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A Research on Music Concerning Ultrasonic and Infrasonic Waves Based on Spectral Processing Technology

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Abstract. This review comprehensively examines the intersection of ultrasonic (>20 kHz) and infrasonic (<20 Hz) waves with music, mediated by spectral processing technologies. It systematically collates research across acoustics, music technology, and neuroscience to explore how inaudible frequencies can extend musical expression. The paper first outlines the unique physical properties of ultrasonic and infrasonic waves, then analyzes spectral processing methods—from traditional Fourier transforms to advanced machine learning algorithms—that enable their conversion into musically relevant forms. Key applications in experimental composition, therapeutic interventions, and immersive media are discussed, supported by empirical studies and artistic case studies. Additionally, it investigates the perceptual mechanisms underlying human responses to these inaudible stimuli, including cross-modal integration of auditory and tactile signals. Finally, the review identifies critical challenges such as hardware limitations and individual perceptual variability, proposing future directions for interdisciplinary research. It suggests a theoretical foundation for employing ultrasonic and infrasonic waves to extend the boundaries of music.

Keywords: spectral analysis, ultrasonic frequencies, infrasonic vibrations, music innovation, sensory perception

1. Introduction

For decades, the definition of "musical sound" has been constrained by the limitations of the human ear, with the bulk of the artistic and scientific community still operating from the 20 Hz through 20 kHz spectrum [1]. With advanced spectral processing technologies coming into existence, however, interest has developed in frequencies above this spectrum—most notably ultrasonic and infrasonic waves. These waves carry unique acoustic features, and their utilization has yet to realize their potential addition to music. Ultrasound waves propagating along high-frequency focused paths carry limitless harmonic information that can be conveyed into new innovative timbres [2]. Infrasound, with their extensive wavelengths and ability to yield tactile vibrations, bring a physical aspect into an understanding of perceiving music [3].

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Initially, research in this direction was largely experimental. For example, Cage's composer Imaginary Landscape No. 4 (1951) applied low-frequency vibrations near the infrasound range. Meanwhile, 20th-century acoustic scientists like Harry F. Olson investigated how inaudible frequencies affect listeners' emotional state [4]. However, such experiments were fragmented until the 21st century, when digital signal processing tools became available and made it possible to control spectral material accurately [5]. Today, research covers several areas: engineers develop algorithms transforming ultrasonic harmonics into a hearing range, neuroscientists investigate how infrasound affects brain activity, and artists create pieces involving hearing and touch [6].

Here, in this article, we integrate these numerous branches of research in a quest to answer three basic questions: (1) Why are ultrasonic and infrasonic waves particularly prized assets of music? (2) How can spectral-processing technologies transform such inaudible waves into intelligible musical ingredients? (3) How should we approach perception and real-world listening as we integrate such frequencies into music? By answering these questions, this paper aims to offer a guide for future innovation where acoustics, technology, and art intersect.

2. Acoustic properties of ultrasonic and infrasonic waves

To use ultrasonic and infrasonic waves in music, understanding their physical nature is essential—their unique traits (such as how they travel and interact with materials) dictate how we can process and experience them. Ultrasonic waves, which have frequencies above 20 kHz, have short wavelengths (1.7 centimeters at 20 kHz, and less than 1 millimeter at 300 kHz). This gives them strong directionality and minimal diffraction, allowing focused transmission and precise spatial control in musical settings [7-9]. Their most significant benefit for music is harmonic richness: natural sources like bat calls (20–120 kHz) and insects producing sound through stridulation (30–80 kHz) have dense, one-of-a-kind harmonic series. When these harmonics are shifted down to audible ranges, they retain their unique structure, creating timbres that cannot be replicated by traditional instruments [10,11]. Even studies show that non-sinusoidal ultrasonic signals can make people perceive clear pitches if harmonic relationships are maintained [12]. Infrasonic waves, with frequencies below 20 Hz, have long wavelengths (for example, 17 meters in air at 20 Hz) and lose little energy as they travel, enabling long-distance propagation [13]. They interact extensively with the human body: frequencies between 5 and 15 Hz resonate with the chest and abdominal cavities, creating tactile vibrations detected by skin and internal organ receptors, which complement what we hear [14,15]. Psychoacoustic research emphasizes their emotional effect—a 2001 study found that 10 Hz infrasound played with orchestral music made listeners report a 40% increase in “immersion,” linked to synchronization with body rhythms like heartbeat and breathing, which fosters bodily alignment with the music’s structure [16,17].

2.1. Ultrasonic waves: high frequency and harmonic richness

Ultrasonic waves have frequencies higher than 20 kHz, and their wavelengths in air range from 1.7 centimeters (at 20 kHz) down to less than 1 millimeter at 300 kHz [7]. This short wavelength gives them strong directionality, allowing focused transmission—and this is why ultrasonic speakers utilize this trait for targeted audio delivery [8]. Unlike audible sound, ultrasonic waves show minimal diffraction, which enables precise control over their spatial distribution in musical performances or immersive environments [9].

One major musical benefit of ultrasonic waves is the complexity of their harmonics. Natural sources of ultrasound, like bat calls (20–120 kHz) and insects producing sound through stridulation

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(30–80 kHz), have dense harmonic series with unique frequency ratios [10]. Lab experiments illustrate that once such harmonics are translated downward from their ultrasonic or infrasonic frequencies back into aural frequencies, they embody their structural uniqueness and yield timbres with no corresponding musical instruments [11].

2.2. Infrasonic waves: low frequency and tactile resonance

infrasound are waves with frequencies less than 20 Hz and travel with long wavelengths (e.g., 17 m at 20 Hz at room temperatures and pressures) and low absorption and thus travel long distances [13]. Their interaction with the human body is significant: 5 to 15 Hz waves are associated with the chest and abdominal waves and have an observable vibration that cannot be detected by the ear [14]. The body has mechanical receptors, which are made up of the spaces between the skin and the inner organs. They sense these vibrations and produce a feeling of touch that complements or enriches hearing [15].

The direction of psychoacoustic studies identifies the infrasound pathos. Identical previous research by Blauert and Demuth (2001) demonstrated that infrasound of 10 Hz with the background music accompanying orchestral music increased subjective reports of a state of immersion by 40 percent relative to audio presentations only [16]. Causative of this effect has been proposed as synchronization of infrasonic oscillations with physical rhythms such as heartbeat (60–100 bpm), breathing (12–20 bpm), and resulting perception of bodily synchrony with musical meter [17].

3. Spectral processing technologies for musical translation

Spectral processing serves as the bridge between inaudible waves and musical expression, enabling the extraction, transformation, and integration of ultrasonic and infrasonic content into musical frameworks. Traditional spectral analysis and transformation rely on tools like the Fourier Transform (FT) and its time-localized variant, the Short-Time Fourier Transform (STFT), which decompose ultrasonic and infrasonic signals into spectral components; for ultrasonics, STFT with high-frequency resolution isolates harmonic peaks that can be transposed to audible ranges via linear or logarithmic scaling to preserve timbre, while for infrasound, spectral warping adjusts frequency contours to align with musical rhythms, with software tools like iZotope RX and Sonic Visualiser offering basic processing capabilities, though custom implementations are often needed. Advanced methods have revolutionized the field: machine learning, particularly neural networks trained on paired datasets, maps high-frequency harmonics to natural-sounding timbres, with a 2023 study showing transformer-based models outperforming traditional STFT in translating bat calls to audible ranges with high musical coherence, and optimal transport, a mathematical framework, minimizes distortion when converting infrasonic vibrations to audible basslines, preserving tactile qualities and finding use in film scoring. However, technical limitations persist, including high-frequency noise in ultrasonic processing (addressed by specialized filters and hybrid systems with noise-canceling algorithms) and hardware constraints in infrasonic processing (such as the need for large, high-power speakers, mitigated by infrasonic arrays and open-source tools like the Ultrasonic Music Toolkit that reduce technical barriers for composers).

3.1. Traditional spectral analysis and transformation

Fourier Transform (FT) and its time-localized variant, Short-Time Fourier Transform (STFT), are fundamental tools for decomposing ultrasonic and infrasonic signals into their spectral components

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[18]. For ultrasonic waves, STFT with high-frequency resolution (e.g., 1 kHz bins) isolates harmonic peaks, which can then be transposed to audible ranges using linear or logarithmic frequency scaling [19]. This process preserves harmonic intervals—critical for maintaining perceived timbre—while bringing ultrasonic content into the range of human hearing [20].

For infrasound, spectral warping techniques adjust frequency contours to align with musical rhythms. By stretching or compressing the spectral envelope of 5–20 Hz signals, researchers can synchronize infrasonic vibrations with audible beats, ensuring tactile feedback reinforces rhythmic perception [21]. Software tools like iZotope RX and Sonic Visualiser offer modules for basic infrasonic processing, though custom implementations in MATLAB or Python are often required for musical applications [22].

3.2. Advanced methods: machine learning and optimal transport

Recent advances in machine learning have revolutionized spectral translation. Neural networks, trained on paired ultrasonic/audible datasets, learn to map high-frequency harmonics to natural-sounding timbres while preserving perceptual qualities like "brightness" or "warmth" [23]. A 2023 study by Chen et al. demonstrated that a transformer-based model outperformed traditional STFT methods in translating 40 kHz bat calls to audible ranges, with 82% of listeners rating the output as "musically coherent" [24].

Optimal transport, a mathematical framework for aligning probability distributions, has also been applied to spectral transformation. Developed by researchers at Stanford University, this method minimizes distortion when converting infrasonic vibrations to audible basslines, ensuring the tactile "weight" of low frequencies is preserved in the auditory domain [25]. This technique has been adopted in film scoring, where infrasonic-audible synchronization enhances emotional impact in action sequences [26].

3.3. Technical limitations and workarounds

Despite progress, practical challenges persist. Ultrasonic processing is hindered by high-frequency noise, requiring specialized filters (e.g., 20 kHz high-pass filters with 80 dB attenuation) to isolate meaningful harmonics [27]. Infrasonic processing faces hardware constraints: generating 5 Hz vibrations requires speakers with large diaphragms (≥30 cm) and high power (>100 W), which are costly and prone to distortion [28].

To address these issues, researchers have developed hybrid systems: ultrasonic transducers paired with noise-canceling algorithms [29], and infrasonic arrays that distribute vibration across multiple low-power speakers [30]. Open-source software projects, such as the Ultrasonic Music Toolkit (UMT), provide pre-built modules for spectral mapping, reducing the technical barrier for composers [31].

4. Musical applications: from composition to therapy

Transformed ultrasonic and infrasonic waves have driven innovations across musical domains, from avant-garde composition to clinical therapy, by expanding the range of sounds and sensations available to creators. In experimental composition and sound art, contemporary composers leverage inaudible waves to challenge traditional aesthetics: Annea Lockwood’s A Sound Map of the Hudson River (2010) incorporates processed ultrasonic fish communication (30–50 kHz) to reveal hidden harmonic patterns of the river’s ecosystem, while Ryoji Ikeda’s data.tron (2007) uses real-time

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ultrasonic processing to generate evolving timbres, redefining music as a multi-sensory phenomenon. In therapeutic contexts, infrasonic-integrated music has shown efficacy in stress reduction and pain management—for example, 8 Hz infrasound paired with raga music reduced anxiety scores by 35% in a 2022 clinical trial—while ultrasonic-to-tactile conversion systems aid individuals with hearing loss in appreciating music by translating 25–40 kHz harmonics into distinguishable vibrations. In immersive media and spatial audio, ultrasonic directionality enables "personalized audio zones" (40 kHz waves focused into 1-meter diameters) for shared spaces like theme parks, allowing tailored sound experiences; meanwhile, infrasonic-tactile feedback in VR gaming (synchronizing 10–15 Hz vibrations with in-game events) increased perceived realism by 62% in a 2021 Microsoft Research study.

4.1. Experimental composition and sound art

Contemporary composers have embraced inaudible waves to challenge conventional musical aesthetics. Annea Lockwood’s A Sound Map of the Hudson River (2010) incorporates ultrasonic recordings of fish communication (30–50 kHz), processed to reveal harmonic patterns that underscore the river’s acoustic ecosystem [32]. The work, performed in immersive sound environments, invites listeners to engage with "hidden" sonic layers of the natural world.

Electronic musician Ryoji Ikeda’s data.tron (2007) uses real-time ultrasonic processing to generate evolving timbres, with 40 kHz signals modulated by visual data to create a synesthetic experience [33]. These examples demonstrate how ultrasonic and infrasonic waves are not merely additions to music but can redefine its conceptual boundaries, framing sound as a multi-sensory phenomenon [34].

4.2. Therapeutic and accessible music

In healthcare, infrasonic-integrated music has shown promise for stress reduction and pain management. A 2022 clinical trial by Patel et al. found that 8 Hz infrasound paired with raga music reduced subjective anxiety scores by 35% in patients undergoing medical procedures, with physiological markers (cortisol levels, heart rate variability) confirming the effect [35]. For individuals with hearing loss, ultrasonic-to-tactile conversion systems—where 25–40 kHz harmonics are translated into vibrations—have improved music appreciation, with users reporting enhanced ability to distinguish melodies [36].

4.3. Immersive media and spatial audio

In virtual reality (VR) and augmented reality (AR), ultrasonic directionality enables "personalized audio zones": 40 kHz waves focused into 1-meter diameters allow multiple users in shared spaces to experience distinct musical content [37]. This technology, deployed in theme parks and interactive installations, enhances immersion by tailoring sound to individual perspectives [38].

Infrasonic-tactile feedback systems, such as those in VR gaming headsets, synchronize 10–15 Hz vibrations with in-game events (e.g., explosions, footsteps). A user study by Microsoft Research (2021) found that such synchronization increased perceived realism by 62% compared to audio-only VR experiences [39].

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5. Perceptual mechanisms: how we experience inaudible music

The integration of ultrasonic and infrasonic waves into music challenges traditional models of perception, requiring an understanding of how the brain processes and integrates multi-sensory information. Regarding cross-modal integration of auditory and tactile signals, infrasonic vibrations activate the somatosensory cortex, which interacts with the auditory cortex to form unified perceptions; EEG studies indicate increased coherence between these regions when infrasound is synchronized with audible music, especially in the theta (4–7 Hz) and alpha (8–13 Hz) bands linked to emotional engagement, such as 12 Hz infrasound paired with a 120 bpm bassline creating a 6:1 frequency ratio that enhances rhythmic entrainment, as shown by heightened motor cortex activity. Meanwhile, ultrasonic-derived timbres, even after processing into the audible range, retain harmonic structures that activate specialized pitch-processing brain regions like the planum temporale, with fMRI data revealing similar responses to these timbres and naturally occurring audible ones, suggesting the brain recognizes preserved spectral patterns. Additionally, there are significant individual differences in perceptual responses to inaudible waves: around 15% of the population has reduced sensitivity to infrasonic vibrations due to anatomical differences in chest cavity resonance, and age-related hearing loss can weaken the processing of high-frequency components in ultrasonic-derived timbres, thus requiring adaptive systems (e.g., personalized infrasonic amplitude adjustment or ultrasonic harmonic emphasis) to ensure consistent musical experiences.

5.1. Cross-modal integration of auditory and tactile signals

Infrasonic vibrations activate the somatosensory cortex, which interacts with the auditory cortex to form unified perceptions [40]. EEG studies show increased coherence between these regions when infrasound is synchronized with audible music, particularly in the theta (4–7 Hz) and alpha (8–13 Hz) bands—associated with emotional engagement [41]. For example, 12 Hz infrasound paired with a bassline at 120 bpm (2 Hz) creates a 6:1 frequency ratio that enhances rhythmic entrainment, as observed in increased motor cortex activity [42].

Ultrasonic-derived timbres, though processed into the audible range, retain harmonic structures that activate specialized pitch-processing regions in the brain, such as the planum temporale [43]. Functional MRI (fMRI) data reveals that these structures respond similarly to ultrasonic-derived and naturally occurring audible timbres, suggesting the brain recognizes preserved spectral patterns [44].

5.2. Individual differences in perception

Perceptual responses to inaudible waves vary significantly across individuals. Approximately 15% of the population exhibits reduced sensitivity to infrasonic vibrations due to anatomical differences in chest cavity resonance [45], while age-related hearing loss can diminish the ability to process high-frequency components of ultrasonic-derived timbres [46]. These variations necessitate adaptive systems, such as personalized infrasonic amplitude adjustment or ultrasonic harmonic emphasis, to ensure consistent musical experiences [47].

6. Specific technologies for handling ultrasonic waves and infrasonic waves

The following are theoretically feasible technical schemes for the spectrum processing of ultrasonic and infrasonic waves. It should be noted that since the research group has not yet carried out relevant experimental verification, the practical feasibility of the following methods cannot be guaranteed.

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6.1. Three implementation paths for audio signal conversion

First, based on the digital signal processing (DSP) technology system, the software architecture is used to preprocess the digital signal stream of the audio waveform (including noise reduction and equalization), followed by encoding conversion (such as PCM, MP3 and other encoding standards) and algorithm operations (including digital signal processing algorithms like Fourier transform and convolution operation). Through the digital operation process, digital-to-analog conversion (DAC) is completed to reconstruct discrete digital signals into continuous analog electrical signals, which are finally driven by the audio amplifier circuit to transducers (such as speakers) to generate audible audio signals. This process relies on the computing power support of digital signal processors (DSP chips) or general computing units (such as CPU and GPU), and features precise parameter regulation and programmable processing procedures.

Second, a pure hardware implementation path is adopted, without the involvement of software or programmable logic: acoustic sensors such as electret microphones or dynamic microphones are used to complete acoustoelectric conversion to obtain original electrical signals, which are then restored by demodulation circuits (such as amplitude demodulation and frequency demodulation modules), or directly converted into mechanical vibrations by means of the inverse piezoelectric effect/magneto strictive effect of functional acoustic materials (such as piezoelectric ceramics and magneto strictive materials). This vibration forms sound waves within the human audible range (20Hz-20kHz) through solid medium conduction or air radiation. This path, by eliminating the digital processing link, has the advantages of fast response speed and low system delay. However, parameter adjustment needs to be realized through hardware circuits (such as variable resistors and capacitor networks), resulting in relatively limited flexibility.

Third, through manual regulation of time-domain stretching (time scale adjustment based on interpolation algorithms) and frequency-domain scaling (frequency axis mapping achieved through resampling), ultrasonic/infrasonic signals or signals in non-audible frequency bands are directly mapped to the audible frequency band. Specifically, frequency compression is achieved by reducing the sampling rate (to move high-frequency signals into the audible range), or frequency expansion is completed by increasing the sampling rate (to stretch low-frequency signals to the audible range). This process is essentially a linear time-domain-frequency-domain scale transformation of the signal. By avoiding complex algorithm processing, this method is the most direct means of signal frequency band migration and has the characteristic of high frequency stability (distortion mainly stems from linear transformation errors). After simple low-pass filtering (to filter out aliasing noise) and automatic gain control (AGC) to adjust the dynamic range, it can be converted into an audio signal meeting musical requirement, suitable for scenarios with high real-time requirements but low processing accuracy requirements.

6.2. Principles based on Amplitude Modulation and aliasing

Principle of Spectrum Migration Based on Amplitude Modulation (AM): Amplitude modulation operates on the core mechanism whereby the instantaneous amplitude of a carrier signal undergoes adaptive adjustments in response to the dynamic variations of a modulating signal. Its mathematical formulation is expressed as $s_{AM}(t)=A_c[1+k_a\ m(t)]\cos(2\pi f_c\ t)$, where A_c denotes the carrier amplitude, k_a represents the modulation coefficient, $m(t)$ stands for the modulating signal, and f_c is the carrier frequency. When the modulating signal couples with an ultrasonic signal, sideband frequency components of $f_c \pm f_m$ (with f_m being the frequency of the modulating signal) are excited

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within the system. This process essentially realizes the controllable migration of the ultrasonic spectrum.

Principle of Deliberate Aliasing Based on the Nyquist Sampling Theorem: The Nyquist sampling theorem stipulates that to avoid aliasing distortion, the sampling frequency fs must satisfy the constraint fs>2fmax, where fmax is the maximum frequency of the signal. If the sampling frequency is intentionally set to be lower than twice the maximum frequency of the signal, aliasing will be induced. In the context of ultrasonic spectrum processing, when the ultrasonic frequency exceeds half of the sampling frequency, its spectrum will undergo a "folding" effect into the low-frequency domain, thereby achieving a specific form of spectrum migration.

7. Challenges and future directions

Despite the clear potential of ultrasonic and infrasonic waves in music, several significant challenges need to be addressed to fully realize their capabilities. Technical and practical barriers include hardware limitations: ultrasonic transducers have low signal-to-noise ratios at frequencies above 50 kHz, hindering harmonic extraction; infrasonic systems face environmental interference from sources like HVAC or traffic, requiring adaptive noise cancellation; and software struggles with real-time processing of high-frequency ultrasonic signals, which demands substantial computational power and often results in latency (≥50 ms) that is unacceptable for live performances. Future progress also relies on interdisciplinary collaboration and standardization, such as partnerships between acousticians, composers, and neuroscientists to develop "perceptual maps" linking ultrasonic harmonic structures to emotional responses for targeted timbre design, and the establishment of standardized evaluation metrics (e.g., "tactile-auditory coherence" or "harmonic preservation index") to enable comparative research. Additionally, expanding access and education is crucial: open-source platforms like Pure Data extensions for spectral mapping can reduce barriers for independent artists, while educational initiatives such as workshops on ultrasonic/infrasonic music theory can cultivate a new generation of creators skilled in these emerging techniques.

7.1. Technical and practical barriers

Hardware limitations remain a primary obstacle. Current ultrasonic transducers suffer from low signal-to-noise ratios at frequencies above 50 kHz, complicating harmonic extraction [48]. Infrasonic systems, meanwhile, struggle with environmental interference—vibrations from HVAC or traffic can mask musical infrasound, requiring adaptive noise cancellation [49]. Software-wise, real-time processing of high-frequency ultrasonic signals demands significant computational power, with latency exceeding acceptable limits (≥50 ms) for live performance [50].

7.2. Interdisciplinary collaboration and standardization

Future progress depends on collaboration between acousticians, composers, and neuroscientists. For example, developing "perceptual maps" that link ultrasonic harmonic structures to emotional responses could guide composers in targeted timbre design [51]. Standardizing evaluation metrics—such as "tactile-auditory coherence" or "harmonic preservation index"—would facilitate comparative research across studies [52].

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7.3. Expanding access and education

Making ultrasonic and infrasonic processing tools accessible to all is crucial. Open-source platforms—like extensions for Pure Data that handle spectral mapping—can reduce barriers for independent artists [53]. Seminars about the theory of ultrasound and infrasound music might also be used as a form of training to create a new breed of artists skilled in the new techniques [54].

8. Conclusion

This remark clarifies how diatonic, ultrasonic, and infrasonic sounds can transform music, which is brought about by contemporary spectral processing. Although viewed earlier as meaningless to the musical experience since their frequencies were in the inaudible spectrum, these waves now enable new possibilities of innovation: ultrasonic waves give harmonic depth to new timbres. Meanwhile, infrasound waves provide a touch element that contributes to emotional knowledge.

Key findings are the efficiency of spectrum conversion with machine learning, how intersensory networks of the brain form the basis of perception of these imperceptible sounds, and many applications of immersive media in art and therapy. Nevertheless, technical problems, like hardware bottlenecks, processing delay, and personal differences in wave perception, remain to be solved.

These issues will involve interdisciplinary efforts, concerted research approaches, and tools that can be easily accessible to solve these problems. These efforts are likely to make ultrasonic and infrasonic waves redefine music as a multisensory experience that is not limited to hearing, which has long been the domain of music, but is targeted at all human senses instead. What we can hear is less about what we can feel in terms of the future of music and more about what we can hear.

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