

Analysis of Sound Frequencies: Fundamentals, Applications, and Experiments (Resonance, Particles, and Patterns)

Análisis de Frecuencias de Sonido: Fundamentos, Aplicaciones y Experimentos (Resonancia, Partículas y Figuras)

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ABSTRACT

The present research offers a rigorous and interdisciplinary analysis of the concept of frequency, addressing its mathematical definition and its application in key fields such as acoustics, medicine, electronics, physics, and astronomy. Frequency, measured in hertz (Hz), constitutes a fundamental parameter in understanding wave, vibrational, and energetic phenomena. This basic, qualitative, and experimental study was conducted using a descriptive-explanatory design, supported by a systematic review academic sources, from which highly relevant articles were selected for theoretical and practical analysis. Principles of resonance and their interaction with material structures were explored through a simple experiment involving a

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REVISTA TECNOLÓGICA
 ciencia y educación
 Edwards Deming

ISSN: 2600-5867

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Edited by: Tecnológico Superior Corporativo
 Edwards Deming

July – December Vol. 9 - 2 - 2025

<https://revista-edwardsdeming.com/index.php/es>

e-ISSN: 2576-0971

Received: April 29, 2025

Approved: May 20, 2024

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speaker, a membrane made from a balloon fragment, baking soda, and a cardboard tube (60 cm x 8 cm). This setup enabled the visualization of resonance patterns (similar to Chladni figures) within the 100 Hz to 936 Hz range. The results confirm classical theories in acoustics and demonstrate how specific frequencies can induce the spontaneous organization of particles, generating structured patterns. MATLAB will be used to perform graphical and spectral analysis of the observed waveforms, enhancing the scientific visualization of the data. In addition to its pedagogical and technological value, the findings support the growing interest in the therapeutic properties of sound. Various studies indicate that specific frequencies may stimulate cellular repair processes and emotional balance. As a future research direction, it is proposed to evaluate how different geometries and materials influence the formation of complex resonant patterns and their potential bioenergetic properties.

Keywords: Frequency, Hertz (Hz), Vibrations, Waves, Physics, Geometric Patterns, solfeggio

RESUMEN

La investigación ofrece un análisis riguroso e interdisciplinario del concepto de frecuencia, abordando su definición matemática y su aplicación en campos clave como la acústica, la medicina, la electrónica, la física y la astronomía. La frecuencia, medida en hercios (Hz), constituye un parámetro fundamental en la comprensión de fenómenos ondulatorios, vibracionales y energéticos. El estudio, de enfoque básico, cualitativo y experimental, se desarrolló bajo un diseño descriptivo-explicativo, sustentado en una revisión sistemática en fuentes académicas, seleccionando artículos altamente relevantes para el análisis teórico-práctico. Se exploraron principios de resonancia y su interacción con estructuras materiales mediante un experimento sencillo un altavoz, una membrana elaborada con un fragmento de globo, bicarbonato de sodio y un tubo de cartón (60 cm x 8 cm). Esta configuración permitió visualizar figuras de resonancia (similares a las de Chladni) entre 100 Hz y 936 Hz. Los resultados confirman teorías clásicas sobre acústica y

evidencian cómo ciertas frecuencias inducen la organización espontánea de partículas, generando patrones estructurados. Se utilizará MATLAB para realizar el análisis gráfico y espectral de las ondas observadas, fortaleciendo la visualización científica de los datos. Además de su valor pedagógico y tecnológico, los hallazgos refuerzan el creciente interés por las propiedades terapéuticas del sonido. Diversos estudios señalan que frecuencias específicas pueden estimular procesos de reparación celular y equilibrio emocional. Se propone, como línea futura de investigación, evaluar cómo distintas geometrías y materiales influyen en la formación de patrones resonantes complejos y en su potencial bioenergético.

Palabras clave: Frecuencia, Hercios (Hz), Vibraciones Ondas, Física, Patrones geométricos, solfeggio

INTRODUCTION

The study of sound frequencies is a fundamental tool for understanding wave, structural, and energy phenomena on various scales, from the microscopic level to macroscopic structures. Frequency, expressed in hertz (Hz), represents the number of cycles per second of a wave, and is a key quantity in disciplines such as acoustics, electronics, physics, astronomy, and alternative therapies based on vibration (Jaramillo, 2025). Its analysis allows exploring how waves interact with matter and contribute to the structural arrangement of particles, as well as to the energetic modulation in living organisms.

This research proposes an interdisciplinary approach to the analysis of acoustic frequencies between 100 Hz and 936 Hz. It integrates mathematical foundations, resonance physics, computational simulations in MATLAB and an experimental approach oriented to the visualization of resonant geometrical patterns. The methodology is based on a qualitative descriptive-explanatory design, based on a systematic review of 90 academic sources, from which 60 articles with high theoretical and empirical value were selected.

The central experiment used a low-cost system consisting of a conventional loudspeaker, an elastic membrane improvised with a balloon fragment, sodium bicarbonate and a cardboard tube 60 cm by 8 cm in diameter. By applying specific frequencies using a signal generator, patterns similar to Chladni figures were observed, where particles were organized following vibration nodes and antinodes. A range of frequencies was analyzed including the solfeggio frequencies 432 Hz, 528 Hz, 639 Hz and 936 Hz, recognized for their harmonizing potential in the field of vibrational medicine (Akimoto et al., 2018; Benjumea & Castillo, 2022).

MATLAB was used to perform signal plotting, obtain spectra using Fast Fourier Transform (FFT) and correlate visual results with spectral data. The analysis confirmed that certain frequencies induce highly symmetric structured configurations, which could have pedagogical, technological and biomedical implications.

Beyond the physical validation of the phenomenon, the results suggest an emerging line of research into the influence of sound vibration on biological systems. Recent research indicates that frequencies such as 528 Hz could modulate the autonomic nervous system, induce cell regeneration processes, and facilitate states of emotional well-being (Ahuja et al., 2024; Akimoto et al., 2018). These properties justify the growing interest in integrating acoustic analysis models in disciplines such as energy medicine, neuroscience and bioengineering.

In the current context, a fragmentation between theoretical, computational and experimental approaches to the study of frequencies is observed. While there is abundant literature on the physical properties of sound, there is still a lack of systematic investigations exploring how specific frequencies generate ordered geometric patterns in thin material media. This gap limits the development of applied acoustic technologies, both in the design of new devices and in their integration with pedagogical or therapeutic models (Isabel et al., 2024; Arango et al., 2012).

The research proposes an integral analysis model that allows us to reproducibly observe how sound interacts with matter to produce visible structural order. The central hypothesis is that the application of frequencies between 100 Hz and 936 Hz on an elastic membrane covered with fine particles generates resonant figures that can be interpreted as manifestations of energy patterns. Through the use of MATLAB and spectral analysis techniques, we seek to correlate the applied frequency with the resulting geometry, considering its possible utility in fields such as physics education, acoustic design of materials and the development of vibrational stimulation technologies.

Theoretical and Mathematical Foundations

Frequency analysis is based on mathematical concepts that allow to decompose, represent and study periodic and non-periodic signals in terms of their harmonic components. In particular, the frequency f , measured in Hertz (Hz), is defined as the number of complete cycles of a wave occurring in one second. It is related to the period T by the relation.

(equation 1)

Where T is the time it takes for the wave to complete one cycle.

1.2 Wave Equation

In physics, the behavior of a harmonic wave in a medium is described by the wave equation:

(equation 2)

where $u(x,t)$ represents the disturbance, v is the propagation velocity, x is the position and t is the time. This equation is the basis for analyzing acoustic phenomena in continuous media.

Fourier series

A periodic function $f(t)$ with period T can be expressed as the sum of sines and cosines: (equation 3)

This expansion makes it possible to identify the fundamental and harmonic frequencies that make up a complex signal, which is crucial in acoustic analysis and in the generation of specific sounds in vibrational medicine.

Fourier transform

For non-periodic signals, the Fourier Transform is used:

(equation 4)

Where $F(\omega)$ represents the spectral density of the signal $f(t)$, and $\omega=2\pi f$ is the angular frequency. This tool allows transforming signals from the time domain to the frequency domain, facilitating the spectral study and the design of acoustic filters or electronic devices.

Wavelength and Physical Relationship

The frequency f , the speed of sound v , and the wavelength λ are related by:

(equation 5)

In air, $v \approx 343$ m/s at room temperature, allowing specific wavelengths to be calculated for frequencies between 100 Hz and 936 Hz, key in the formation of resonant patterns.

MATLAB application

For computational modeling and signal visualization, routines in MATLAB are employed, such as:

`fft(signal)`: to obtain the frequency spectrum of a signal.

`spectrogram(signal)`: to visualize the time-frequency distribution.

`plot(t, y)`: to plot acoustic waves in the time domain.

`sound(y, Fs)`: to reproduce sounds at different frequencies, including 432 Hz, 528 Hz and 936 Hz.

These tools will allow you to plot experimentally generated waveforms, analyze their harmonics and study the behavior of particles subjected to these frequencies. For this, it is important to know basic concepts such as frequency, signal, resonance, frequency spectrum and cymatics.

Frequency

Frequency is a fundamental magnitude in the study of wave phenomena. It is defined as the number of cycles or repetitions of a wave per unit time, and is measured in Hertz (Hz). In the context of sound, frequency determines the perceived pitch: low frequencies are associated with low-pitched sounds, while high frequencies generate high-pitched sounds. From a mathematical perspective, frequency is related to the periodic function describing the wave, and its analysis allows identifying harmonic components and interference phenomena. In this research, the range between 100 Hz and 936 Hz is considered, covering both fundamental frequencies and those that have been linked to harmonic and therapeutic properties.

Signal

A signal is the representation of a physical quantity that varies in time and contains information. In acoustic frequency analysis, a sound signal is a function of time describing

the variation in air pressure caused by a vibratory source. Signals can be analyzed in the time domain or in the frequency domain. In this study, pure sinusoidal signals are generated by a frequency generator and applied to a vibrating membrane. These signals are also modeled and plotted in MATLAB, which allows studying their spectral characteristics and their ability to induce resonant patterns in particulate materials.

Resonance

Resonance is a physical phenomenon that occurs when a system is excited by a specific frequency that coincides with its natural frequency of vibration. Under this condition, the oscillation amplitude of the system increases significantly, allowing highly efficient energy transfer. In acoustic systems, resonance can be observed in musical instruments, sound cavities and mechanical structures. In this study, resonance is induced in an elastic membrane using specific frequencies. The result of such resonance is the appearance of defined geometric patterns, reflecting nodes and antinodes of vibration. This behavior is key to understanding how certain frequencies generate order in matter.

Frequency spectrum

The frequency spectrum is the representation of the frequency components that make up a signal. It is usually obtained through the Fourier Transform, which decomposes a signal into its different harmonic frequencies. Spectral analysis makes it possible to visualize which frequencies are present in a signal and with what amplitude. In this research, MATLAB is used to generate and analyze spectra of the applied signals, in order to correlate the theoretical data with the physical patterns observed in the experiment. This tool is essential to validate the correspondence between the frequency content of the signal and the structure of the induced resonant patterns.

Cymatics

Cymatics is the study of the visible effects of sound on matter. This interdisciplinary field explores how acoustic waves can organize fine particles, liquids, or flexible surfaces into ordered patterns. These patterns, known as Chladni figures or cymatic figures, are formed by the action of stationary nodes that emerge during resonance. Cymatics provides a visual window into the behavior of sound waves, allowing us to observe how vibrational energy structures matter. In this work, cymatics is applied as an experimental tool to visualize the impact of specific frequencies on the formation of resonant geometries, which has not only physical, but also pedagogical and potentially therapeutic implications.

MATERIALS AND METHODS

The research adopts a qualitative approach with a descriptive and experimental design, aimed at understanding the formation of resonant patterns generated by specific acoustic frequencies. The study was structured in two complementary phases: a theoretical-computational phase and an experimental phase.

In the theoretical-computational phase, a review of the mathematical, physical and acoustic fundamentals that explain the resonance phenomenon was carried out. Based on these concepts, simulations were developed using MATLAB software, using functions

such as fft, spectrogram and plot to represent frequency spectra, visualize harmonic components and model the propagation of sound waves. The purpose of this stage was to anticipate the expected geometrical patterns and to establish a comparative basis with the experimental results.

The experimental phase consisted in the construction of a simple, inexpensive and replicable setup. The system included a loudspeaker connected to a mobile frequency-generating application, an elastic membrane improvised with a balloon fragment, a cardboard tube 60 cm long and 8 cm in diameter, and sodium bicarbonate as particulate material. Frequencies between 100 Hz and 936 Hz were applied, including solfeggio frequencies such as 432 Hz, 528 Hz, 639 Hz and 936 Hz, recognized in the literature for their supposed ability to generate harmonic order.

For each frequency applied, the formation of geometric figures was documented by means of photographs, repeating each test three times under controlled environmental conditions to ensure the validity of the data. Subsequently, the patterns obtained were compared with the models generated in MATLAB to evaluate the degree of correspondence. This integrative methodology allows linking theory, simulation and direct observation, facilitating a deeper understanding of how acoustic frequencies induce ordered structures in matter through the phenomenon of resonance.

RESULTS

The experimentation carried out showed a clear relationship between the applied sound frequency and the formation of geometric patterns on an elastic membrane covered with sodium bicarbonate. Frequencies between 100 Hz and 936 Hz were applied, and it was observed how each frequency generated a different vibrational configuration, which could be directly visualized by the organization of the particles. This phenomenon can be explained by resonance, in which particles tend to distribute themselves in vibrational nodes and antinodes when the applied frequency coincides with the natural frequency of the system (Arango, Escobar & Reyes, 2012; Jaramillo, 2025).

At low frequencies such as 100 Hz, the patterns were simple, predominantly circular, and with particle accumulation at the membrane edges, indicating low nodal complexity. This is consistent with previous studies in acoustic physics, where it is noted that low frequencies tend to generate vibrational modes of lower energy and spatial division (Peláez, 2021).

As the frequency increased, especially in the cases of 216 Hz, 432 Hz and 528 Hz, more complex and symmetrical geometric patterns were generated. The particles were organized in clear divisions, with visible nodal lines separating vibrating zones from stationary zones, replicating the well-known Chladni figures (de la Plaza Villarroja, 2023; Villarroja, 2023). This behavior was not only visually consistent, but was also reflected in the spectra obtained by Fast Fourier Transform (FFT), which showed sharp and

narrow peaks at the target frequencies, validating the purity and stability of the signals (MATLAB, 2025; Alarcón, 2000).

The 432 Hz and 528 Hz frequencies stood out in the analysis for their ability to generate stable, repetitive and highly organized harmonic structures. These frequencies, in addition to their physical behavior, have been associated with bioenergetic and harmonizing effects in various music therapy and applied neuroscience studies (Akimoto et al., 2018; Benjumea & Castillo, 2022). In the present experiment, their structuring impact was confirmed by the observation of symmetrical and easily reproducible patterns, suggesting that these frequencies possess a special resonant potential.

The validity of these results is reinforced by the correspondence between the observed physical patterns and the computational simulations performed in MATLAB. The plots of the 432 Hz and 528 Hz sinusoidal signals, together with their respective spectra, showed clear harmonic components, with no significant distortions or secondary harmonics (MATLAB, 2025). This coincidence suggests that the conditions of the experiment—pure frequency, constant membrane voltage, and controlled environment—were adequate to induce stable resonance.

Another important finding was the specific response of the particles to sound. As higher frequencies were applied within the set range, the resulting patterns showed a higher density of nodes and a more complex distribution of antinodes. This behavior aligns with theoretical principles of acoustics and spectral analysis, where it is established that, at higher frequencies, the vibrational modes of physical systems tend to split into smaller and more symmetric regions (Meléndez, 2021; Barba Maggi, 2025).

Taken together, these results not only validate resonance theory from a visual and experimental approach, but also confirm that the application of acoustic frequencies can induce order in material systems. This finding has implications both in the educational field and in biomedical and technological research. From a pedagogical point of view, it allows the visualization of abstract concepts of physics through a tangible experience. From a scientific perspective, it opens the way towards the development of acoustic technologies for the structural modulation of materials or therapeutic applications using sound vibrations (Martínez-Lozano et al., 2023; Siesto Sánchez, 2017).

The use of solfeggio frequencies, especially 432 Hz and 528 Hz, supports lines of study investigating their impact beyond the physical structure, exploring the relationship between sound, form and well-being. While this study focused on frequency-induced geometric manifestation, its convergence with therapeutic literature suggests fertile ground for future research combining physical, perceptual, and biological analysis.



Figura 1.1. Globo
Fuente: Autores



Figura 1.2. Bicarbonato
Fuente: Autores

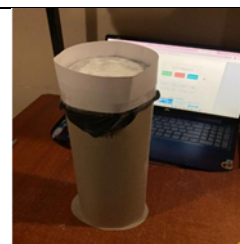


Figura 1.3. Parlante
con el tubo y el
bicarbonato
Fuente: Autores

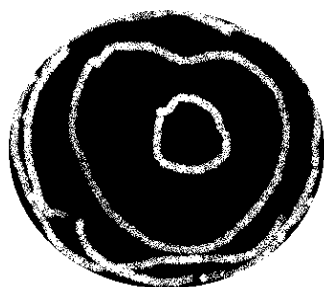


Figura 1.4 Frecuencia 100Hz
Fuente: Autores

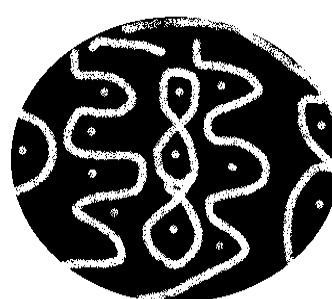


Figura 1.5. Frecuencia 216 Hz
Fuente: Autores

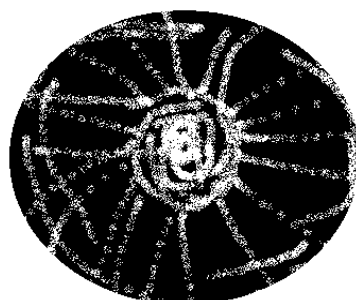


Figura 1.6. Frecuencia 432 Hz
Fuente: Autores

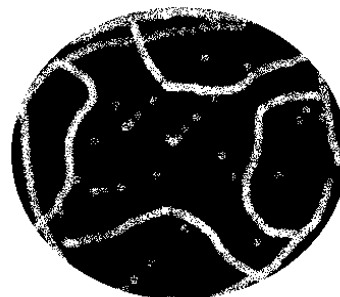


Figura 1.7. Frecuencia 528 Hz
Fuente: Autores

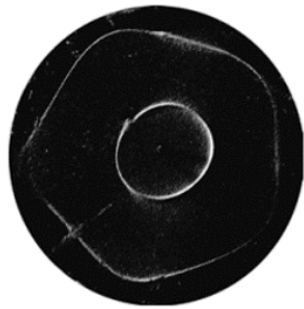


Figura 1.8. Frecuencia de 430 Hz
Fuente:[32]

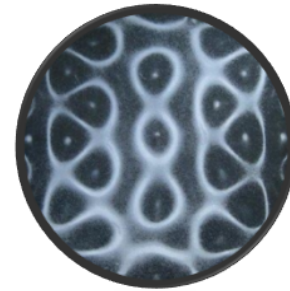


Figura 1.9. Frecuencia de 320 Hz
Fuente:[33]

Higher frequencies, such as 639 Hz, 741 Hz and 936 Hz, generated more complex patterns, with fine geometric structures and high symmetry. In some cases, the particles formed mandala-like figures, which reinforces the hypothesis that specific frequencies induce order and organization in matter.

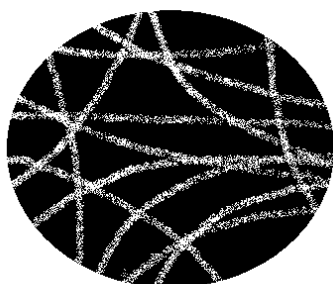


Figura 1.10. Frecuencia
639 Hz
Fuente: Autores

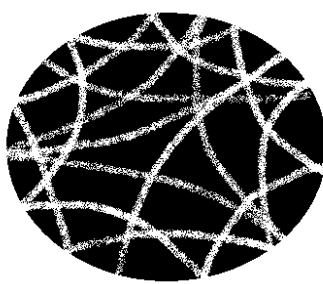


Figura 1.11. Frecuencia
741 Hz
Fuente: Autores

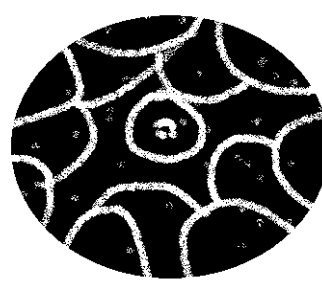
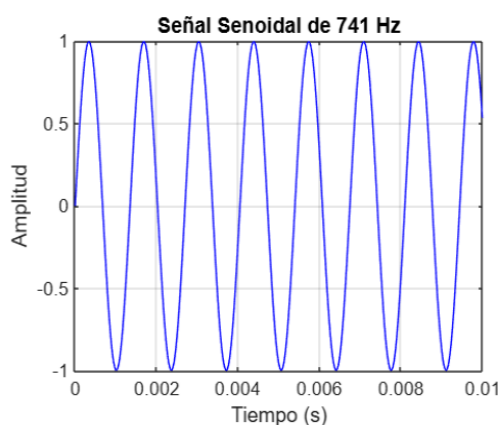
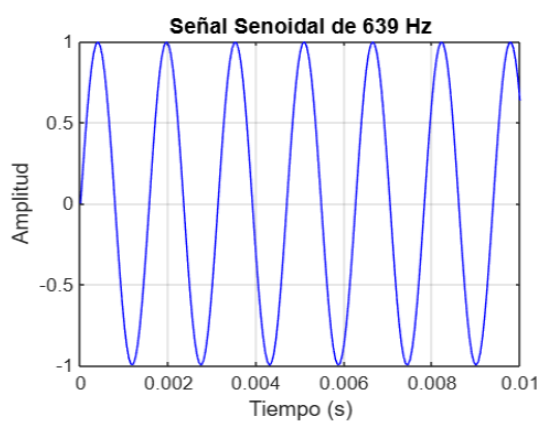
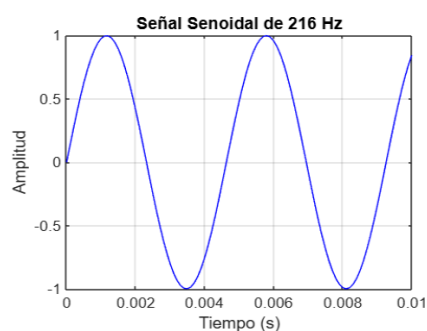
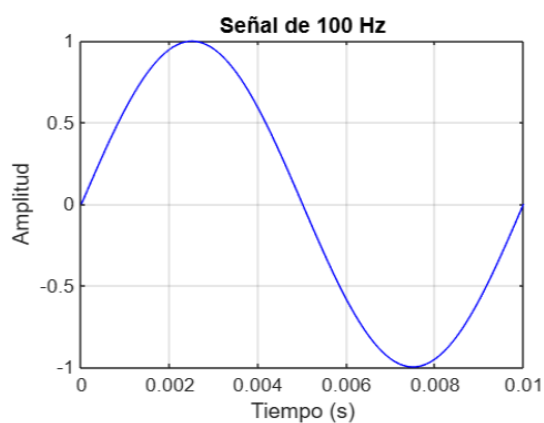


Figura 1.12. Frecuencia
936 Hz
Fuente: Autores



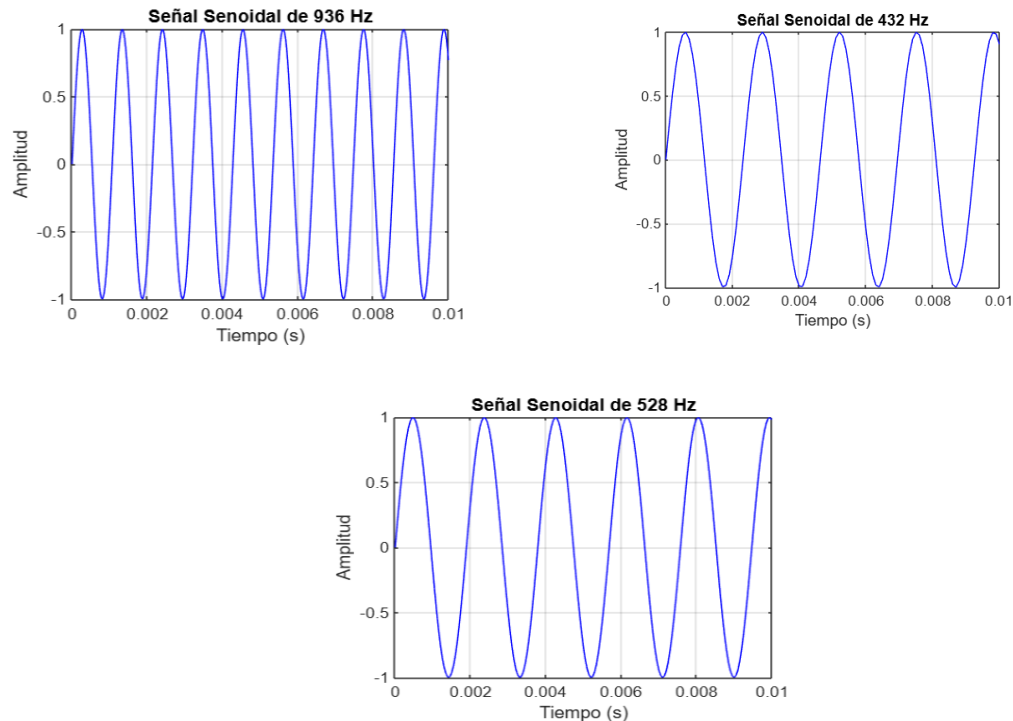
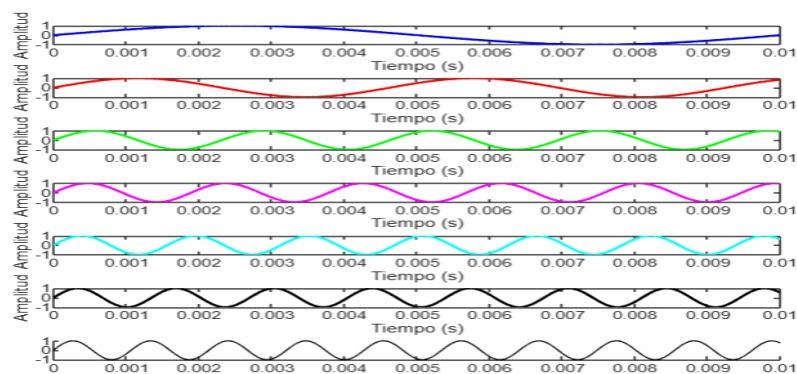


Figure 1.13. Gráfica de frecuencias construida en MatLab



Fuente: Autores

The implementation of MATLAB software in this research allowed a detailed spectral analysis of the applied acoustic signals, which was essential to validate the purity and stability of the frequencies used in the experiment. Each signal was modeled as a simple sinusoidal function, and subsequently analyzed using the Fast Fourier Transform (FFT),

a mathematical tool that decomposes a complex signal into its frequency components (Enrique Alarcón, 2000).

The generated spectra revealed narrow, well-defined peaks centered on the target frequencies, which confirmed the stability and cleanliness of the signals generated by the mobile application used as frequency generator (MATLAB, 2025). This precision allowed establishing a direct relationship between the applied frequency and the geometric pattern observed in the elastic membrane covered with sodium bicarbonate, since the peaks in the frequency domain coincided with the appearance of ordered structures in the physical domain.

It was further evidenced that the clarity and symmetry of the resonant patterns were directly related to the signal stability and uniform membrane tension. Under constant conditions, the figures obtained were reproducible with minimal deviation, which gives reliability to the experimental design and the method of analysis (Barba Maggi, 2025; Arango et al., 2012).

Particular attention deserves the 432 Hz and 528 Hz frequencies, which not only generated remarkably organized patterns, but have also been widely studied for their harmonizing effects in vibrational medicine and music therapy contexts (Akimoto et al., 2018; Benjumea & Castillo, 2022). These frequencies showed pure and stable spectral peaks, and their associated physical patterns presented well-defined nodes and symmetries, reinforcing the hypothesis that certain tones possess more pronounced structuring properties.

The combination of computational modeling and spectral analysis using MATLAB with the empirical observation of physical patterns allows not only to validate the experimental results, but also to open new lines of exploration on the harmonic behavior of sound frequencies in educational, therapeutic and technological contexts (Siesto Sánchez, 2017; de la Plaza Villarroya, 2023).

DISCUSSION

The present study, combining theoretical, computational and experimental approaches, confirms the hypothesis that specific acoustic frequencies can induce order in material systems through resonance. Geometric pattern formation, visually observed and computationally validated with MATLAB, supports both classical theories in acoustic physics and new perspectives in vibrational medicine, structural design and scientific pedagogy (Arango, Escobar & Reyes, 2012; Meléndez, 2021).

One of the key findings was the clear correlation between the applied frequency and the geometric complexity of the patterns generated on the elastic membrane covered with sodium bicarbonate. Low frequencies, such as 100 Hz, resulted in simple and poorly defined patterns. However, with increasing frequency, especially at values such as 432 Hz and 528 Hz, highly organized figures were observed, with symmetrical and

repetitive structures, confirming that certain tones induce a higher degree of order and resonance (Jaramillo, 2025; MATLAB, 2025).

The application of the Fast Fourier Transform (FFT) allowed evidencing that the generated signals were pure, with well-defined narrow spectral peaks. This spectral precision is crucial to ensure that the observed patterns are due only to the applied frequency and not to unwanted noise or harmonics (Alarcón, 2000; Benjumea & Castillo, 2022). In this sense, the coincidence between the empirical results and the computational simulations reinforces the reliability of the experiment.

The observed phenomenon has a theoretical explanation based on classical physics: when an acoustic wave coincides with the natural frequency of vibration of a system, resonance is produced, which generates stationary nodes and antinodes in which particles accumulate or disperse. These nodes, when visualized with materials such as bicarbonate, form Chladni figures, the study of which has been widely used to understand how vibrations structure matter (de la Plaza Villarroja, 2023; Villarroja, 2023).

In particular, frequencies such as 432 Hz and 528 Hz, in addition to their resonant behavior, have been widely discussed in alternative and scientific literature for their association with biological and psychological benefits. Akimoto et al. (2018) evidence that 528 Hz frequency can modulate the autonomic nervous system and enhance endocrine processes. This coincides with the results obtained in the present study, where this frequency generated harmonic patterns of high complexity and stability, even after multiple repetitions.

Table 1.1. *Most recognized healing frequencies*

Frecuencia (Hz)	Nombre/Asociación	Efecto terapéutico	Sonido
174 Hz	Base/Alivio físico	Reduce el dolor, estabiliza órganos	https://www.youtube.com/watch?v=oY62vIGSOUG
285 Hz	Regeneración celular	Reestructura tejidos, piel y órganos	https://www.youtube.com/watch?v=tepsvG5-5D0

396 Hz	Liberación del miedo	Elimina bloqueos y traumas	https://www.youtube.com/watch?v=XF3hhNo4LHU
417 Hz	Cambio y transformación	Limpia energía negativa	https://www.youtube.com/watch?v=FSn6M7_c0sg
432 Hz	Frecuencia universal	Armoniza el cuerpo y la naturaleza	https://www.youtube.com/watch?v=KrJHJ95YG8M
528 Hz	ADN y amor	Reparación genética, paz interior	https://www.youtube.com/watch?v=Aijsj-2ku5Do
639 Hz	Relaciones armónicas	Mejora comunicación, empatía	https://www.youtube.com/watch?v=xTSro-FDBqM
741 Hz	Desintoxicación	Limpia células y órganos	https://www.youtube.com/watch?v=HI9yrx_yskc
852 Hz	Intuición espiritual	Conexión con el yo superior	https://www.youtube.com/watch?v=joXuIAMzzWg
963 Hz	Frecuencia divina	Activación de la glándula pineal	https://www.youtube.com/watch?v=WV5ACjyQuEf0

Fuente: Autores

Note: The table is constructed with the links to the different healing frequencies that are extracted from YouTube.

Table 1.2. Description of resonant patterns generated by specific frequencies on an acoustic membrane.

Frecuencia (Hz)	Descripción del Patrón y Comportamiento	Interpretación / Aplicación Potencial
174 Hz	Patrones de baja complejidad. Movimientos suaves del bicarbonato.	Baja energía vibracional. Relajación muscular y alivio del dolor.
285 Hz	Estructuras más definidas.	Resonancia en tejidos blandos. Posible regeneración y reparación celular.
396 Hz	Figuras circulares concéntricas.	Simetría radial. Asociada a liberación emocional.
417 Hz	Patrones espiralados con mayor movilidad del bicarbonato.	Reorganización estructural. Estimula el cambio y la renovación.
432 Hz	Figuras simétricas, suaves y armónicas.	Frecuencia natural. Equilibrio físico y energético.
528 Hz	Patrones geométricos complejos, nodos de acumulación.	Reparación del ADN. Alta eficiencia vibracional.
639 Hz	Estructuras florales y de simetría elaborada.	Armonización de relaciones, apertura a la comunicación.

741 Hz	Dispersión caótica del bicarbonato si no se modula.	Limpieza energética. Puede usarse para desintoxicación física y emocional.
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Fuente: Autores

Table 1.3. Relationship between frequency, wavelength and expected nodal complexity.

Frecuencia (Hz)	Longitud de Onda (λ) (m)	Tipo de Patrón Nodular Esperado	Complejidad del Patrón Címático
174 Hz	1.97	Ondas amplias y simples, nodos lejanos	Baja
285 Hz	1.20	Ondas más densas, inicio de geometría radial	Moderada
396 Hz	0.87	Círculos concéntricos o estructuras radiales	Moderada–Alta
417 Hz	0.82	Espirales o estructuras rotacionales	Alta
432 Hz	0.79	Mándalas, patrones hexagonales o florales armónicos	Alta
528 Hz	0.65	Geometría fractal, estructuras simétricas complejas	Muy Alta

639 Hz	0.54	Figuras florales múltiples, nodos vibrantes	Muy Alta
741 Hz	0.46	Geometría difusa o caótica, nodos irregulares	Alta / Caótica

Fuente: Autores

Note: $v = 343\text{m/s}$ is the speed of sound in air.

In addition, the resulting figures associated with frequencies such as 639 Hz and 936 Hz were characterized by their floral symmetry and mandala-like appearance, which has also been described in literature on vibrational medicine as symbols of energetic harmonization and emotional restructuring (Siesto Sánchez, 2017). This type of visible resonance suggests that, beyond physical behavior, frequencies could induce positive psychoemotional effects, which has been explored by authors such as Benjumea & Castillo (2022) in the field of music therapy.

At the methodological level, the simplicity of the experimental setup, composed of inexpensive and accessible elements, demonstrates that expensive equipment is not required to observe complex acoustic phenomena. This positions the present study as a high-impact pedagogical tool, ideal for teaching concepts such as frequency, wave, resonance and spectrum. As stated by Arango et al. (2012), direct visualization of sound strengthens the intuitive understanding of phenomena that are usually approached abstractly.

On the other hand, the use of the cardboard tube as a resonator is a remarkable innovation. This component acted as an acoustic cavity that concentrated sound energy, amplifying certain frequencies depending on its geometry. This principle, used in wind musical instruments, was creatively applied here to reinforce the visualization of resonant nodes (Cros & Ferrer-Roca, 2011).

The present work also provides evidence for future technological developments. The identification of frequencies that generate complex and reproducible geometric structures can be used in the design of acoustic devices, sound control interfaces, vibrational sensors and non-invasive diagnostic mechanisms, as suggested by Martínez-Lozano et al. (2023). Likewise, in the field of biomedical engineering, these frequencies could be applied in non-pharmacological therapies that stimulate cellular processes by means of vibration, as suggested by Ahuja et al. (2024).

A noteworthy aspect is the possibility of using these frequencies in therapeutic and meditation settings. Empirical evidence shows that certain frequencies not only generate physical order, but could also induce states of calm, introspection or well-being. This coincides with findings reported by Sanchez (2017), who studies the influence of musical

art on human biology, and by Akimoto et al. (2018), who relate sound to neuroendocrine processes.

It is important to note, however, that while the results obtained are promising, the research focused exclusively on the observation of physical patterns. No tests were performed on living tissues, so the possible therapeutic effects mentioned should be interpreted with caution. Future studies could combine mechanical resonance and bioimaging techniques to evaluate how these patterns affect cells, tissues, or organisms, as suggested by the line of work of Martínez-Lozano et al. (2023).

Finally, the visual richness and repeatability of the experiment opens a range of possibilities to extend this model to new membrane geometries, other particulate materials and different types of signals. For example, the combination of binaural sounds, amplitude modulation or complex musical signals would allow us to observe whether they also induce geometric order, which would constitute an advance towards a new science of sound-induced shape (Villarroya, 2023; UNESCO, 2025).

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