited through convenience sampling within a single university context, which may limit the generalization of findings to broader musical communities. Second, the study employed an electrically driven air compressor, which may have influenced participants' listening and interaction activities due to the noise. Third, sessions were limited to 45 minutes, which captures first encounters and short-term learnability but does not address longer-term skill development. Finally, although we compared musicians and non-musicians, the musical background was self-reported, and the small sample size limits quantitative comparisons.

Our ambition is to realize a musically complex performance system built upon the *Aerophone Kit* to further demonstrate its practical and aesthetic viability. To achieve this, further iterations and more extensive sound exploration need to take place. First, the current pneumatic keyboard configuration represents only one possible interface geometry. Future iterations could explore alternative physical layouts and interaction forms, including handheld or breath-driven configurations inspired by instruments such as the melodica. Whether the system could be powered by human breath, as well as by foot-operated bellows, is an area we would like to explore further. These approaches would further emphasize bodily engagement while improving portability.

While a step sequencer was developed at an earlier stage of the project using punch cards and whistles, it was not included at this stage as more implementation time was needed. Future development will reconsider reintroducing the sequencer to allow for greater flexibility and musical expressivity for users.

The term 'oscillator' proved confusing for certain participants, as it carries different meanings within the domains of soft robotics and music. Future research into the *Aerophone Kit* should consider replacing the term 'oscillator' with a more musically-appropriate term, such as 'pulse generator' or 'beat generator', to make it more intuitively clear what the function of the oscillators is within our *Aerophone Kit* context.

Several participants expressed a desire for an expanded pitch range, particularly toward lower frequencies, noting that the current system tends to favor higher tones. This limitation was perceived as constraining the system's musical depth and expressive potential. Extending the available range is possible but requires further exploration, such as the implementation of increased air pressure or reduced air leakage, larger resonant volumes, and alternative valve and tube geometries.

Finally, the modular nature of the *Aerophone Kit* opens opportunities for distributed and multi-instrument configurations. Future work could explore ensembles of interconnected pneumatic instruments, including mobile or robotic elements that respond to environmental conditions or human presence. In such scenarios, sound produced by pneumatic logic could function both as musical output and as an audible trace of the system state, potentially feeding back into soft robotics research by making internal circuit behavior perceptible through sound.

7 Conclusion

This paper presents the *Aerophone Kit*, a modular toolkit for designing fully pneumatic musical instruments based on fluidic logic. Originating from laboratory observations in soft robotics research, the system demonstrates how sound generation, modulation, and temporal behavior can emerge directly from airflow, pressure, and material properties without reliance on electronic or digital computation.

We detailed the system architecture and modular components, characterized the acoustic behavior of whistle-based sound generation, and demonstrated how pneumatic circuits can be configured into musically meaningful prototypes, including a pneumatic keyboard and a pneumatic oscillator. Empirical characterization showed that these components can be reliably tuned while remaining sensitive to operating conditions, enabling both stability and expressive variability.

A structured user study with musicians and non-musicians examined how participants engaged with pneumatic sound generation through physical configuration and interaction. Results show that participants were able to produce, control, and explore sound using the system, and that variability arising from pneumatic dynamics was often perceived as an expressive quality rather than a limitation.

Our initial findings show that pneumatic logic presents an exciting opportunity to explore pneumatic circuits as a foundation for musical instrument design. By emphasizing embodied interaction, material agency, and emergent behavior, the *Aerophone Kit* contributes an alternative perspective to the ongoing NIME discourse on embodied, material-centered, and non-digital approaches to musical interface design.

8 Ethical Standards

This research was conducted in accordance with ethical standards for human subjects research. This study was approved by Eindhoven University of Technology (Approval No. 633). The user study was carried out with the informed consent of all participants, and participation was voluntary, with the right to withdraw at any time.

The research involved no animal subjects, and all materials used in construction are non-toxic and environmentally safe. Noise levels generated by the air compressors fell within acceptable workplace limits.

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