SCALE MODEL EXPERIMENTS FOR ECHO PHENOMENA OF YINGYING PAGODA

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ABSTRACT In this paper, the echo phenomena of Yingying Pagoda(ancient Chinese architecture), which may be resulted from interferences of reflection and diffraction by the pagoda eaves when pulse sound source is at some suitable positions, are investigated by an 1:2 scale model. There are valleys in frequency spectrum due to the interferences. On the other hand, taking eaves as wedges approximately, numerical spectral estimates are obtained from the closed-form impulse solution for diffraction of pulse point-source radiation by an infinite rigid wedge. The results of the numerical computations are similar to those of the model experiments. The study is a helpful guide to reconstruction or maintenance of this kind of ancient buildings.

INTRODUCTION

Acoustic model testing began in 1913 with Sabine's spark photography[1]. Since the work of Spandock and others in a wide range of acoustical research, the scale mode techniques have been widely used for investigating the propagation, reflection, and diffraction of sound waves[2]. Particularly, Such techniques are effective tools for the acoustic systems where no satisfactory mathematical analyses have been established.

In the present paper, the echo phenomena of Yingying Pagoda are investigated by an 1:2 scale model. Yingying Pagoda is situated inside the Pujiu Temple, Shanxi Province, China. What heard at some positions near the pagoda is sounded like frog-tone after striking against the ground with stone, which is called "the Pujiu's frog sound". Such phenomena were recorded in the local chronicles in the Qing dynasty. Ref. [3] shows that the frequency range and the time interval between the adjoining echo sound pulses from the pagoda are similar to that the sound pulse in frog sound.

With passage of time, the pagoda has been damaged by rains and winds. So accurate measure could not be obtained easily. This factor and the noise around the pagoda can be avoided by the model techniques. This study will offer the guide for reconstruction and repair of the ancient building. It is important to protect the ancient cultural heritages.

SCALE MODEL EXPERIMENTS

Yingying Pagoda is a square brick building with eaves based on the low hill. Its surface is very smooth due to wind and rain. The height of the pagoda is 36.67m. The eaves are concave and approximate to arc in shape. The sketch of Yingying Pagoda and and an stretching eave are shown in Fig.1 and Fig.2.

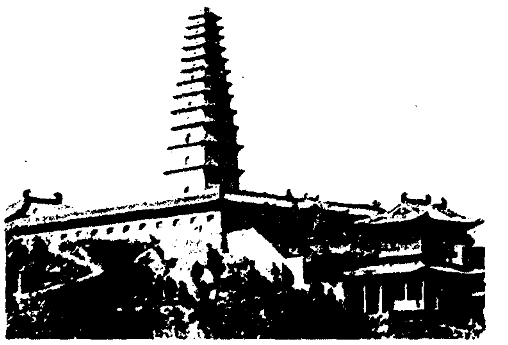


Fig.1 The sketch of Yingying Pagoda

Fig.2 An stretching eave of the pagoda

Model

The technique of using acoustic scale models requires that all physical laws governing the behavior of the prototype also govern the scale model situation. So the physical quantity, i.e. functions of time, length and mass, may be scaled to the desired ratio between prototype and model. Sound attenuation in air is not nessesary when the absolute measurements are not required from the model.

An essentially free field environment to house the model was achieved in the semianchoic chamber of Institute of Acoustics(IOA). Yingying Pagoda is nearly 40m in height. The positions where the frog sound can be heard are also at least 20m from the pagoda. The structure of eave is similar with each others and the distance between the adjacent floors is at least 1m. Considering structures of the pagoda, the frequency range of the sound from the pagoda and the propagation of sound by the reaction from the eaves and the wall, a scale model of parts of the structures is built. The third floor is chosen as a typical model with scale 1:2. The stretching length of the model eave is 0.425m. The eave is put on the terrazzo ground of semanchoic chamber, see Fig.3. The terrazzo ground is taken as a side wall of the pagoda. The eave is poured with concrete and smooth surface.

Sound Source

The source for pulses is a cylindrical electric spark with radius of 1.5cm, which can produce a pulse with width 0.105ms, positive peak 1.1V and negative peak 0.93V.

Model Results

Tests were carried out in the semianchoic chamber of IOA. The model and measure configuration is shown in Fig.3. High density signal analyzer(B&K 2033) receives sound through an 1/8 inch condense microphone(B&K 4138) and transfers the data into a computer. The sampling frequency is 51.2kHz. The sound source is placed at 1.36m above the floor of the semianchoic room and the horizontal distance between the source and the eave is 1m. The

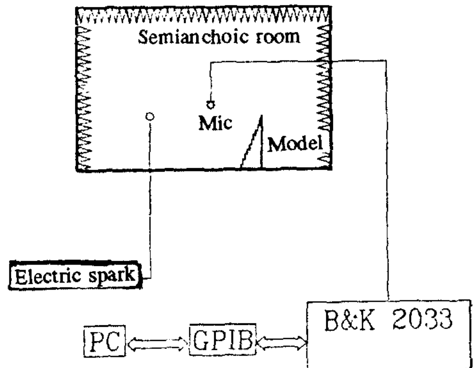
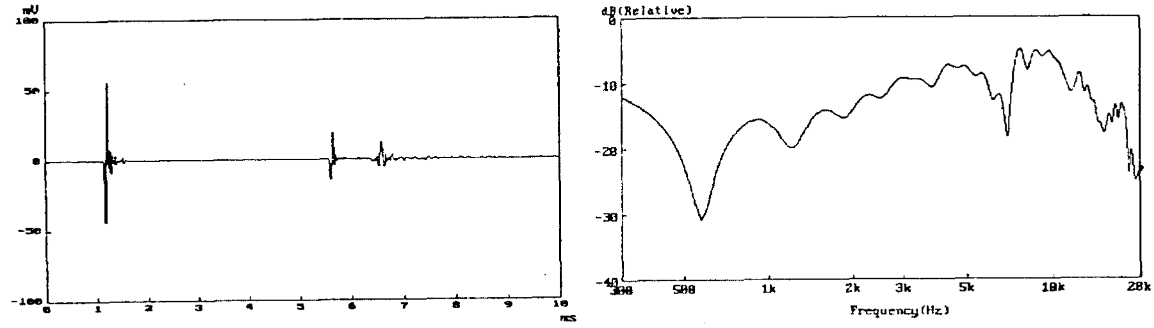


Fig.3 The diagram of configuration

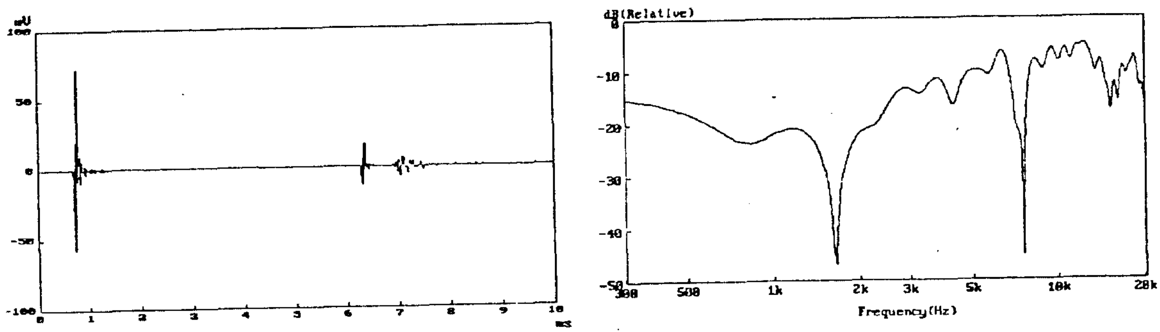
microphone is placed at 0.5m in horizontal distance from the eave.



(a) Waveform

(b) The spectrum by eave

Fig.4 Receiving point A at 0.83m above the ground of the semianchoic room



(a) Waveform

(b) The spectrum by eave

Fig.5 Receiving point at 1.03m above the ground of the semianchoic room

Tests are made at the different positions of the microphone. The waveforms and their spectra relative to the direct waves are given in Fig.4 and Fig.5 at the receiving point A 0.83m and B 1.03m above the ground of the semianchoic chamber, respectively. In the waveforms, the first pulse is direct from the source to the receiver, the second pulse is reflected by the ground of the semianchoic chamber, the third wave is mixture of reflected wave and diffracted wave caused by the eave of the pagoda. The spectra are obtained by separating the third wave from the time signal related to the direct wave.

APPROXIMATE SIMULATION IN NUMERICAL COMPUTATIONS

When an impulse from a delta function point source propagates over a wedge, the diffracted wave creates. An exact impulse solution of an infinitely rigid wedge is reduced in ref. [4].

Acoording to ref. [4], source coordinates are (ρ', ϕ', 0); receiver coordinates are (ρ, ϕ, z). The angle of the wedge is called ψ. Then, the diffracted wave over a wedge is

$$p_d(t) = \frac{c\nu}{8\pi\rho\rho'\sinh\beta}\left\{\frac{\sin[\nu(\pi\pm\phi\pm\phi')]}{\cosh\nu\beta-\cos[\nu(\pi\pm\phi\pm\phi')]}\right\}, \qquad t>\tau_0 \tag{1}$$

where c is the sound speed, the curly bracket consists of the sum of four terms obtained by using the four possible combinations of $\pi\pm\phi\pm\phi'$, and

$$\begin{aligned} \beta &= \cosh^{-1}[c^2t^2-\rho^2-\rho'^2-z^2)/2\rho\rho'] \\ \nu &= \pi/\psi \\ \tau_0 &= L/c = \sqrt{(\rho+\rho')^2+z^2}/c \end{aligned} \tag{2}$$

where z is the offset between the sound source and the receiver along the apex of wedge, τ_0 is the least time over the wedge.

Taking the model as a combination of two wedges approximately, the sound wave diffracted by the eave is obtained,

$$p(t) \approx p_{ref} + p_{dA}(t) + p_{dB}(t) \tag{3}$$

where p_{ref} is a wave reflected by the eave chest, p_{dA} is a wave diffracted by the eave apex, and p_{dB} is a wave diffracted by the intersect apex of the wall and the eave. Multiple reflections are not taken into consideration because they do not occur at the real positions where the frog sound may be heard.

Calculations are carried out with respect to infinitely rigid wedge. The spectra relative to the direct waves corresponding to the above receiving points A and B are given in Fig.6 and Fig.7.

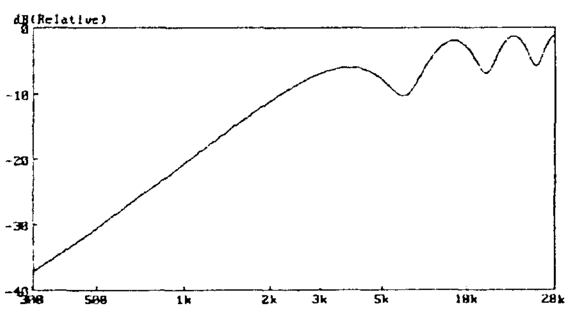


Fig.6 The computing spectrum at point A

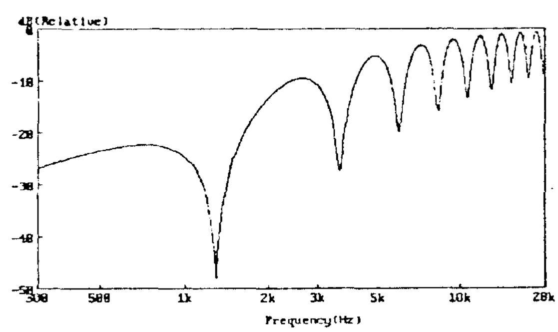


Fig.7 The Computing spectrum at point B

The size of the pagoda eaves should be much longer than the wave length, at least, be comparable to the wave length. However, the model is only 2m long and 0.425m wide, so the calculated values for infinite wedge are different from the results of the model at low frequency. Besides, the shape of the eave is rather complicated and close to arc; the eave consists of a series of step of 5cm. Therefore, it would cause the sound scatter which is different from that of the wedge at very high frequency. From above, the results for the computations do not square with the real results for the model. However, it is theoretically shown that the pattern of impulse sound reflection and diffraction by infinite wedge is consistent with that by eave.

So far, the exact computation method has not been obtained yet for such complicated structure, and the exact expression has also not been found in document. The further investigations on this problem remains to be done.

CONCLUSION

In this paper, the echo phenomenon of Yingying Pagoda is studied through acoustical scale model experiment. The sound wave reflected at the eave surface interferes with the diffracted wave by the eaves of the pagoda and causes the sophisticated changes of frequency spectrum received at some suitable position. There are obvious valleys in the spectra. In addition, taking the eave as the combination of wedges, the results similar to the model are obtained by the numerical simulation.

With respect to Yingying Pagoda, there are litlle discrepancies between the valley frequencies in the spectrum of sounds. The valley frequencies are not in the main range of frog sound. The structure of each floor of the pagoda makes it same for reflected angle, position of reflected ray and time difference between each pulse sound. Therefore, the frequency spectra of sounds received from the pagoda eaves are almost same.

For the prototype of the pagoda, the properties of sound source, air attenuation and influence of environment condition should be considered.

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