DESIGN AND PERCUSSION SOUND EVALUATION OF HARMONIC GLASS PLATE

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Glass materials have been used for musical instruments, such as the glass harmonica and glass harp. A stringed instrument, such as the guitar, can generate the harmonics sound due to the characteristics of string vibration modes. The plate-like percussion instruments, such as the glockenspiel, produce no harmonics sound effects. This paper presents a new design of harmonic glass plate (HGP) that can produce three harmonics with respect to the fundamental frequency of a musical note made of glass materials. The mechanical properties of rectangle glass plate are first determined by experimental modal analysis in obtaining structural natural frequencies and tuned by finite element analysis (FEA). The design procedure is briefly reviewed by adopting geometry optimization method in FEA to obtain the special shape design of HGP that can produce harmonics sound. The percussion sound of the HGP is also measured and calibrated to meet the standard frequency of a musical note. The overtone frequencies of the HGP are also shown with additional two harmonics that make the HGP sound better than the rectangle glass plate. This paper shows the potential new category design of glass percussion instrument.

1. Introduction

Percussion instruments (PIs) have been widely played in musical performance. There are two categories of PIs, i.e. tuned and un-tuned. Xylophones and glockenspiels are typical tuned PIs, and bass drums and triangles are un-tuned. Glass materials have been used for musical instruments, such as the glass harmonica and glass harp. The tuned PIs made of glass are few. This work presents the new design of harmonic glass plate (HGP) that is transformed from the harmonic steel plate (HSP)[1,2]. The geometry optimization for the metal plate to produce special percussion sound characteristics is base on the work by Wang *et al*.[3] Wang and Hsieh[4] investigated the chord sound plate design considering the geometry scaling effects.

The xylophones is one of the typical tuned PIs. Many researchers have dedicated to the percussion sound analysis[5, 6]. Bretos *et al*.[7] adopted finite element analysis (FEA) to discuss the effect of undercut for the wooden bar on the modal parameters. Petrolito and Legge[8] developed a general approach in designing musical structures by applying constrained optimization methods. Wang[9] discussed the design analysis of PIs by integrating finite element analysis and experimental modal analysis (EMA). Three typical PIs are demonstrated, including the xylophone, metallophone and copper gong. Armaki *et al*.[10] studied different species of wood in making the bar for xylophones.

They pointed out two important timbre descriptors, i.e. the frequency-dependent damping and spectral bandwidth, linked with physical characteristics of wood species.

Wang *et al*.[11] used the pitch, tonal properties and duration of percussion sound to characterize three types of tuned PIs, i.e. the vibraphone, xylophone, and glockenspiel. Wang *et al*.[12] studied the percussion sound characteristics of the vibraphone for different playing techniques. Both temporal response and spectral contents are shown and physically interpreted to quantify the percussion sound.

This work shows the feasibility of using glass material to manufacture harmonic glass plate (HGP) for percussion instrument. First, the material properties of glass are calibrated by FEA and EMA methods. The relationship of material properties and dimension of plate to transform the new design of harmonic glass plate from steel material is formulated. The modal properties and percussion sound of HGP is finally evaluated.

2. Determination of glass material properties

This section shows the integration of FEA and EMA[9] to calibrate the mechanical properties of glass material that is used to manufacture the harmonic glass plate (HGP). Base on the experimental modal parameters, the material constants are updated to fit the theoretical natural frequencies in accordance with the experimental ones.

2.1 Model verification of rectangle glass plate

Figure 1 shows the procedure of model verification (MV) that is to obtain the equivalent analytical model to the real structure. There are two steps to carry out MV. First, the finite element (FE) model is built to perform theoretical modal analysis so as to obtain theoretical natural frequencies and corresponding mode shapes. Second, EMA is performed on the real structure to measure the frequency response functions by using the impact hammer as the actuation force to excite the structure and applying the accelerometer to measure the acceleration response. The curve fitting process or modal parameter extraction method is then applied to determine experimental modal parameters, including natural frequencies, mode shapes and modal damping ratios. Base on the experimental data, the FE model can be updated, in particular the material constants, to have the matched modal parameters obtained from FEA and EMA. At this stage, the FE model can be equivalent to the real structure, i.e. the glass material constants can be well calibrated.

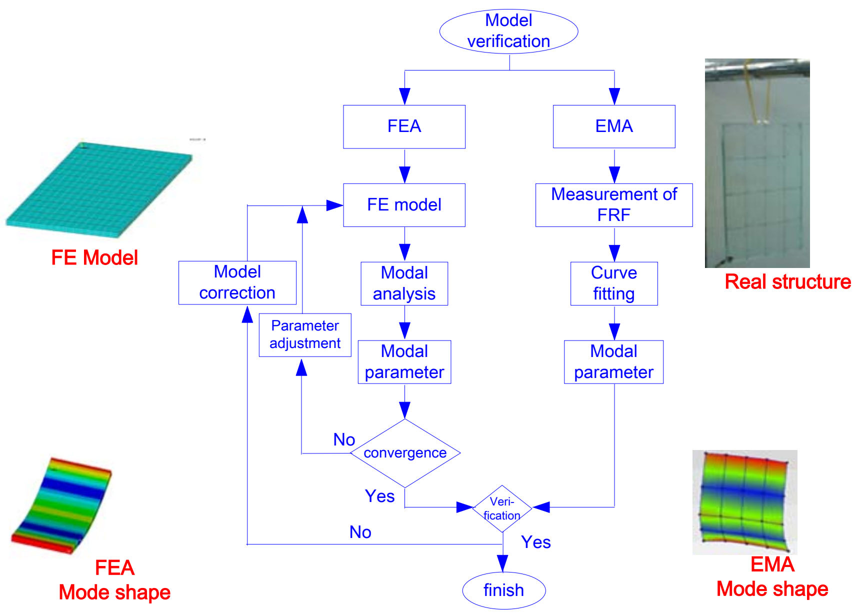
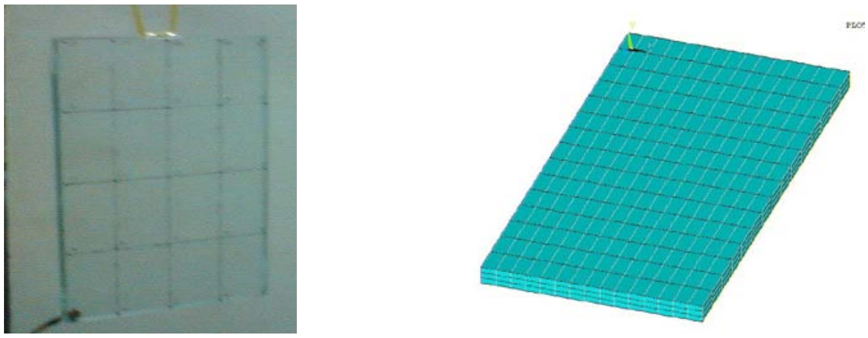


Figure 1. Procedure for model verification.



(a) picture (b) FE model

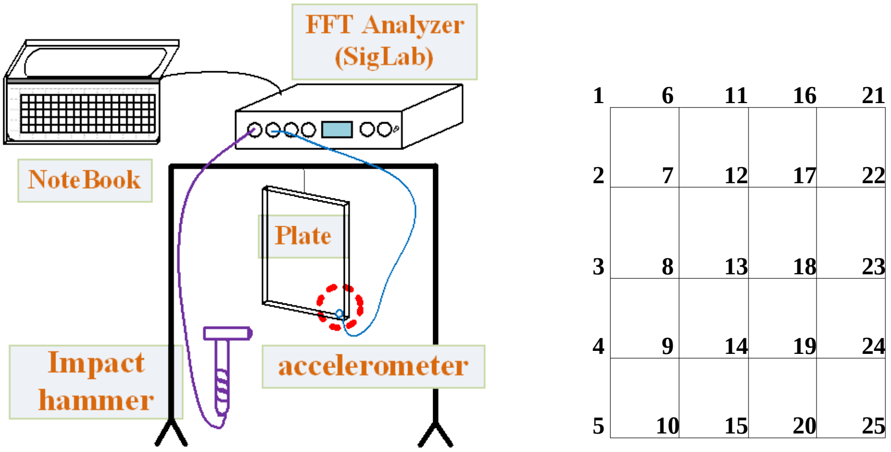
Figure 2. Rectangle glass plate (RGP).

Figure 2(a) shows the rectangle glass plate (RGP) which physical properties are shown in Table 1. Figure 2(b) is the FE model for the RGP and constructed by the eight-node solid element (SOLID45) in ANSYS software. There are 1024 nodes and 675 elements. Since the RGP is suspended in free boundary condition for EMA, no displacement constraints are required. For the computation of frequency response functions, the point nodal force is applied at the prescribed location in accordance with the experiments.

Figure 3(a) shows the experimental setup for EMA on the rectangle glass plate. Figure 3(b) shows the grid points on the plate for performing EMA. The accelerometer is fixed at Point i=25, and the impact hammer is used to apply the point force over all of 25 points, i.e. j=1,2,…,25, respectively. 25 sets of FRFs $H_{ij}(f) = A_i / F_j$ between the i-th acceleration and the i-th force can be obtained. The curve fitting software, ME'scopeVES, is then applied to obtain experimental modal parameters.

Table 1. Physical properties of rectangle glass plate (RGP).

Length (mm)	200
Width (mm)	100
Thickness (mm)	8
Weight (g)	387.35
Density (kg/m^3)	2420.93
Young's modulus (GPa)	67
Poisson's ratio	0.23



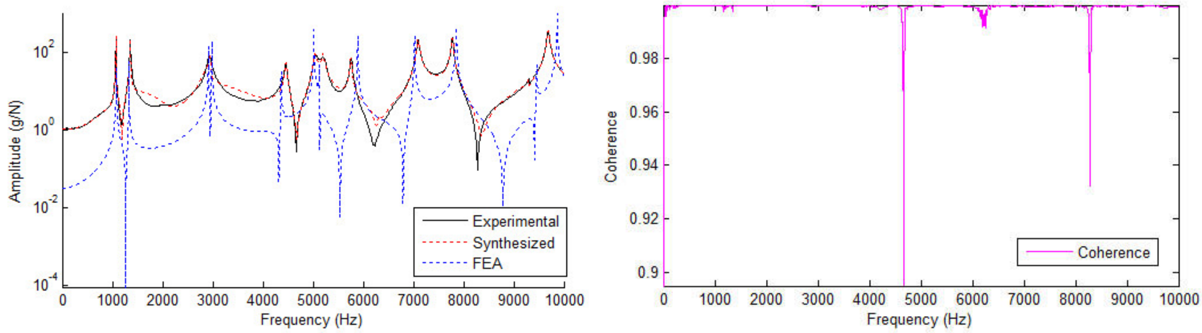
(a) Picture (b) Grid points for EMA

Figure 3. Experimental setup for rectangle glass plate (RGP).

2.2 Results and discussions for model verification of RGP

Figure 4(a) shows the comparison of FRFs ($i = 25, j = 25$) for the RGP. Figure 4(b) shows the corresponding coherence function for the FRF measurement. The coherence values are mostly close to 1 except at some anti-resonance frequencies. This indicates the experiments are reliable and good for post-processing. In Fig. 4(a), that the synthesized FRF matches very well with the experimental ones indicates the success of curve fitting process. One can observe that both the FEA and experimental FRFs also agree reasonably and, in particular, the resonant frequencies match very well.

Table 2 summarizes the comparison of natural frequencies of the first five modes between EMA and FEA for brevity, and Table 3 shows their corresponding mode shapes. One can observe that both mode shapes obtained from FEA and EMA reveal very good agreement in term of physical meaning of modal characteristics. The structural natural frequencies also match well within about 2% errors. From the agreement of FRFs and modal parameters between FEA and EMA, the FE model of RGP can be validated and equivalent to the real structure. Importantly, the glass material constants as shown in Table 1 are calibrated and can be used for further design analysis on the harmonic glass plate (HGP).



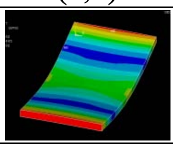
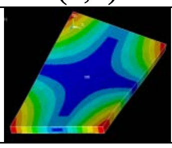
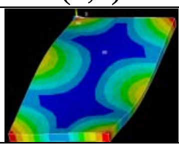
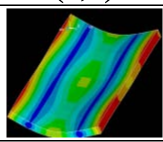
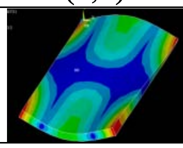
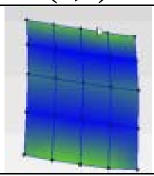
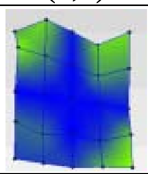
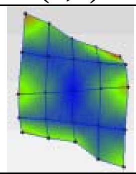
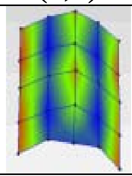
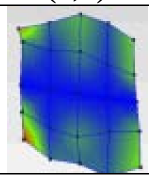
(a) FRF (b) coherence

Figure 4. Frequency response function (FRF) and coherence function of RGP for $i = 25, j = 25$.

Table 2. Comparison of natural frequencies between EMA and FEA for glass rectangle plate.

EMA			FEA		Frequency error (%)	Physical meaning (*m*,*n*)
mode	Natural frequency (Hz)	Damping ratio (%)	mode	Natural frequency (Hz)		
E-1	1075.7	0.11	F-1	1082.6	0.64	(3,1)
E-2	1359.5	0.25	F-2	1335.7	-1.75	(2,2)
E-3	2958.0	0.16	F-3	2917.5	-1.37	(3,2)
E-4	4481.7	0.41	F-4	4367.8	-2.54	(1,3)
E-5	5230.5	0.68	F-5	5123.3	-2.05	(2,3)

Table 3. Comparison of natural frequencies between EMA and FEA for glass rectangle plate.

Mode	(3,1)	(2,2)	(3,2)	(1,3)	(2,3)
FEA					
Mode	(3,1)	(2,2)	(3,2)	(1,3)	(2,3)
EMA					

3. Dimensional design for harmonic glass plate

Wang and Chien [1, 2] have shown the design of harmonic steel plate (HSP) that can produce the percussion sound with the harmonics effect, i.e. the first and second overtone frequencies are nearly twice and three times of fundamental frequency, respectively. Such a harmonic sound effect can make the percussion sound more comfort and in harmony. This work will use the glass material to manufacture the harmonic glass plate (HGP) similar to the HSP. This section shows the geometry relation base on the dimension and material properties for reproducing the new geometry design of HGP from HSP.

The natural frequencies of simply-supported rectangle plate can be expressed as follows [4]:

$$f_{mn} = \frac{\omega_{mn}}{2\pi} = \frac{\pi}{2}\left[\frac{m^2}{L_x^2} + \frac{n^2}{L_y^2}\right]\sqrt{\frac{D}{\rho t}} . \tag{1}$$

where L_x, L_y, and t are the length, width and thickness of the rectangle plate, respectively. (m,n) are mode number in the x and y directions, respectively. ρ is the density, and D is the plate rigidity as follows:

$$D = \frac{Et^3}{12(1-v)} . \tag{2}$$

where E and v are Young's modulus and Poisson's ratio, respectively. From above equations, one derive the relation for the plate natural frequencies of mode (m,n) as follows:

$$f_{mn} \propto \frac{t}{L^2}\sqrt{\frac{E}{\rho}} . \tag{3}$$

Let s denote for HSP and g for HGP, and the relation equations can be obtained as follows:

$$f_{mn}^{s} \propto \frac{t_s}{L_s^2}\sqrt{\frac{E_s}{\rho_s}} . \tag{4}$$

$$f_{mn}^{g} \propto \frac{t_g}{L_g^2}\sqrt{\frac{E_g}{\rho_g}} . \tag{5}$$

For the same musical note, the fundamental frequency of the plate must be the same, i.e. $f_{mn}^{s} = f_{mn}^{g}$. The dimensional scale factor R to transform the HSP to HGP for the redesign of geometry shape can be derived:

$$R = \frac{L_g}{L_s} = \sqrt{\frac{t_g}{t_s}}\sqrt[4]{\frac{E_g / E_s}{\rho_g / \rho_s}} . \tag{6}$$

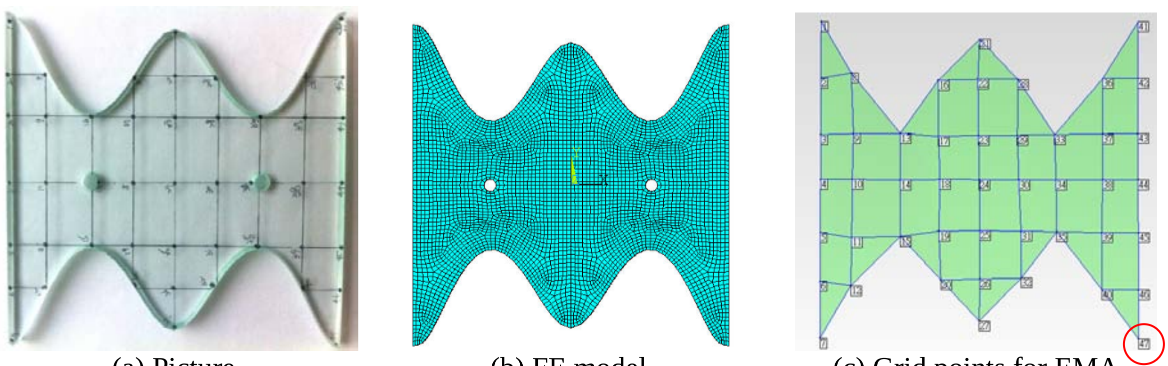
Equation (6) provides a quick evaluation of the shape design of HGP from HSP. The fine tune on the structural natural frequencies of HGP can then be analyzed accordingly.[3]

4. Model verification and percussion sound of harmonic glass plate

Figure 5(a) shows the HGP made of the glass which material properties are calibrated and shown in Table 1. The HGP is manufactured by the computer numerically controlled (CNC) water-jet machine. The manufacturing errors are carefully adjusted to fit the requirement of the fundamental frequency of HGP being equal to the standard pitch frequency of a musical note. In this paper, the musical note F6 with the standard pitch frequency 1396.9 Hz is presented. Figure 5(b) shows the FE model of HGP that consists of 35,144 eight-node solid elements (SOLID45). The two central holes are designed for placing the plate on the base for fixture consideration.

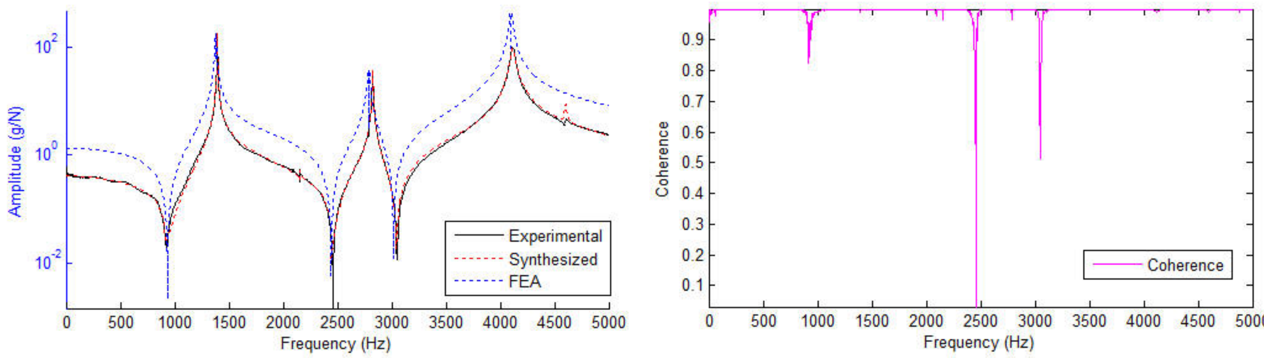
EMA is also carried out on the HGP similar to the RGP as shown in Fig. 3(a). The grid point layout is shown in Fig. 5(c). The accelerometer is fixed at Point 47 as circled in Fig. 5(c), and the impact hammer is applied over the 47 points, respectively. A set of 47 FRFs can be measured. Figure 6(a) shows the FRF for $i = 47, j = 47$ and reveals very good agreement between FEA and experimental results. Figure 6(b) also show the corresponding coherence and reveals the good experimental quality. Table 4 summarizes the comparison of modal parameters between EMA and FEA. One can observe both theoretical and experimental results agree very well in terms of natural frequency errors and the match of modal characteristics. The first three modes are (m,n)=(3,1), (1,3) and (3,3), respectively.

Figure 7 shows the percussion sound measurement of the HGP for the musical note F6. Figure 8(a) shows the time domain response for single stroke, and Figure 8(b) shows the corresponding frequency domain response. There are three major peaks in the spectrum. Their frequencies refer to those natural frequencies in Table 4. The mode shapes are also depicted on the top of each resonance. From Fig. 8(b), the first peak frequency is 1396 Hz matching very good with the standard frequency of F6. The overtone frequencies are 2828 Hz and 4128 Hz having the frequency ratios with respect to the fundamental frequency 2.028 and 2.957, respectively. The percussion sound of the HGP meets the requirement of pitch frequency for F6 and reveals the harmonic effect with two overtone frequencies in harmonics.



(a) Picture (b) FE model (c) Grid points for EMA

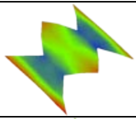
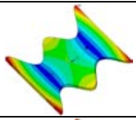
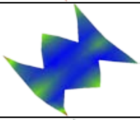
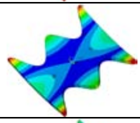
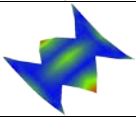
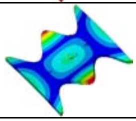
Figure 5. Harmonic glass plate.



(a) FRF (b) coherence

Figure 6. Frequency response function (FRF) and coherence function of HGP for $i = 47, j = 47$.

Table 4. Comparison of natural frequencies between EMA and FEA for harmonic glass plate.

EMA				FEA			Frequency error (%)	Physical meaning (*m*,*n*)
mode	Natural frequency (Hz)	Mode shape	Damping ratio (%)	mode	Natural frequency (Hz)	Mode shape		
E-01	1394.0		0.10	F-01	1396.9		-0.2	(3,1)
E-02	2828.0		0.10	F-02	2787.2		1.5	(1,3)
E-03	4116.6		0.49	F-03	4092.8		0.6	(3,3)

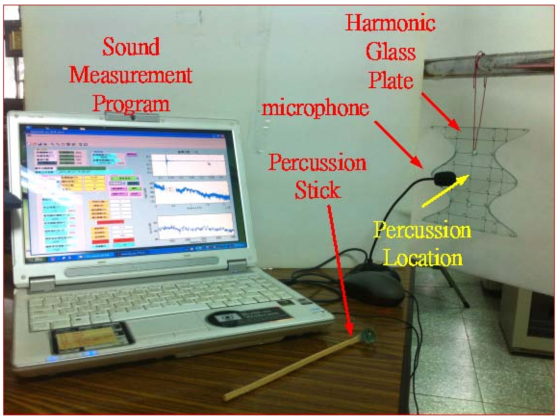
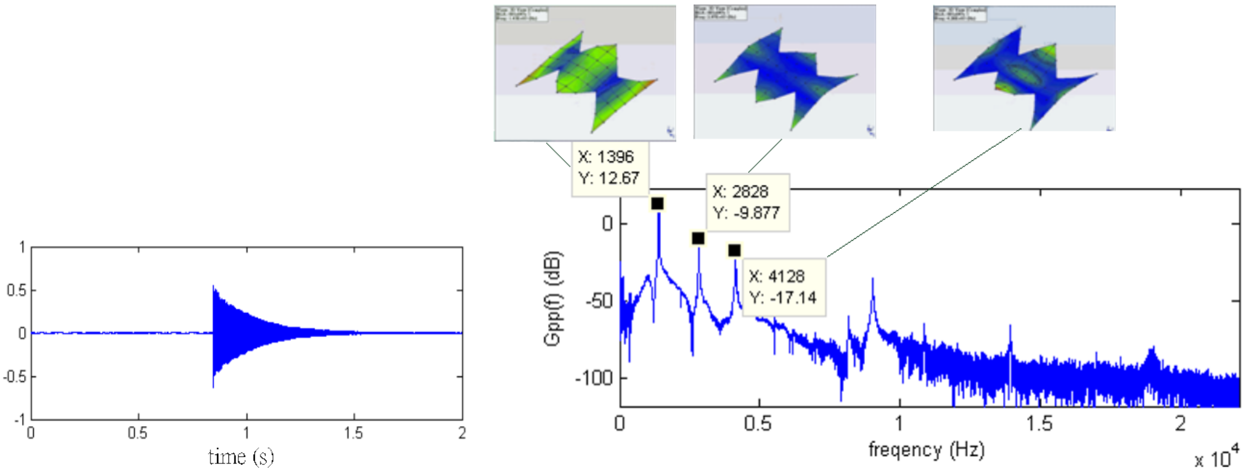


Figure 7. Percussion sound measurement of harmonic glass plate for Note F6.



(a) time domain (b) frequency domain

Figure 8. Percussion sound response of harmonic glass plate for Note F6.

5. Conclusions

This paper presents the dimensional design analysis for harmonic glass plate (HGP) that is originally made of steel.[1, 2] The HGP is designed to have percussion sounds revealed harmonic effects. The glass material properties are first determined by using EMA and FEA techniques to calibrate the FE model, in particular for obtaining material mechanical properties. The HGP can then be redesigned accordingly and manufactured. Modal parameters of the HGP are verified, and the percussion sound of HGP is also measured and fulfilled the requirement of a musical note. The special percussion sound containing harmonic effects can be produced. The complete set of HGPs containing two or three octaves of musical notes can be designed accordingly and manufactured to make a new type of tuned percussion instrument.

6. Acknowledgments

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