MECHANICAL ADMITTANCE BASED PHYSICAL ATTRIBUTES REPRESENTATIONS OF RIBBED PLATES

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Mechanical admittance has tight relationships with physical attributes and it's a vital factor that determines the property of radiated sounds. In order to find acoustic cues for identifying physical attributes (Elastic modular, density, Poisson ratio, global damping ratio and the combined form of them) of ribbed plates, mechanical admittance is introduced as a bond or medium between them. Firstly, monotonic relationships between mechanical admittance features and physical attributes of ribbed plates are built via correlation analysis under the condition of invariable size and shape. Secondly, the correlations between mechanical admittance features and sound features are analyzed. These sound features are extracted from ideal impact sound (ratio of sound to force) or from timbre toolbox (as a comparison). The results show that: 1) Mechanical admittance features explain physical attributes well, which confirmed their tight relationships; 2) Poisson ratio seems to have a low weight in mechanical admittance so that there's no admittance feature related with Poisson ratio when all four attributes are uncontrolled; 3) Acoustic cues from ideal impact sounds can explain more attributes than those from timbre features. As a whole, mechanical admittance based method proposed in this paper builds the relationships between sound features and physical attributes through mechanical admittance and provides a new sight of acoustic cues extraction for sound source identification.
Keywords: admittance, physical attributes, acoustic cues, ribbed plates

1. Introduction

Most of us have the experiences of "sounding object" in our daily life, and we are able to determine whether the impacted object is hollow or solid, metal or wood, soft or hard even what item it exactly being only by one sound. This phenomenon reveals the fact that these impact sounds may carry some property information of the objects. The acoustic cues corresponding to physical attributes are essential to sound source identification. Researchers tried hard to find *invariant acoustic information/cues* that would identify attributes of different objects via psycho-acoustical method in the past two decades. Acoustic cues of single physical attribute (such as stimulate position, material, shape and size, hollow, mallet hardness) is investigated when other attributes and circumstances are controlled avoiding the interaction of other fators. Earlier studies on sound source identification mainly utilize real bar and plate with a few typical materials (such as glass, wood and aluminium), but those materials are not enough to obtain stable and fine relationships between acoustic cues and attributes. Recent studies have a tendency of using synthesized sounds which allow flexible choice of materials and geometric dimensioning [1]. Though there are a lot of studies on this topic, to author's knowledge, no one has obtained *invariant acoustic information/cues* so far. Since impact sounds are determined by so many attributes, the *invariant acoustic information/cues* must be a very complicated one if it exists. This study is not trying to find the complicated *invariant* *acoustic information/cues* at once but providing a different angle which may helpful. Unlike subjective psycho-acoustical methods, the method in this study seems much more objective which establishes the relationships between attributes and acoustic cues via mechanical admittance.

Mechanical admittance has tight relationships with physical attributes and it's one of the vital factors that determine what the radiated sound sounds like. As shown in Fig. 1, mechanical admittance $G(\omega)$ is the system function between input force response $F(\omega)$ and output velocity response $V(\omega)$, which reflects the physical attributes. Several typical studies have supported this viewpoint: Skudrzyk used the mean-value theory to build a formulation between mechanical admittance features (mean value and modal density) and mass of the plate [2]; Xie calculated the modal density of mechanical admittance via mass density, thickness, area and Yong's modular of the plate [3]; and Elie identified Yong's modular, mass density, modal damping factor through mechanical admittance features based on previous studies [4]. From Fig. 1, we can also conclude that mechanical admittance has important contribution to both $V(\omega)$ and received impact sound $S(\omega)$. Actually, the tight connection of Long-time averaged spectral envelope and mechanical admittance (called mobility in references [4,5]) has been found in Elie's recent study. Although studies above investigated the relationships of mechanical admittance and attributes, mechanical admittance and radiated sound separately, the potential relationships between attributes and acoustic cues have not been investigated yet. Motivated by this idea, this study is trying to establish relationships between attributes and acoustic cues via mechanical admittance.

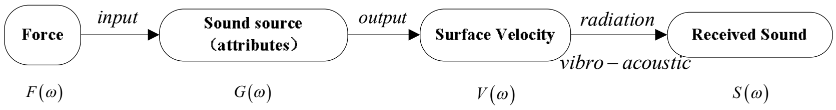


Figure 1: The formation of typical impact sound.

This study is mainly about ribbed plates, which are widely used in aircrafts and ships to ensure better structural strength than that of flat panels. Studies about ribbed plates can be helpful for target identification or mechanical fault diagnosis.

The purpose of this study is finding acoustic cues related with physical attributes (about material) via mechanical admittance, result of which may lay the foundation of further study of automatic sound source identification of ribbed plates (in different materials). Section 2 introduces the properties of mechanical admittance and the acoustic cues extraction method based on them. In Section 3 and Section 4, the relationships between admittance features and physical parameters as well as relationships between admittance features and impact sound features are separately analyzed by a correlation analysis method. Eventually, the conclusions are summarised in Section 5.

2. Mechanical admittance based acoustic cues extraction method

2.1 Theories of the driven-point admittance

The input admittance (or mobility) of a structure is the ratio in the frequency domain between the velocity of the structure and the excitation force [2]. Input admittance is affected by positions of the driven force and the receiving velocity, because points at the wave notes can hardly stimulate or pickup vibration modals. Hence, driven-point admittance is specified in this study avoiding potential problem caused by the positional differences. Typical driven-point admittance for flat plates can be written as Eq. (1) and Eq. (2) [4].

$$G_A(\omega) = j\omega \sum_{k=1}^{N} \frac{\Phi_k^2(A)}{m_k\left(\omega_k^2 + j\eta_k\omega_k\omega - \omega^2\right)}, \tag{1}$$

$$\eta_k = \frac{2\alpha_k}{\omega_k}. \tag{2}$$

Where A denotes the driven-point, Φ_k, ω_k, m_k and α_k are the modal shape, the modal frequency, modal mass and the modal damping ratio of the k th mode, respectively.

Unlike flat plates referred in Skudrzky's study, ribbed plates are not structures with continuous compliance and mass properties [2]. That means ω_k can not be calculated directly though simple equations. Lin provides an accurate model that the ribbed plate is treated as the coupling of a plate and a bar, and ω_k can be calculated after the decoupling process [6]. That seems to be complicated, but lucky the Computer Aided Engineering technology (CAE) is strong enough to calculate modals of complex structures rapidly via finite element method (FEM) and the boundary element method (BEM). With the CAE software (using LMS Virtual.lab in this study), the admittance functions can simply be acquired by Eq. 3.

$$G_A(\omega) = \frac{V_A(\omega)}{F_A(\omega)}. \tag{3}$$

Where $V(\omega)$ was the velocity response of the impacted ribbed plate (calculated in the *Transient Force Response Case* in Virtual.lab), $F(\omega)$ is the driven force response which will be described in Section 2.2. Besides the advantage of rapid calculating, using CAE software can be more flexible on the choice of basic physical attributes and easier to achieve the impact sound synthesis.

2.2 Property of simulated mechanical admittance

Instead of 3-d elements, 2-D triangle elements of 10mm are used through the FEM and BEM analysis since the thickness of rib is not more than the thickness of the basal plate [6]. Fig. 2 shows the structure mesh of a ribbed plate, the rib divides the panel into two equivalent rectangle components. Driven-point of the force (or receiving point of the velocity response) is located at one tenth of the diagonal of the panel. For sake of consistency in different experiments, the driven force is synthesized. As shown in Fig. 3, time-function of the force consists of two half-Gaussians and forms an asymmetrical bell-shape which rises faster than it decays [4]. The bell-shape waveform is restricted in 1ms avoiding multi-impact.

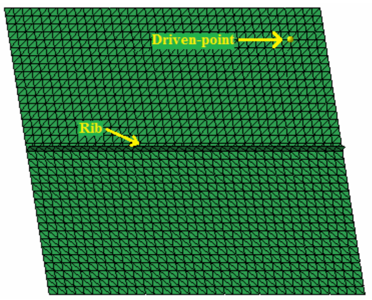


Figure 2: Mesh and driven-point

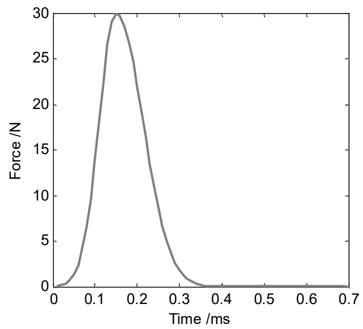


Figure 3: Temporal driven-force

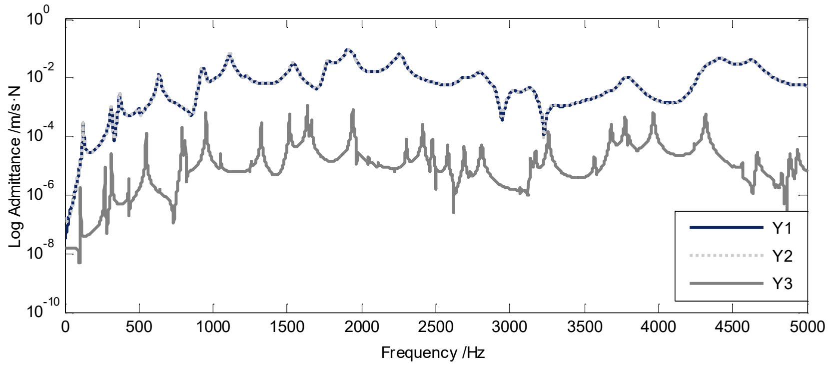


Figure 4: Spectrums of different mechanical admittances

In order to clarify the properties of simulated mechanical admittance under the factors of driven force and material, 3 mechanical admittances are calculated in Fig. 4 via Eq. 3. Y1 and Y2 are in the same materials (physical attributes) but different driven forces; Y1 and Y3 have the same impact force but in different materials. As expected, driven-point admittance is dependent with the driven force when the position of driven-point is fixed (Y1, Y2 are the same), and the material attributes determine the driven-point admittance (Y1, Y3 are different). These properties make it possible to build the potential relationships between physical attributes and admittance features.

Recent study finds another property of mechanical admittance that lateral bridge admittance of a violin is greatly related with logarithm amplitude of corresponding harmonics sounds [5].

2.3 Introduction of mechanical admittance based method

A general framework of the mechanical admittance based method for acoustic cues extraction is shown in Fig. 5. The fundamental of this method is the synthesis of mechanical admittances and impact sounds of ribbed plates. Then, correlation analysis between mechanical admittance features and physical attributes, mechanical admittance features and sound features are conducted successively. Eventually, acoustic cues representing physical attributes are obtained as results of the correlation analysis. These acoustic cues might be used in further study of automatic sound source identification.

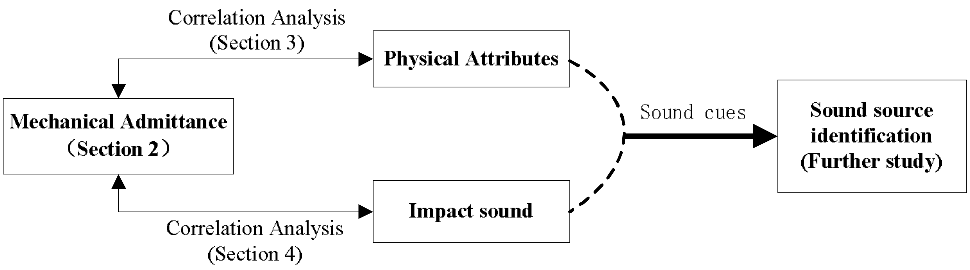


Figure 5: General framework of mechanical admittance based method

3. Relationships between attributes and admittance features

As concluded in Section 2.2, attributes determines the mechanical admittance, so there must be some admittance features that explain the attributes well. This section deals with the correlation analysis between physical attributes and admittance features. The virtual material library and basic admittance features used in the study are separately provided in Section 3.1and Section 3.2. The results and conclusions are discussed in Section 3.3.

3.1 Virtual material library

Materials in real life usually have an inhomogeneous and disperse distribution [7]. That will not be helpful to the investigation of finer disciplines between attributes and admittance features. Lutfi indicates that synthesized methods will be used more and more frequently in the following studies of sound source identification since it is more flexible for people to obtain sounds of continuous attributes [1]. In Virtual.lab, an isotropic material can be defined with four attributes: elastic modular (E), mass density (ρ), Poisson ratio μ and modal damping ratio ζ (global damping ratio in this study). Since our goal is trying to achieve metal material presentation of ribbed plates, the shape and size of ribbed plates are fixed (cf: Fig. 3 and Table 1) and materials attributes (cf: Table 1) are restricted to the ranges of metal. Every material used in section 2 and section 3 is obtained by uniform interpolation method of the attributes range displayed in Table1.

3.2 Basic features of mechanical admittance

Typical spectral and temporal features of mechanical admittance used in this study are listed in Table 2, containing the main admittance features used in Elie's study about plates and features from reference [8]. Among these features, modal density are extracted in two different ways (the finding peaks technique and the T-ESIRT technique), initial slope is obtained by linear fitting at the range of 0~$f_0/2$ (or 0~50 when $f_0 > 50$), mean admittance is averaged in the high frequency range of 4000~5000Hz.

Table 1: Physical attributes ranges of virtual materials.

Material Attribute	Range	Unit	Fixed Size	Range	Unit
E	60-500	GPa	Size of the panel	360×360	mm^2
ρ	2-10	Mg/m3	Height of rib	10	mm
μ	0.2-0.45		Thickness	2	mm
ζ	0-2%				

Table 2: Basic admittance features ("T" denotes the temporal features).

Admittance Feature	Unit	Abbr.	Admittance Feature	Unit	Abbr.
Spectral centroid	Hz	SC	Mean admittance	$m/s \cdot N$	Gc
Centroid bandwidth	Hz	SCBW	Spectral variance	$m/s \cdot N$	Var
Spectral irregularity		SI	Spectral standard	$m/s \cdot N$	STD
Spectral envelope area	$(m/s \cdot N)^2$	SEA	Temporal centroid (T)	s	TC
Spectral roll-off	Hz	SRO	Zero across rate (T)		ZCR
Modal density	Hz^{-1}	nw1;nw2	Decay time (T)	s	DT
Initial slope	$m/s \cdot N \cdot Hz$	P	Decay slope (T)	$m/s^2 \cdot N$	DS
Fundamental frequency	Hz	f0	Crest factor (T)		CF

3.3 Result of correlation analysis

To ensure the stability of relationships between attributes and admittance features, two parts of correlation analysis experiments are conducted under the method of control variates. The first part is conducted under the circumstance that all the four attributes are interpolated (all four attributes are uncontrolled), and the second part is conducted when single one of the attributes is interpolated (the other attributes are controlled to a fixed value). When one attribute is controlled in the second part, it will be fixed to $E = 280\text{Gpa}$ (or ρ=6Mg/m^3 , or μ=0.325 , or ζ=1%). The scatter diagrams and fitting curves of relationships obtained in experiments (only monotonous relationships in both experiments with correlation coefficient larger than 0.75 are shown) are displayed in Fig. 6.The subscripts "1","2","3"and"4"represent the case when only one attribute E , ρ , μ or ζ is uncontrolled, separately. It is noted that B is a combined attributes which equal to $\alpha\sqrt{E/p}$, and α is a constant factor for unit converter. The monotony condition ensures that every one feature value corresponding to one attribute value. Actually, we can represent three basic attributes (E , ρ and ζ) with admittance features from four relationships in Fig. 6. The probable reason that there's no admittance feature corresponding to Poisson ratio μ can be explained by the limited small range (0.2~0.45) in Table2.

The relationship of P and E is introduced from the defect detection theory of foundation pile. Initial slope of admittance spectrum reflects the dynamic stiffness. Zhang's study shows a linear relationship between dynamic stiffness and elastic modular for a pile [9]. This relationship seems to work in the ribbed plates.

The crest factor CF is expected as feature that explains the damping ratio ζ since both of them reveals the attenuating property of the sound.

The representation of B by f0 can be partly explained by the isotropic panel theory [3]. Modal frequencies can be described by Eq. 4.

$$\omega_{mn} = \sqrt{\frac{D}{\rho h}} k^2 = \sqrt{\frac{D}{\rho h}} \left[\left(\frac{m\pi}{a} \right)^2 + \left(\frac{n\pi}{b} \right)^2 \right], \quad \text{Where } D = \frac{Eh^3}{12(1-\mu^2)}. \tag{4}$$

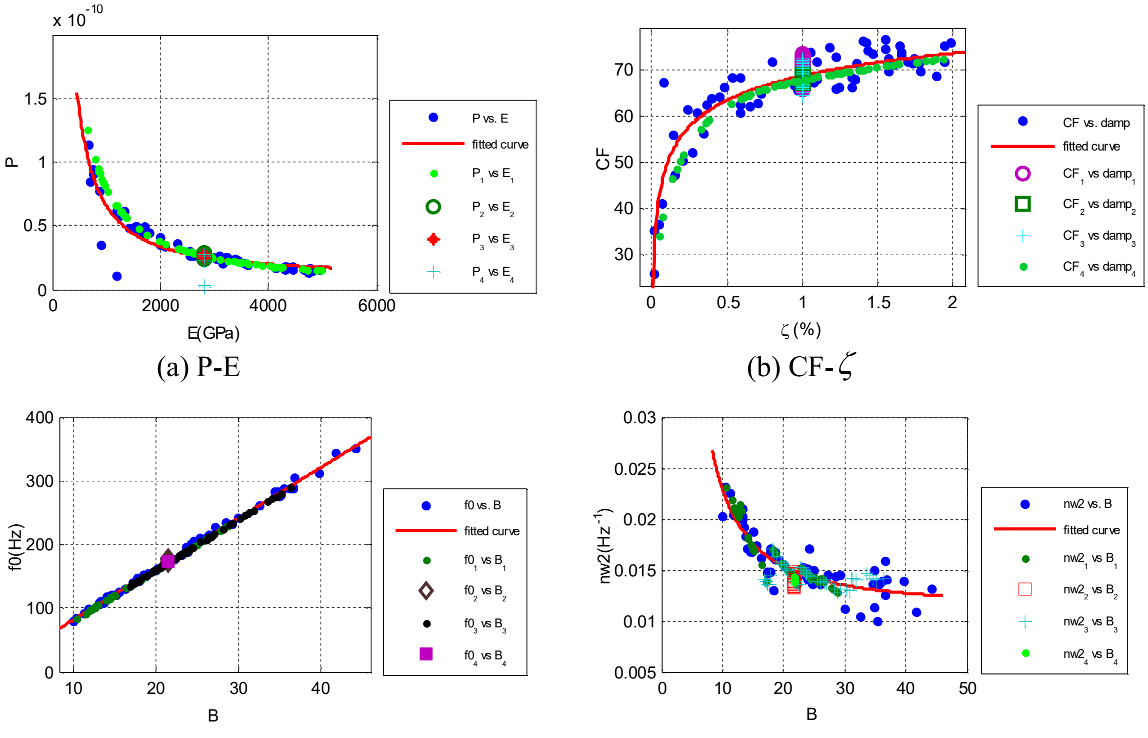
Where h is the thickness of a panel. Fundamental frequency f0, can be evaluated by $f_{1,1}$

$$f_{1,1} = \frac{\pi h}{2L^2\sqrt{3}} \times \sqrt{1/(1-\mu^2)} \times \sqrt{E/\rho}. \tag{5}$$

The first term on the right side of Eq. 5 is a constant, and the second term $\sqrt{1/(1-\mu^2)} \in (1.02 \sim 1.12)$ varies in a very small range, that ensures B to be proportional to f_{11}. Compared with f_{11} of original panel, the rib of the ribbed plate has limited affects on f_{11}. Thus f0 seems to be linear with B.

The relationship between nw2 and B dates back to Xie's modal density study of plates, but modal density seems not regressive at the higher frequency for ribbed plates [3]. Actually, we can observe from the FEM analysis that the rib stirs the distribution of modals (especially higher order) of the basic panel.

There are many features strongly related with Poisson ratio in the second part of the experiments, nevertheless there's none in first part of the experiments. That may be explained by its low weight in the mechanical admittance, the fact that $\sqrt{1/(1-\mu^2)}$ has little influence on f0 is a good example.



(a) P-E (b) CF-ζ

(c) f0-B (d) nw2-B

Figure 6: Scatter diagrams of obtained relationships

4. Relationships between attributes and sound features

This section is trying to find acoustic cues of admittance features (which related with physical attributes) obtained in section 3. To achieve this goal, correlation analysis of sound features and admittance features is applied. Considering that mechanical admittance and physical attributes are independent from driven force (cf: section 2), force information seems to be useless for attributes identification. Thus we use ideal sound for sound features extraction. The ideal sound defined here is the sound without driven force information, which can be calculated simply by $S(\omega)/F(\omega)$. As a comparison, traditional sound features extracted from timbre toolbox are also considered as basic sound features. Results of different sound features are shown as follow.

4.1 Ideal sound cues

All sound samples are synthesized using FEM- MEM-BEM method (MEM: Modal Expansion Method) and all material attributes are randomly interpolated in the range displayed in Table 1 [10]. Fig 7 shows the spherical sound field (with a radius of 1m) and the reference point. Every sound sample is restricted to 1s with a sampling rate of 44.1 kHz.

Ideal sound features are extracted using the same features obtained in section 3. The scatter diagrams of features extracted from mechanical admittance (labelled with subscript "1") and ideal sound (labelled with subscript "2") against corresponding attribute are displayed in Fig. 8. As references, fitting curves based on admittance features are also displayed. f0- B , CF- ζ and P-E preserves the monotonous tendency, however, nw2-B is not regressive anymore. Modal density nw2 seems to be affected during the vibro-acoustic process. Thus we have got acoustic cues for three main attributes (E, ρ and ζ , the low weight Poisson ratio is negligible) through ideal sound features.

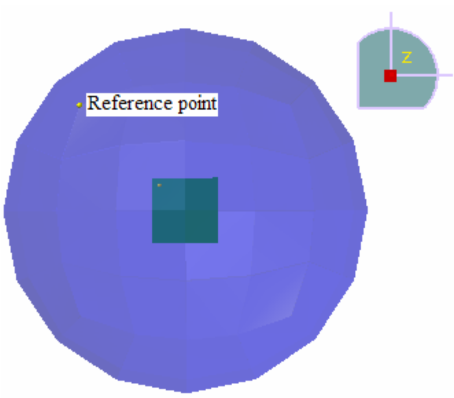
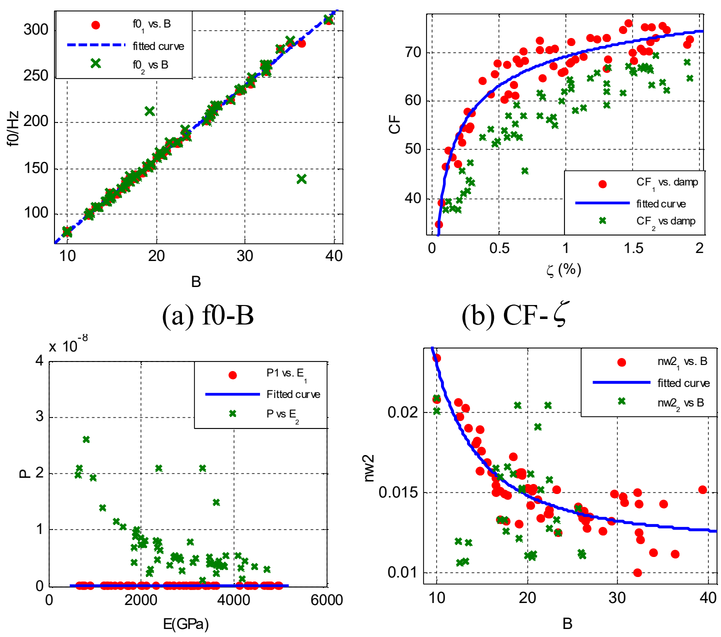


Figure 7: Sound field and reference point of the simulation.



(a) f0-B (b) CF- ζ

(c) P-E (d) nw2-B

Figure 8: Features from admittance and ideal sound.

4.2 Acoustic cues from timbre features

Timbre features are extracted directly from impact sounds. Features extracted are based on short-term Fourier transform, harmonic sinusoidal components, auditory model based on the equivalent rectangular bandwidth concept and the energy envelope [11]. The main result of correlation analysis of 164 timbre features and admittance features extracted in section3 are shown in Fig 9.

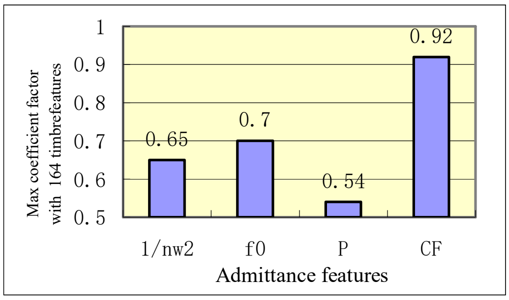


Figure 9: Max coefficient factors of admittance features and timbre features

Except for CF, coefficient factors between admittance features and timbre features are week (less than 0.70). The most relevant two timbre features with CF (corresponding to attribute ζ) are ERBgam_FrameErg_iqr and ERBfft_FrameErg_iqr. Thus we get two acoustic cues corresponding to damping ratio via timbre features as a consequence.

5. Conclusion

Relationships between mechanical admittance features and physical attributes (mainly about material attributes) of ribbed plates are analyzed, and acoustical representations of elastic modular, mass density and global damping ratio are obtained. Acoustic cues from ideal sound seem to explain more physical attributes than those from original impact sound. Most physical attributes relevant mechanical admittance features can be explained as an extension of plate theory. The reason why there is no feature strongly related with Poisson ratio when all four physical attributes are uncontrolled may be explained by its low weight in mechanical admittance.

The method of extracting physical attributes relevant acoustic cues via mechanical admittance features provides a new sight of sound source identification.

Acknowledgement

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