Proceedings of 2011 International Conference on System Science and Engineering, Macau, China - June 2011

Integration of FEA and EMA Techniques for Percussion Instrument Design Analysis

Percussion Instrument Design Analysis

Bor-Tsuen Wang
Department of Mechanical Engineering
National Pingtung University of Science and Technology
Pingtung, 91201, Taiwan
wangbt@mail.npust.edu.tw

***Abstract*—Percussion instruments are frequently used in musical performance. The percussion sound radiation characteristics are strongly related to structural vibration modes. This paper presents the approach of virtual testing (VT) by the integration of finite element analysis (FEA) and experimental modal analysis (EMA) techniques for the design analysis of several types of percussion instruments. First, the procedure for model verification is introduced and shown the basic principle for validating the finite element model by adopting FEA software and performing EMA. The sound spectrum of percussion instrument can then be measured to identify the most contributed structural modes and compared with those modal parameters obtained from FEA and EMA. Three types of percussion instruments, including a xylophone bar, a metallophone plate and a gong, are shown to demonstrate the idea of VT for the redesign of new type of percussion instruments. This paper shows how the structural modal properties affecting the radiated sound of percussion instruments and reveals the philosophy for geometry modification to achieve the target designs of percussion instruments.**

***Keywords*—percussion instrument, percussion sound, virtual testing, finite element analysis (FEA), experimental modal analysis (EMA), modal parameter**

I. INTRODUCTION

Percussion is to hit one body against another. Percussion instruments can be played by being struck, shaken or scraped [1]. The classification of percussion instruments can be as tuned and untuned or pitched and unpitched. Tuned percussion instruments produce specific pitches or notes, just like wind, brass and string instruments, and can play melody and serve harmonic in music. Untuned percussion instruments generate an indefinite pitch sound, like the clap sound. The resultant sound of the untuned contains complex frequencies through which no pitch is discernible. This paper will discuss the design analysis of tuned percussion instruments, in particular for the struck types.

Three types of percussion instruments are studied in this work, i.e. the xylophone, metallophone and gong. Xylophones and metallophones are categorized as the tuned percussion instruments. Xylophones are made of wooden bars of various lengths that are struck by plastic, wooden, or rubber mallets. Each bar is tuned to a specific pitch of the musical scale. Metallophones are similar to xylophones except made of tuned metal bar. A gong is a percussive sonorous or musical instrument of Chinese origin and manufacture, made in the form of a broad thin disk with a deep rim, which has spread to Southeast Asia - a type of flat bell. In Taiwan, the gong is used in many occasions, such as traditional opera or religions celebration. The gong is made of copper and one of frequently used traditional Taiwanese instruments.

Chaigne [2] showed the numerical and experimental techniques in studying musical instruments. Rossing et al. [3] provided a rigorous review on the acoustic response of various kinds of percussion instruments. The radiated sound spectrum strongly correlated to structural vibration modes. Bork et al. [4] adopted finite element analysis (FEA) to study the vibro-acoustic relation for a marimba bar. Wang and Liao [5] performed both experimental modal analysis (EMA) and FEA on a xylophone bar and characterized the percussion sound induced by specific structural modes. They [6] also showed the principle for geometry modification to tune the xylophone bar for different notes.

Since the percussion sound response is related to the structural vibration characteristics, special geometry designs of percussion instruments will result in target sound spectrum content. Petrolito and Legge [7] optimized the undercuts of xylophone beam to tune for special harmonic sound response. They [8] further generalized the constrained optimization approaches, in particular for the design of xylophone beam. Henrique and Antunes [9] showed a systematic approach to optimally design the xylophone beam, which has special overtones. Aramaki et al. [10] presented the assessment of sound quality of xylophone bar.

This work will integrate finite element analysis (FEA) and experimental modal analysis (EMA) techniques to perform virtual testing (VT) on the design of these percussion instruments.

II. VIRTUAL TESTING FOR PERCUSSION INSTRUMENT DESIGN

Figure 1 shows the general idea of virtual testing for structural design, including three basic steps. First, model verification (MV) is performed on the structure to validate the analytical model with experimental results. The purpose of MV is to obtain a validated analytical model to be used for response

978-1-61284-471-8/11/$26.00

prediction in the next step. When the predicted response is verified with experimental results, the analytical approach can then be adopted to perform model modification or structural design modification in the third step. With the iteration on the design modification and response prediction, the target design can be obtained base on the design specification. In this paper, the VT procedure will be applied to the design analysis of several percussion instruments.

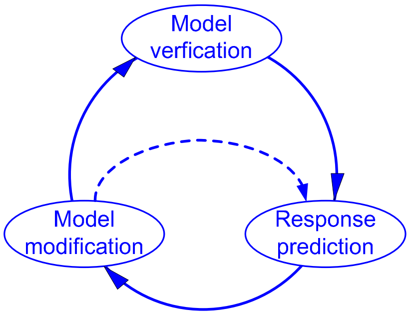


Figure 1. General procedure for Virtual Testing (VT)

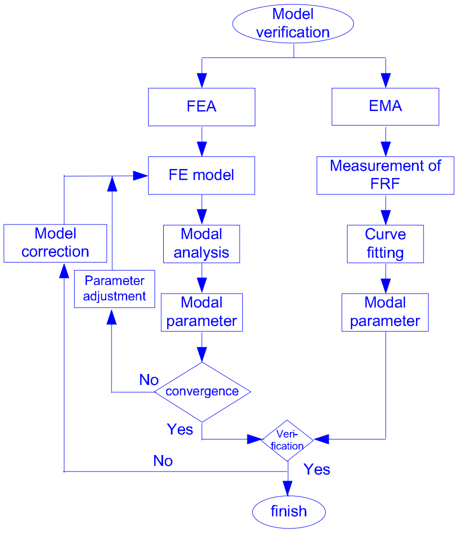


Figure 2. General procedure for model verification

Figure 2 shows the procedures for MV by integrating FEA and EMA techniques applied to a structural analysis. The main idea of model verification is to compare modal domain data obtained from FEA and EMA. FEA is an analytical approach and other numerical solutions work as well. One can construct the mathematical model corresponding to the real structure, considering proper modeling of geometry and material parameters as well as boundary conditions. The theoretical modal parameters can be determined from FEA. EMA or modal testing is an experimental technique to obtain structural modal parameters from a real structure. The basic step is to measure the frequency response functions (FRFs) between the acceleration and impact force when the impact hammer is applied as the actuator and the accelerometer is as the sensor. One can then obtain structural modal parameters from the measured FRFs by carrying out the curve-fitting process or so called experimental modal parameter extraction method. In summary, EMA can be performed to obtain the modal parameters of the real structure as well.

To validate the FE model being equivalent to the real structure, one has to ensure the modal domain data from FEA and EMA agreeing to each others. If the comparison between modal data is not good enough, necessary model correction on the FE model must be made until the comparison can match well. The completion of model verification is to obtain an equivalent validated analytical FE model that can be applied to response prediction as well as structural design modification as shown in Figure 1.

This paper aims to show the virtual testing (VT) idea for the design analysis of percussion instruments. Three types of percussion instruments, including a xylophone bar, a metallophone plate and a gong, are shown to demonstrate the idea of VT for the redesign of new type or new feature of percussion instruments.

III. CASE STUDIES

This section will show the application of VT technique to the design analysis of three types of percussion instruments. The radiated sound of the xylophone bar, metallophone plate and copper gong are, respectively, studied and characterized to show their sound spectrum dominated by some particular structural modes. The physical interpretation of percussion sound spectrum is also presented for the tone color characteristics of different percussion instruments.

A. Xylophone Analysis

The xylophone is made of wood materials and frequently played in musical performance. The xylophone bar with C note (261.63Hz) is studied [5]. Figure 3 shows the flow chart for model verification via the integration of FEA and EMA for the xylophone bar. The objective in performing model verification is to obtain validated analytical model. The FE model of the xylophone bar structure is constructed to perform modal analysis for obtaining structural modal parameters. The ANSYS software, a finite element base commercial code, is adopted to construct the analytical model of the xylophone bar by using 8 nodes brick elements. The theoretical modal analysis can be performed to get the structural natural frequencies and mode shapes. By doing convergence test on the FE model as well as necessary model adjustment on geometry and material constants, the theoretical modal parameters can be obtained and compared with those from EMA. The agreement of modal parameters, including natural frequencies and mode shapes, between FEA and EMA indicates that the analytical model is equivalent to the real structure.

Figure 4 shows the comparison of FRFs obtained from experimental, synthesized and theoretical analyses. The conventional EMA is performed by using the impact hammer to excite the xylophone bar and using the accelerometer attached on the bar to measure the acceleration. The FRF between the acceleration and impact force can be obtained by a typical FFT analyzer. After the curve-fitting process, the structural modal parameters, including natural frequencies, mode shapes and modal damping ratios, can be obtained. Then, the synthesized FRF can be determined from the experimentally extracted modal data. That both the synthesized and experimental FRFs agree very good as shown in Figure 4 indicates the success of curve-fitting operation and thus ensures the correctness of modal parameters determined from EMA on the real structure.

Through harmonic response analysis of FE model for the xylophone bar, the theoretical FRF between the acceleration and excited impact force corresponding to the experiments can also be obtained. Figure 4 also shows the theoretical FRF generally agrees well with the experimental one. The importance of the comparison among the FRFs by frequency domain data is to validate the analytical model of the xylophone bar that can be adopted for structural modification to redesign a particular xylophone bar with target frequency.

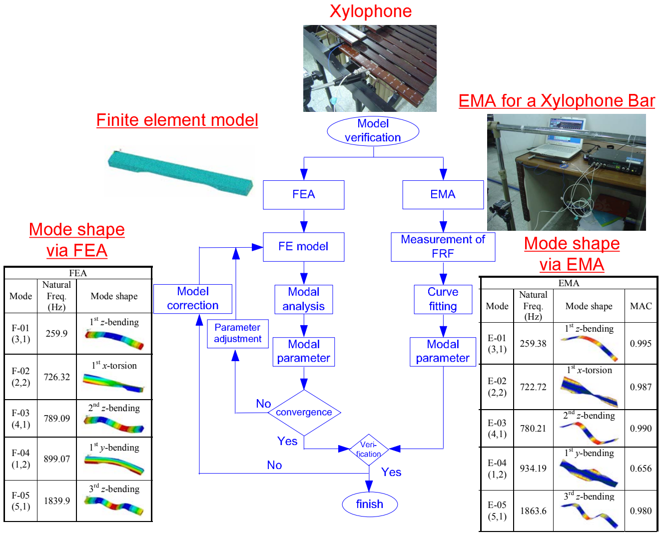


Figure 3. Model verification for a xylophone bar

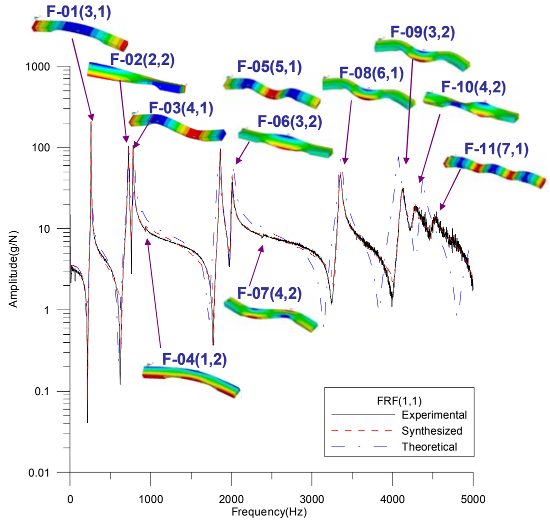
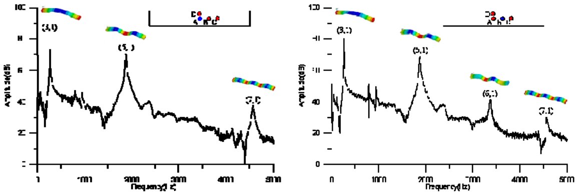
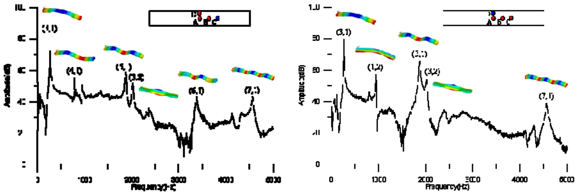


Figure 4. Comparisons among experimental, synthesized and theoretical FRFs with the corresponding mode shape characteristics for xylophone bar

From Figure 4, it is also noted that there are about 11 structural vibration modes in the frequency range below 5000Hz, and their mode shapes are depicted on the top of each resonance. For example, F-01(3,1) denotes the first flexible bending mode characterized as the (x,y)=(3,1) mode. The mode shapes become complex with more nodal lines at higher frequencies.



(a) Struck at Point A (b) Struck at Point B



(c) Struck at Point C (d) Struck at Point D

Figure 5. Sound spectrum of xylophone bar struck at different locations

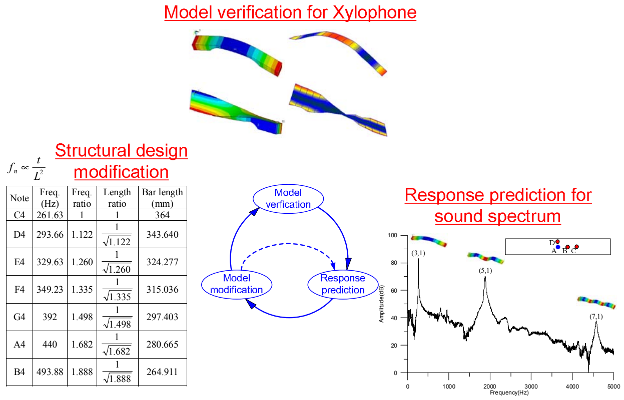


Figure 6. Response predication and design modification for xylophone bar

With the knowledge of structural modal properties, one can characterize the percussion sound spectra for different struck locations on the xylophone bar as shown in Figure 5. For the struck at Point A, i.e. the center location on the bar, only three modes are effectively excited, because the striking location is right on the nodal lines of those mode shapes that can not be activated. For other struck points, more resonance peaks occurred within the frequency range up to 5000Hz consist of the tone colors for the xylophone bar. Different striking locations on the bar result in different tone color. Most importantly, Mode (3,1) that is the first flexible mode with natural frequency 261.63Hz contributes to the sound for C pitch frequency.

Figure 6 reveals the flow chart in structural design modification. The first step is to conduct model verification and validate the analytical model for the xylophone bar as discussed in Figure 3. The frequency response functions (FRFs) obtained from experimental, synthesized and theoretical analyses are compared and revealed very good agreement as presented in Figure 4. The mode shape characteristics are also shown corresponding to each resonance of the sound spectrum as demonstrated in Figure 5. The next step is to perform response prediction via the validated FE model to identify the structural modal frequencies that will dominate the radiated sound. In this case, the percussion sound spectrum of the xylophone bar is of interest. The most contributed sound are from modes (3,1), (5,1) and (7,1), that are typical plate mode shape notation for (x, y) axes as shown at the right of Figure 6. In particular, the first resonance frequency is the fundamental frequency, i.e. the musical note C for the case study. Finally, the structural FE model can be modified for its geometry variation to obtain specific xylophone length design for different musical notes as shown in the left bottom table of Figure 6 [6]. One can observe that different length ratios can be determined to obtain the different notes or pitches of xylophone bars. The VT technique is useful for the xylophone design and manufacture.

B. *Metallophone Analysis*

The metallophone as shown on the top of Figure 7 similar to the xylophone can produce specific pitches by striking on the metal plate. Figure 7 shows the procedures for performing model verification on the metallophone plate for C note (1046.5Hz) [11]. Both FEA and EMA are carried out, respectively, for the metal plate. The analytical FE model can be validated by the comparison of modal parameters between those obtained from FEA and EMA. Figure 8 also shows very good comparison of FRFs among experimental, synthesized and theoretical results and demonstrates the success of model verification. The corresponding mode shape for each resonance is also depicted on the top of each resonance peak.

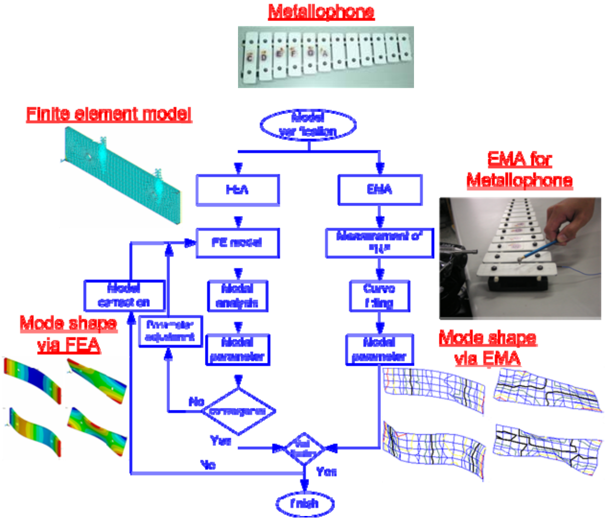


Figure 7. Model verification for a metallophone plate

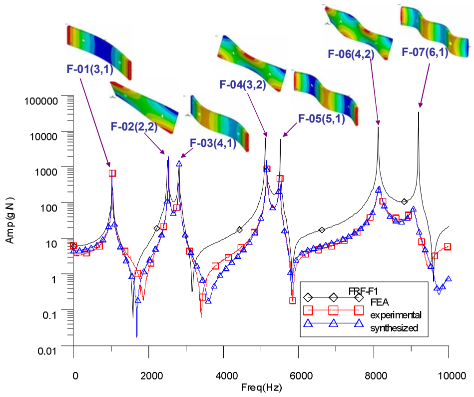
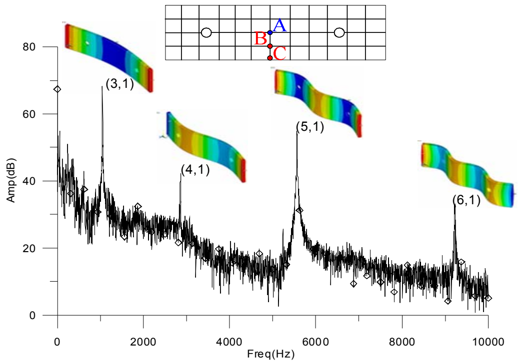
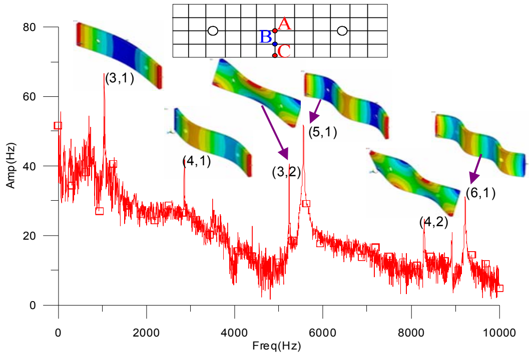


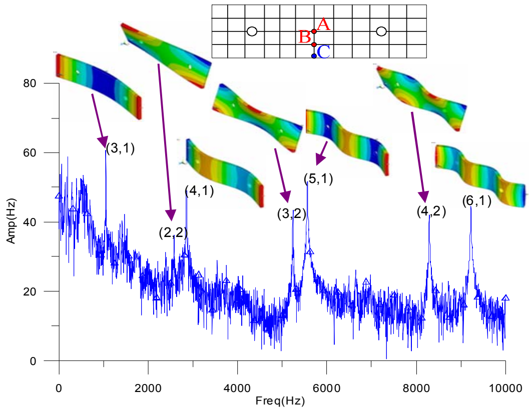
Figure 8. Comparisons among experimental, synthesized and theoretical FRFs with the corresponding mode shape characteristics for metallophone plate



(a) Struck at Point A



(b) Struck at Point B



(c) Struck at Point C

Figure 9. Sound spectrum of metallophone plate struck at different locations

The sound spectrum of the metal plate after striking can be found strongly correlated to structural modal properties. Figure 9 shows the sound spectrum of the metal plate struck at different locations. One can observe the peak resonances are dominated by some particular structural modes. For Figure 9(a), the striking location is at Point A right at the center of the plate, and thus those mode shapes with nodal points at Point A can not be excited. In particular, the first modal frequency is designed right at 1046.5 Hz, which is the desired frequency for C note. The other peak resonances as revealed in the sound spectrum consist of the timbre, tone color or overtones of the metallophone plate.

The percussion radiated sound of metallophone plate is dominated by those structural modes whose center points are not at the nodal lines. For normal strike at the center, modes

(3,1) and (5,1) are identified as the most dominant modes and shown in Figure 9(a). One can perform structural design modification on the plate geometry to produce specific frequencies of percussion sound for the metal plate. Figure 10 show the idea of VT to the new design of metal plate by performing modal analysis on the new geometry of metal plate to predict the radiated sound characteristics. The two special shape of metal plate as shown at the left of Figure 10 can produce the sound consisting three tone frequencies corresponding to Notes C, E, and G, which are known for the composition of the C major triad. The special feature for the new shape of metal plate is that the three tone frequencies for the C major triad can be heard in just one strike. Wang and Jian [12] showed the case study on such a new design of metallophone plate.

The VT technique integrates FEA and EMA for model verification to validate the analytical FE model of the metallophone plate. The verified model can then be used to theoretically determine the metal plate modal properties and thus to predict the radiated sound spectrum. Finally, the structural geometry of metallophone plate can be redesigned to target frequency contents base on the validated analytical FE model.

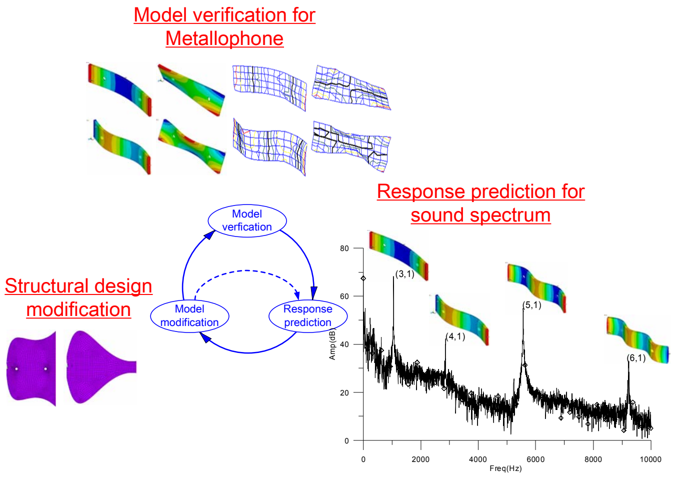


Figure 10. Response predication and design modification for metallophone plate

C. *Copper Gong Analysis*

The gong is made of copper and one of frequently used traditional Taiwanese instruments. The percussion sound characteristics of a gong depend on the structural vibration modes. For the design analysis of the gong, Figure 11 shows the procedure for the first step in performing model verification on a gong [13]. The FE model of the gong is constructed to perform modal analysis and obtain the structural natural frequencies and mode shapes. EMA on the gong is also carried out to experimentally obtain the modal properties that are compared with those obtained from FEA. By the model correction on the FE model to ensure the good match on the modal parameters obtained from both FEA and EMA, the FE model of gong can then be verified.

Figure 12(a) shows the measured sound spectrum for the gong struck at the center [14]. One can observe there are four major resonance peaks. Those corresponding mode shapes of the gong are also depicted above the peaks as shown in Figure 12(a). Only those radial modes significantly contribute to the radiated sound. For the gong struck at the location away from the center as shown in Figure 12(b), many structural modal responses can be excited and contribute to the radiated sound. Since the gong is normally struck at the center, the natural frequencies of those radial modes will dominate the percussion sound of the gong.

Figure 13 shows the general idea of applying the VT technique to redesign the gong for specific sound quality requirement. The model verification is first performed to validate the analytical FE model of the gong. The gong modal frequencies of those radial modes can be shown to be the dominant frequencies of sound spectrum after percussion. The verified FE model of the gong can then be used to perform design modification and thus to predict the modal characteristics of new design of gongs. Those geometry dimensions of the gong as shown at the left of Figure 13 can be changed to perform FEA so as to obtain the modal frequencies, in particular for those radial modes. Special sound characteristics of new gongs can be designed accordingly. The VT technique is shown as an effective tool for percussion instrument design.

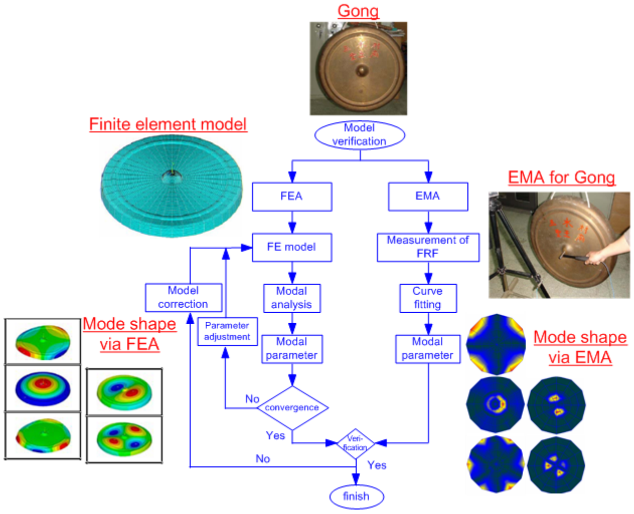
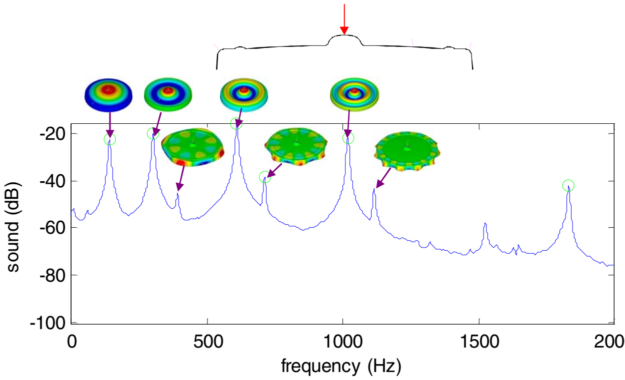


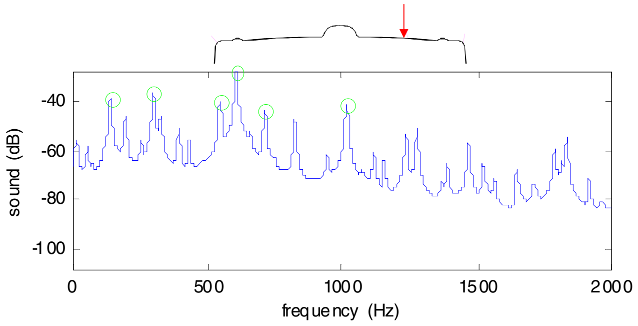
Figure 11. Model verification for a gong

IV. CONCLUSIONS

This paper addresses the analytical procedures for the design of percussion instruments. In particular, the xylophone, metallophone and gong are shown to demonstrate the adoption of FEA and EMA techniques for the principle of virtual testing in designing the new ones. The main idea of VT technique consists of three steps, i.e. (1) model verification, (2) response prediction, and (3) model modification or design modification. In model verification, both FEA and EMA should be carried out to verify the analytical FE model for the structure of instrument. The radiated sound characteristics can be found strongly correlated to the structural modal frequencies for some specific modes. The validated analytical FE model for the instrument can then be changed for different geometry or dimensions so as to obtain the modal data of new design instruments. Through the iteration procedure base on the required target frequency contents such as for different notes or different tonal characteristics of the instrument, the new design of instrument can be obtained. This work lays out the systematic approach in designing the percussion instruments. The methodology of VT applied to structural design for three types of percussion instruments is shown effective and can be useful for other instruments as well.



(a) Struck at the middle of gong



(b) Struck at the side of gong

Figure 12. Sound spectrum of copper gong struck at different locations

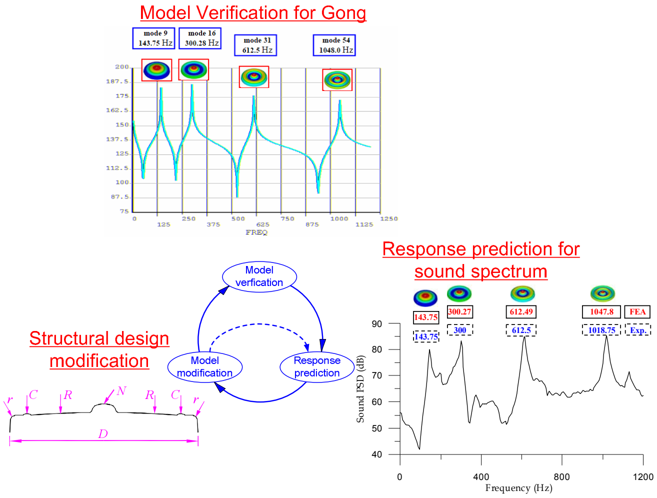


Figure 13. Response predication and design modification for a gong

ACKNOWLEDGMENT

This work is partially supported by National Science Council, Taiwan, grant No.: NSC 99-2221-E-020-004. The authors would also like to thank all students who contributed to this study.

REFERENCES

[1] Fletcher, N.H., and Rossing, T.D., 1991, Physics of Musical Instruments, Springer-Verlag, New York.

[2] Chaigne, A., 1999, "Recent Advances in Vibration and Radiation of Musical Instruments," Flow, Turbulence and Combustion, Vol. 61, No. 1-4, pp.31-41.

[3] Rossing, T. D., Yoo, J., and Morrison, A., 2004, "Acoustics of Percussion Instruments: An Update," Acoust. Sci. & Tech. Vol. 25, No:. 6, pp.406-412.

[4] Bork, I., Chaigne, A., Trebuchet, L.C., Kosfelder, M., and Pillot, D., 1999, "Comparison between Modal Analysis and Finite Element Modelling of a Marimba Bar," ACUSTICA, Vol.: 85, No.: 2, pp. 258-266.

[5] Wang, B. T., and Liao, W. T., 2009, "Experimental Modal Analysis and Model Verification of a Xylophone Bar," The 17th National Conference on Sound and Vibration, Taipei, Paper No.: B-06. (in Chinese)

[6] Wang, B. T., and Liao, W. T., 2009, "Correlation Study of Percussion Sound and Vibration of Xylophone Bar and its Geometry Modification Design Analysis," 2009 The Forth Conference of NPUST and USTB, Pingtung, Paper No.: C-14., pp. C-72--C-78. (in Chinese)

[7] Petrolito, J., and Legge, K. A., 1997, "Optimal undercuts for the tuning of percussive beams," Journal of the Acoustical Society of America, Vol. 102, pp. 2432-2437.

[8] Petrolito, J., and Legge, K. A., 2005, "Designing Musical Structures Using a Constrained Optimization Approach," Journal of the Acoustical Society of America, Vol. 117, pp. 384-390.

[9] Henrique, L. L., and Antunes, J., 2003, "Optimal Design and Physical Modelling of Mallet Percussion Instruments," ACTA Acustica United with Acustica, Vol.89, No.: 6, pp. 948-963.

[10] Aramaki, M., Bailleres, H., Brancheriau, L., Kronland-Martinet, R., and Ystad, S., 2007, "Sound quality assessment of wood for xylophone bars," Journal of the Acoustical Society of America, Vol. 121, pp. 2407-2420.

[11] Wang, B. T., and Lin, Y. S., 2007, "Vibration and Sound Correlation Study for a Metal Bar of Metallophone," Proceedings of the 20th Conference of Acoustical Society of Republic of China, Taipei, Taiwan, Paper No.: C5. (In Chinese)

[12] Wang, B. T., and Jian, X. M., 2010, "Model Verification and Percussion Sound Characteristics of Metallophone with Chord Sound," The 17th International Congress on Sound and Vibration, Cairo, Egypt, Paper No.: 376.

[13] Tsai, G. C., Wang, B. T., Lee, Y. S., and Chang, Z. W., 2005, "Study of Vibration and Sound Characteristics of Copper Gong," Journal of the Chinese Institute of Engineers, Vol. 28, No. 4, pp. 713-719.

[14] Wang, B. T., and Chen, S. C., 2008, "Sound and Vibration Characteristic Discussion the Gong Navel form Copper Gong," Proceedings of the 21st Conference of Acoustical Society of Republic of China, Taipei, Taiwan, Paper No.: A1-4. (In Chinese)