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SOUND REFLECTION FROM VIBRATING SURFACE

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SUMMARY

The walls of a room are normally assumed to be rigid when we evaluate sound fields. In real conditions, however when the walls are excited by low-frequency sound, reflection sounds are phase modulated. As the wall moves inward, the frequency of the reflection sound increases and as the wall moves outward, the frequency decreases. This modulation is a nonlinear phenomenon known as inter-modulation. In a highly reverberant space, there are multiple reflections from the room boundaries, and the effect of the modulation is thought to be more significant than that caused by a single reflection sound. This distortion has been thought to adversely affect the acoustic quality of an auditorium. The authors formulated the mathematical basis of this phenomenon and numerically investigated it by computer simulation. Simulation results show that the amount of the modulation (i.e. the distortion ratio) is greater in a small and highly reverberant space than that expected in a large and non-reverberant space.

INTRODUCTION

The acoustic field in a room is generally modeled as a linear system. The sound wave travels according to the linear wave equation and is reflected on the boundary surface imposed by linear boundary conditions. However if the boundary condition is changed we have to take non-linearity into account.

For example, when boundary surfaces of a room (floor, wall and ceiling) are excited by the bass sound of a musical instrument played within the room or traffic vibrations from outside, the boundary conditions which must be satisfied by the moving boundaries might be nonlinear.

When such boundaries vibrate, the frequency of the reflection sound fluctuates.

This is because the propagation time from the source to an observation point changes while the boundary moves. This phenomenon can be formulated as phase modulation which produces nonlinear distortion such as inter-modulation.

A reverberation chamber with moving diffusers or movable walls are investigated by K. Bodlund(1)and C. E. Ebbing(2). However since the purposes of those researches are to increase the diffuseness of a reverberation chamber. They don't address about the frequency characteristics of the transmitted sounds. Also, displacement of the boundary is large, but the speed of movement is not so high.

This article investigates the frequency characteristics of the reflection sounds from vibrating surfaces.

Until this century, the only musical instrument which could produce a loud bass sound was a pipe organ. The interiors of concert halls and churches were finished with stone, brick, or plaster and thus the boundary displacement was thought to be so small that the effects of the vibration of the boundary surfaces seemed to be negligible. These days bass sound with a large amplitude is often reproduced by electric equipment in a room whose interior is finished with thin and light material, or even covered with air-inflated membranes. In these cases the boundary surface cannot be assumed to be a non-vibrating surface.

Not only for concert hall acoustics but also for virtual reality(VR) simulation engineering, such as an aircraft cockpit or spacecraft simulations, including inter- modulation effects will give us more realistic results.

This investigation can be extended to offer a new simulation method for various kinds of sound fields including non-linearity.

I DISTORTION OF A REFLECTION SOUND CAUSED BY WALL VIBRATIONS

A. Amplitude Modulation

When a wall is displaced by vibration, the length of the sound path from the sound source to an observation point changes. The attenuation loss during the sound propagation is temporally changed, since the distance between observation point and the boundary varies due to the boundary vibration. The amplitude of the reflection sound from the boundary which is deformed to a concave shape can be larger than that from convex shape therefore the reflection sound can be formulated in the amplitude modulation formula.

B. Phase(Frequency) Modulation

When the wall is displaced, the length of the sound path from the sound source to an observation point changes. The propagation delay time can be modulated. When the delay time changes, the phase of the reflection sound is modulated.

C. Dip frequency shift caused by the change in the delay time

In a real condition, in which observed sound consists of the direct sound and many reflections, there must be peaks and dips in the frequency characteristic function due to interference. When the delay time changes, the dip frequency is shifted and the amplitude of a frequency component close to the dip frequency is modulated.

II MATHEMATICAL FORMULATION OF PHASE MODULATION DISTORTION

The authors assume that (1)Amplitude Modulation(AM) is negligible because of small changes of the propagation time which are caused by small changes in the propagation distance. The authors consider about Phase Modulation. The symbols which will be used in this article are listed below,

c : sound speed (m/s),
α : sound absorption coefficient of the wall,
θ : the angle of incidence (rad).

a : amplitude a_c : sound pressure amplitude (Pa) of the reflection sound

a_{c0} : normalized sound pressure amplitude (Pa) of the sound source

a_m : amount of phase modulation (rad)

ω_c : angular frequency (rad/s) of the reflection sound

ω_m : angular frequency (rad/s) of the wall vibration

ϕ_c : initial phase (rad) of the reflection sound

ϕ_m : initial phase (rad) of the wall vibration

In this study we assume that $\omega_c > \omega_m$.

Here we will formulate the relationship between the reflection sound and wall vibration following to the Frequency Modulation theory.

A. Single sound ray with a reflection

First, we look at a single sound ray from an imaginary source S' to a receiving point R with a reflection. Due to the displacement amplitude d of the wall, the location of the imaginary source S' fluctuates with displacement amplitude $2d$ as shown in Fig.1.

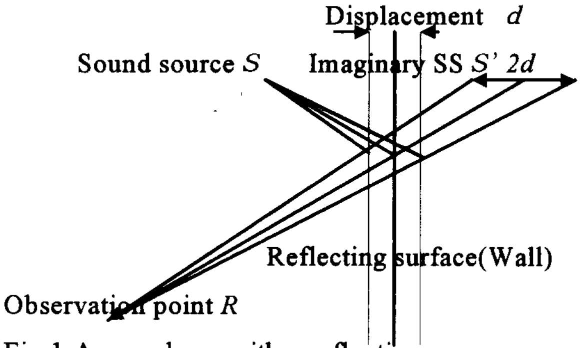

Fig.1 A sound ray with a reflection

Thus the reflection wave $x(t)$ observed at R is,

$$x(t) = a_c \sin\{\omega_c t + \phi_c + a_m \sin(\omega_m t + \phi_m)\} \cdots (1)$$

where

$$a_c = \frac{a_{c0} \cdot (1-\alpha)}{\overline{S'R}^2} \quad \cdots (2)$$

$$a_m \cong \frac{2d \cos\theta \omega_c}{2\pi c}. \quad \cdots (3)$$

The spectrum of the observed sound can be written as

$$\begin{aligned} x(t) &= a_c \sin[\omega_c t + a_m \sin(\omega_m t)] \\ &= a_c \sum_{v=0}^{\infty} J_v(a_m) \sin(\omega_c \pm v\omega_m)t \\ &= a_c [J_0(a_m) \sin\omega_c t + J_1(a_m)\{\sin(\omega_c + \omega_m)t + \sin(\omega_c - \omega_m)t\} \\ &\quad + J_2(a_m)\{\sin(\omega_c + 2\omega_m)t + \sin(\omega_c - 2\omega_m)t\} + \cdots \ ]. \end{aligned}$$

B. A single sound ray with multiple reflections

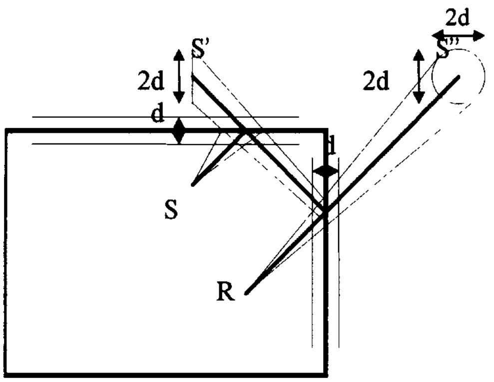

Fig.2 A sound with 2 reflections

Suppose a sound ray arrives at the receiving point R after l reflections on different parts of the room. The reflection wave $x(t)$ observed at R is written similarly to Eq.(1), but a_m should be replaced with A_m.

A_m is vector sum of effects of each reflections written as

$$A_m \sin(\omega_m t + \Phi_m) = \sum_{i=1}^{l} a_{mi} \sin(\omega_m t + \phi_{mi}) \ldots (4)$$

The expectation of the modulation factor A_m can be obtained as the square-root of the sum of the squared amplitude a_{mi}.

Because of the absorption caused by multiple reflections, a_c of Eq.(2) is rewritten as,

$$a_c = \frac{a_{c0} \cdot (1-\alpha)^l}{\overline{S'R}^2} \cdots (5).$$

C. Direct sound and sound rays with multiple reflections

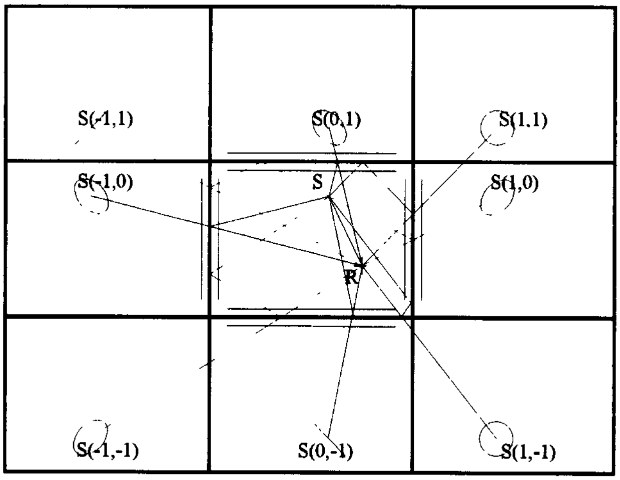

Fig-3 Direct sound and reflections

When the direct sound and many reflection sounds with different phase modulation indices are combined, the frequency characteristics function of the observed sound wave should be different from that of a single reflection.

The sound wave $x(t)$ observed at a certain point in a room should be written as

$$x(t) = a_d \sin \varpi_c t + \sum_n a_{cn} \sin\{\omega_c t + \phi_{cn} + A_{mn} \sin(\omega_m t + \Phi_{mn})\} \cdots (6).$$

Where a_d is the amplitude of direct sound.

D. Assumption regarding diffuse field

One of the purposes of this research is to establish a method of simulating sound fields under diffuse field conditions, for architectural acoustics. Thus the authors consider phase modulation(PM) in diffuse field conditions although in some interference conditions the PM distortion ratio can be larger than that under the diffuse field condition.

III NUMERICAL EXPERIMENT

We use a sound ray method following Eq.(6).

A. Diffuse field condition in a rectangular room

Although the sound field in a rectangular room is not perfectly diffuse, in higher frequency regions the sound field can be assumed to be diffuse. In our simulation, the carrier frequency was chosen high enough that the sound field can be assumed to be diffuse. The authors chose a rectangular room for the numerical experiment. The ratio of each side of the room is set in an irrational number in order to meet well the diffuse field condition.

B. The other assumption

1. AM neglected

When a sound ray reflects on the wall surface, only the propagation delay time is affected by the location of the boundary. However it must be likely that the frequency of a test signal is close to the dip frequency at which AM(as discussed in I-C.) can occur.

2.Pistonic motion of the walls

All the boundaries are assumed to be flat while they are vibrating.

3. Phase condition of the wall vibration

All the vibration modes around the room boundaries are assumed to be in phase, and all the vibration amplitudes of the surfaces are assumed equal.

4.Equal sound absorption coefficient

For simplicity, in this calculation, the same sound absorption coefficient of the wall in all direction is assumed. The calculation method can be extended into for wider conditions.

5. Point source

The sound source is a point source.

C. Threshold

Since the number of the reflections becomes infinity, we set the threshold of the amplitudes of the reflection sounds below where calculation should be stopped.

IV CALCULATION EXAMPLES

Samples of frequency characteristics calculations are presented in Fig.5a to 8c. The conditions for the calculations are written below.

General specifications

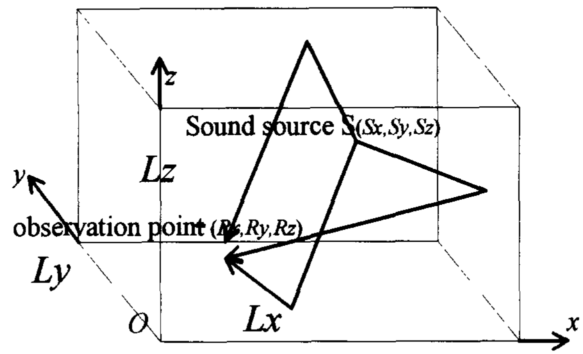

Fig-4 Parameters of the calculation sample

Lx = 6.54 Ly = 5.19 Lz = 4.12
Sx = 4.96 Sy = 4.32 Sz = 3.76
Rx = 0.62 Ry = 0.68 Rz = 0.75 (m)
Mean free path 4V/S = 3.4 (m)
f_c = 500, f_m = 100 (Hz)

First we checked the effect of threshold. Fig-5.a and b show the difference between the results calculated under the different thresholds. The other conditions are

d (displacement amplitude) = 5 (mm) $\alpha = 0.03$

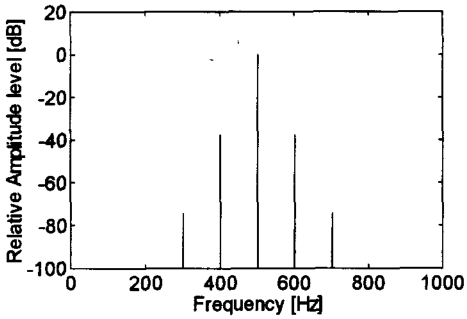

Fig. 5a Threshold = -60(dB)

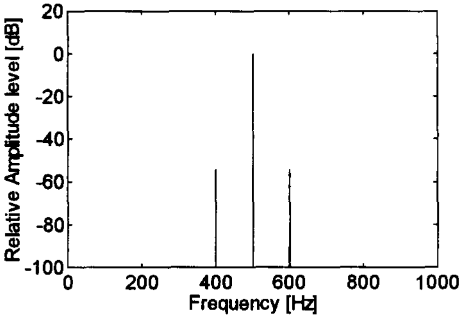

Fig. 5b Threshold = -30(dB)

This result shows that many higher order reflections have non-negligible effects on the phase modulation. The results shown below are calculated with the threshold of -60 (dB).

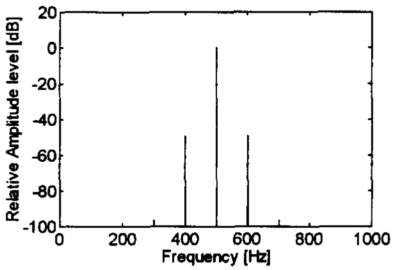

Fig. 6a
scale factor = 1/2
α = 0.1 d= 1(mm)

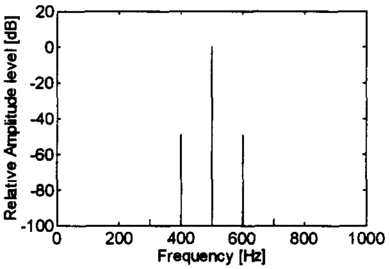

Fig. 6b
scale factor = 1/1
α = 0.1 d= 1(mm)

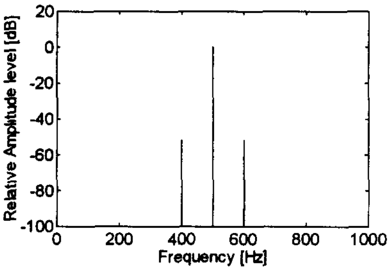

Fig. 6c
scale factor = 2/1
α = 0.1 d= 1(mm)

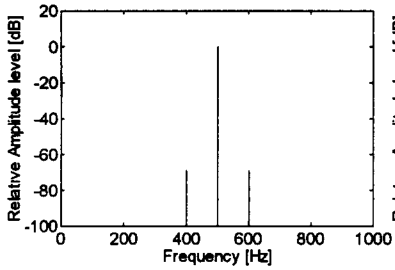

Fig. 7a d = 0.1 (mm)
α = 0.1 scale factor=1/1

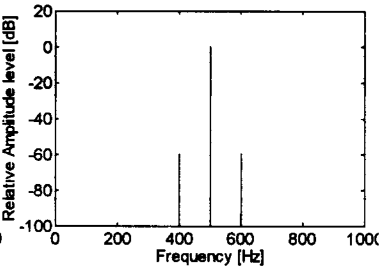

Fig. 7b d = 0.3 (mm)
α = 0.1 scale factor=1/1

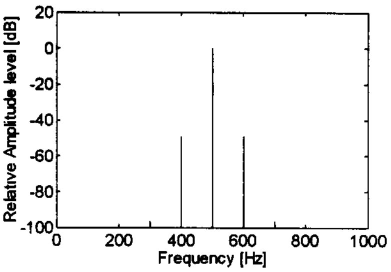

Fig. 7c d = 0.3 (mm)
α = 0.1 scale

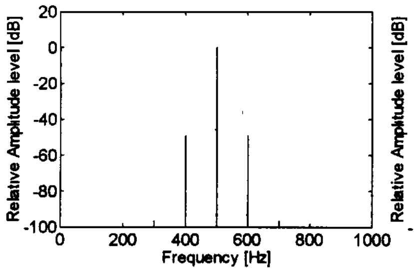

Fig. 8a α = 0.1
d = 0.1 (mm)
scale factor = 1/1

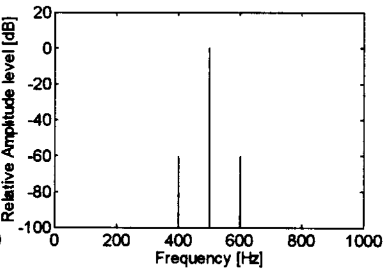

Fig. 8b α = 0.3
d = 0.1 (mm)
scale factor = 1/1

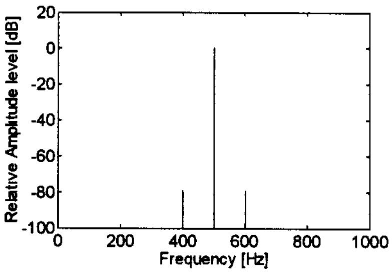

Fig. 8c α = 0.6
d = 0.1 (mm)
scale factor = 1/1

V OBSERVATION AND RESULTS

The distortion ratio of the whole sound (i.e. direct sound and many lower- and higher-order reflections) in the reverberation room is much higher than that of a single sound ray with a reflection. The distortion ratio becomes higher when:

1) The room is smaller, (Fig.6a b c)
2) The displacement amplitude of the wall is larger, (Fig.7a b c)
3) The room is more reverberant. (Fig.8a b c)

Many higher order reflections with the amplitude lower than the threshold are still neglected in these calculations. However they are important factors which cause distortion.

VI CONCLUSION

The authors have investigated mathematical basics of the PM distortion of the reflection sound from vibrating surfaces in a room. The result of simulation seems reasonable. Thus we have found the global tendency.

There must be some cases that we cannot ignore the effect of vibrating surface. For example, in a space surrounded by air-inflated membrane the displacement amplitude can be very large. Because the distortion ratio can be large in a small space, this effect should be more crucial in a small listening room rather than an auditorium.

This research has just started and has formulated only mathematical basics. In the future we have to generalize the simulation conditions in order to meet a real condition.

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(1) “A normal mode analysis of the sound power injection in reverberation chambers at low frequencies and the effects of some averaging methods” JSV(1977)55(4),563-590 “A study of diffusion in reverberation chambers provided with special devices” JSV(1977)50(2),253-283

(2) ″Experimental evaluation of moving sound diffusers for reverberant rooms″ JSV (1971)16(1),99-118