

# Vibro-Acoustic Spatial Modulation for Enhancing Environmental Experience in Interior Spaces

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## Abstract

Low-frequency noise is present in everyday indoor environments due to the operation of air conditioning systems and various other devices. Still, its effects have mainly been discussed in the context of discomfort and physical stress under high sound-pressure conditions. In this paper, we provide an overview of the impact of relatively weak low-frequency components on the structure of sound environments and spatial impressions using two different approaches. First, we analyzed acoustic indices for signals containing a 40 Hz low-frequency component added to white, pink, and brown noise. We confirmed that the addition of low-frequency components changes the time fluctuation characteristics and spectral structure depending on the type of noise. In particular, for pink noise and brown noise, which contain a lot of energy in the low-frequency band, the addition of a 40 Hz component produced clear changes in the index values. Next, as an exploratory test based on these results, low-level infrasound (33 Hz and 40 Hz) was added to the background sound in an ample indoor space, and participants' spatial impression evaluations were investigated. A temporary decrease in evaluation items such as comfort, naturalness, and calmness was observed during the addition of infrasound, but evaluations tended to recover when the infrasound was stopped. Analysis of the recorded data confirmed a relative increase in low-frequency band energy at the participants' positions, and that changes in the sound field structure and subjective evaluations occurred simultaneously. These results suggest that weak low-frequency components can affect the structure of a sound environment and the spatial impression while interacting with background sounds and the spatial sound field. The findings presented in this paper complement the conventional framework that treats low-frequency sound as simple noise and provide basic information for evaluating and designing indoor sound environments.

*Keywords:* Numerical integration, Multibody dynamics (MBD), Analysis error, Ordinary differential equation

## 1. Introduction

Low-frequency sound is present in everyday indoor environments due to the operation of air conditioning equipment, ventilation systems, and various other devices. It is often not perceived as a distinct sound [5]. However, when it comes to the evaluation and control of sound environments, there is still insufficient understanding of how low-frequency components contribute to a space's overall characteristics. Conventional low-frequency sound research has often focused on discomfort and physical effects under high sound pressure conditions, and there has been limited systematic examination of the impact of relatively weak low-frequency components on the structure and impression of a sound environment [1][2][3].

In recent years, indices that reflect not only simple sound pressure level, but also spectral structure and temporal fluctuations have been used to evaluate sound environments [4]. It is empirically known that adding specific frequency components to a noise signal changes the perceptual impression. Still, it is difficult to say that the way this change manifests in acoustic indices has been fully clarified [2][3]. In particular, few reports examine,

under relatively simple conditions, the direction of change in acoustic indices when low-frequency components are added to noise (white, pink, brown).

In this paper, we first analyze how acoustic indices change when a 40 Hz low-frequency component is added to a noise signal, and summarize the impact of low-frequency components on the structure of a sound environment at the index level. Next, as an applied verification of these results, we explore how the impression evaluation of a space changes when low-level, low-frequency sound is added to a large-scale indoor space. Across both studies, we aim to demonstrate that low-frequency components, when combined with background sounds, can affect the objective characteristics and subjective impressions of a sound environment. Methodology.

## 2. Acoustic Analysis of Noise Signals with Added 40 Hz Component

We examine how the structure of a sound environment changes when low-frequency components are added to background noise, based on acoustic indices. The background noises studied are three types: white noise,

pink noise, and brown noise, all of which are widely used representative stochastic process sounds. A 40 Hz sinusoidal component was superimposed on these noise signals, and the results were compared with those of noise alone (Figure 1).

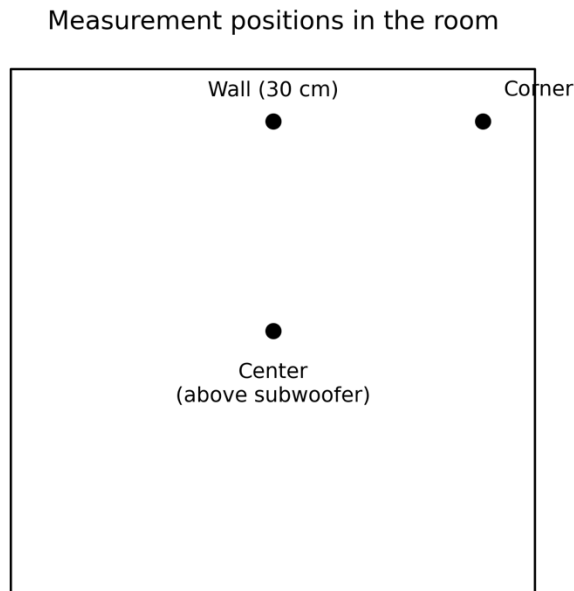


Figure 1. Measurement positions in the room used for acoustic analysis: the room center (directly above the subwoofer), a position 30 cm from the wall, and a corner position.

All noise signals and low-frequency components were generated as digital signals. When comparing noise-only conditions with low-frequency components, each signal was normalized before analysis to ensure that differences in overall sound pressure level did not affect the results. The amplitude of the 40 Hz component was not set so high as to completely dominate the noise component, but rather at a level intended to impart local structure to the low-frequency band. This setting allows capturing the effect of adding low-frequency components on the structure of the sound environment, as a change in an index.

For the analysis, we used acoustic indices that reflect the time-varying characteristics and spectral distribution of sound, rather than the sound pressure level itself. These indices aim to quantitatively express the "structure" and "complexity" of the sound environment, and are suitable for detecting differences that are difficult to detect through simple level changes. We applied the same analysis procedure to each condition and compared the index values between the noise-only and low-frequency-added conditions.

The analysis showed that adding a 40 Hz component resulted in specific changes in acoustic indices across all noise conditions (Figure 2). Still, the manifestation of these changes varied greatly depending on the type of noise. When low-frequency components were added to white

noise, changes in index values were relatively limited, and many indices related to time fluctuations and spectral structure did not differ significantly from the noise-only condition. One reason is that white noise has equal energy across all bands, making structural changes due to the addition of a single frequency component less noticeable.

In contrast, adding a 40 Hz component to pink and brown noise produced clearer changes in the index values. Because these noises contain relatively more energy in the low-frequency range, the addition of a 40 Hz component is likely to directly affect the structure of temporal fluctuations and the frequency distribution. In particular, indices reflecting the dominance of the low-frequency range and the regularity of temporal fluctuations showed trends that differed from those observed under noise-only conditions.

These results indicate that the addition of low-frequency components does not simply increase sound pressure level, but can reconstruct the structure of the sound environment depending on the type of background noise. In other words, the effect of low-frequency components interacts with the spectral and temporal characteristics of the background noise, and the magnitude and direction of the influence vary depending on the type of noise. This is a feature that is difficult to capture within the conventional framework that uniformly treats low-frequency sound as "noise."

The changes at the index level shown in this chapter are fundamental results that show that low-frequency components can affect the structural aspects of a sound environment and serve as the premise for the exploratory verification in real spaces described in the next chapter. In other words, this suggests that the phenomenon in which the properties of a sound environment change when low-frequency components are combined with background sounds may be reflected in actual spatial experiences.

LF-band energy (30–50 Hz) with and without 40 Hz component

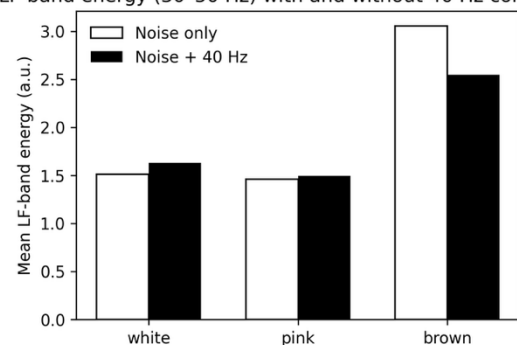


Figure 2. Mean low-frequency band energy (30–50 Hz) for white, pink, and brown noise with and without an added 40 Hz component. Adding the 40 Hz component increased low-frequency energy in all noise types, with larger changes observed for pink and brown noise.

### 3. Exploratory Validation in a Real Indoor Space

The results of the index analysis presented in the previous chapter indicate that low-frequency components can change the structure of the sound environment depending on the type of background noise. In this chapter, we conduct an exploratory experiment to examine how the changes observed at the index level can correspond to people's spatial experiences in actual indoor spaces.

The experiment was conducted in an ample indoor space with a ceiling height of approximately 2 m, a width of approximately 10 m, and a depth of roughly 30 m. The air conditioning system was constantly running in this space, and the presence of low-level background noise was used as the reference condition. Low-frequency sounds were presented using a subwoofer, with 33 Hz and 40 Hz components superimposed on the background noise. The sound pressure level of the low-frequency sounds was approximately 55–60 dB at a position approximately 3 m from the subwoofer where the participant was seated, as measured with an auxiliary smartphone. This level was not high enough to be perceived as distinct noise, but instead was distributed throughout the space as a weak, low-frequency component that blended into the background noise.

To understand the characteristics of the sound field formed by the addition of low-frequency sound, recordings were made at multiple locations (2 m, 3 m, near a side wall, and in a corner) with different distances and positions from the subwoofer. Analysis of the recording data revealed that, under the low-frequency sound condition, energy in the 30–50 Hz band increased significantly, particularly around 3 m, which was close to the participant's position, and that relatively strong low-frequency components were formed compared to the background sound condition. However, the increase was more minor near the side wall and in the corner, and the distribution of low-frequency components clearly exhibited positional dependence (Figure 3).

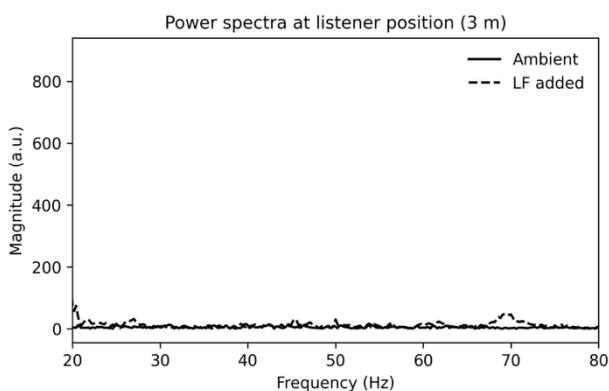


Figure 3. Representative power spectra at the listener position (3 m) under ambient and low-frequency exposure conditions. The low-frequency exposure condition shows a clear increase in spectral energy around 33 Hz and 40 Hz compared with the ambient condition.

In the subjective evaluation experiment, participants remained seated in the same position and experienced three consecutive conditions: no low-frequency sound, a state with low-frequency sound added, and a state after the sound was turned off, and rated their impression of the space under each condition. The results showed that when low-frequency sound was added, scores on evaluation items such as "comfort," "naturalness," and "calmness" tended to decrease. In many cases, the evaluations recovered when the low-frequency sound was turned off. The change in the assessment of "calmness," in particular, was relatively significant, suggesting that low-frequency components may affect aspects of emotional stability.

These results are consistent with the index analysis presented in the previous chapter. In other words, they show that the structure of the sound environment changes when low-frequency components are combined with background sounds, and that this change can be reflected in the evaluation of spatial impressions in real spaces. However, the experiments presented in this chapter are exploratory, and further research is needed to specifically separate the effects of individual differences in evaluation and spatial conditions.

### 4. Discussion

This paper outlines the changes in acoustic indices when low-frequency components are added to noise signals, and the effects of low-level, low-frequency sound in real space as an applied verification. The results of the index analysis shown in Chapter 2 confirmed that adding a 40 Hz component can change the structure of the sound environment depending on the type of background noise. In particular, for low-frequency-weighted noises such as pink and brown noise, adding low-frequency components had a clear impact on time fluctuations and spectral structure.

In the real-space experiment described in Chapter 3, participants' spatial impression evaluations temporarily changed when low-frequency components were added. These changes were reversible and recovered when the low-frequency sound was stopped, suggesting that even low-frequency components at levels not perceived as evident noise can affect spatial experience.

Considering both together, it is possible that low-frequency components do not act independently, but rather change the characteristics of the sound environment by interacting with the properties of background sounds and the structure of the spatial sound field. Although a quantitative correspondence has not yet been demonstrated directly between the structural changes confirmed in the index analysis and the fluctuations in subjective evaluations in real spaces, it is noteworthy that at least a tendency in the same direction has been observed.

The real-space experiment discussed in this paper is merely exploratory, and limitations prevent fully separating factors such as the number of participants, spatial conditions, and differences in frequency

composition. However, the significance of this paper lies in the fact that it has shown, from two perspectives, index analysis and real-space verification, that low-frequency components can affect both the structure of a sound environment and the spatial impression. These results are expected to provide basic knowledge for systematically examining the role of low-frequency sound through a more detailed experimental design and statistical verification in the future.

## 5. Conclusion

In this paper, we provided a preliminary overview of the effects of low-frequency components on acoustic environments by combining an index-based acoustic analysis with an exploratory validation conducted in a real indoor space. The analysis of noise signals with an added 40 Hz component demonstrated that acoustic indices respond differently depending on the type of background noise, suggesting that low-frequency components can influence the structural characteristics of sound environments.

Furthermore, the exploratory experiment conducted in a large indoor space showed that adding low-level low-frequency sound to background noise was associated with temporary changes in perceived indoor impressions, which tended to recover after the low-frequency sound was turned off. These observations indicate that even low-frequency components at levels not perceived as explicit noise may affect spatial experience.

The results presented here complement conventional approaches that treat low-frequency sound primarily as an undesirable noise component. Instead, they suggest that low-frequency components may interact with background sound and spatial sound fields in shaping acoustic environments. Further systematic investigations under varied acoustic and spatial conditions are required to clarify the role of low-frequency sound in indoor environmental perception.

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## Authors Introduction

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