**Energy flux in a periodicity couple space**

**ABSTRACT**

Periodicity couple space is a specific couple space that hasn’t been much studied. As a typical periodicity couple space, the sound field of the staircase in the EE building of University of Western Australia is studied in this paper. Experiment had been done in this space, measuring the frequency response of some positions as well as their reverberation times. Some interesting phenomenon is revealed to show the repeated regulation in this periodicity space. Using the room acoustics theory and especially the couple rooms theories that studied before, the sound field of the periodicity couple space could be successfully explain.

PACS numbers:

**I. INTRODUCTION**

## II. EXPERIMENT SETUP

Firstly, the construction of the staircase in the EE building is about to be described. As shown in Figure 2, the staircase is a rectangular enclosure with 15.42 m height, 6.19 m length and 2.95 m width. Four and a half floors are contained inside the enclosure with 3.429 m height between each one. Space right angle coordinate system is made as figure 2 to describe the position, with the length as the x-axis, width as the y-axis and height as the z-axis.

In order To study the different frequency responses inside the staircase, the loudspeaker was located at point S with the coordinate (5.29, 0.9, 3.51), whose unit is meter. The white noise was generated by the loudspeaker and the response from 20 Hz to 8000 Hz were measured at 25 different points, as Figure 2 a) shown The measuring points were arranged with 1 point at each staircase and 2 measured points at each floor except the second floor, where the location of the loudspeaker. The coordinates of these 25 points are presented in table 1.

Table I. The coordinates of every position

By placing the measuring points as the arrangement, the entire pathway in this staircase was covered to ensure each section will have the same measurement. Dividing the white noise signal from the measured signal in the frequency domain, the room frequency responses from 20 Hz to 8000 Hz could be calculated. During the measurement, the B&K’s Pulse system and sound level meter are used as well as the microphone from Beijing ShengWang (BSW).

The reverberation has also been taken into consideration. By placing the loudspeaker at points S, 10, 16 and 22, the reverberation times (*T*60) of relative positions have been measured. For example, while placing the speaker at point S, the *T*60 position 2, 5, 6 will be measured, while placing the speaker at point 10, the *T*60 position 8, 11, 12 will be measured and so on. The maximum length sequence was emitted by the loudspeaker, the same as the room response measurement, and received by the B&K’s sound level meter during the *T*60 measurement, 3 times each position. And then B&K Dirac software will transfer the frequency response into the impulse response and calculate the *T*60.

**II**I**. EXPERIMENTAL RESULT AND ANALYSIS**

To analysis the staircase, it can be simply divided into 10 similar spaces couple with an aperture as Figure 2 b) presented, which is a periodical couple spaces. at high frequency range, the frequency responses are quite uniform at the measuring points inside each space. As the example, figure 3 presented the room frequency response at different measuring points inside the space 2 and space 9, 10.

Shown from Figure 3, the higher frequency responses (from 100 Hz to 8000 Hz) are quite uniform at different measuring points inside one space. To the contrary, from 20 Hz to 100 Hz, the amplitude responses vary from point to point even in the same space. According to the different situation, the frequency responses from 20 Hz to 100 Hz and the one from 100 Hz and 8000 Hz will be analysis in different way. Firstly, focus on the frequency from 100 Hz to 8000 Hz, the total pressure of each point were calculated and averaged in the same spaces to get the corresponding average pressure response from 100 Hz to 8000 Hz. Presented in Figure 2 a) and b), space 3, 5, 7, 9 are the periodical locations and space 2, 4, 6, 8, 10 are the different periodical locations as well. Connect the corresponding spaces, figure 4 presents the change of the average pressure response of these two periodical locations. The solid curve shows the change versus the periodical locations space 2, 4, 6, 8, 10 and the dash one shows the change versus the periodical locations space 3, 5, 7, 9.

With the loudspeaker placing at space 3, the response at space 3 had the maximum value. There is little responses difference (0.8 dB) between space 2 and 4 since they are the right and left side to sound source space, respectively. Moreover, the response in space 5 is slightly higher than the one in space 4 because of the distance. In figure 2 a), the distance between the geometrical center of space 3 and 4, 5 are 3.54 m and 3.43 m, respectively. Focusing on these two different curves, both of them decrease in the approximately identical slope with the process of the space. In the solid curve, space 3 has 3.6 dB higher than space 5, space 5 has 4.4 dB higher than space 7 and space 9 has 3.2 dB higher than space 9, the mean decrease value is 3.7 dB. In the free field, 6 dB will decrease when doubling the distance while in this staircase, there are only 3.7. The SEA could explain this phenomenon in later section. In the dash curve, space 4 has 5.3 dB higher than space 6, space 6 has 3.0 dB higher than space 8 and space 8 has 0.5 dB higher than space 10, the mean decrease value is 2.9 dB, similar with the mean decrease value of the solid curve. The more accurate theoretical expression will be given in the following section.

Figure 5 shows the frequency responses from 20 Hz to 100 Hz, the dash curve and solid curve present the response amplitude variation from space 3, 5, 7, 9 and space 4, 6, 8, 10 respectively. Both of the response amplitude decrease with the increase of distance. Compare figure 4 and 5, the amplitude of the response from 20 Hz to 100 Hz is much higher than the one from 100 Hz to 8000 Hz, which means the total response amplitude will be determined by the low frequency sound. Turn to these two curves, different and variation slopes they got during the decreasing with the process of the spaces. In the solid curve, space 3 has 3.4 dB higher than space 5, space 5 has 3.8 dB higher than space 7 and space 9 has 6.8 dB higher than space 9, the mean decrease value is 4.7 dB. In the dash curve, space 4 has 1.1 dB higher than space 6, space 6 has 3.5 dB higher than space 8 and space 8 has 2.1 dB higher than space 10, the mean decrease value is 2.2 dB. This is because from 20 Hz to 100 Hz, the modes exist separately and do not superpose together, so to study the frequency from 20 Hz to 100 Hz, the continuum spectrums are needed to identify which mode controls the sound field in this space. Figure 6 presents the typical continuum spectrum from 20 Hz to 100 Hz in space 4.

After analyzing the modes of the continuum spectrum from 20 Hz to 100 Hz in 10 spaces, the nature frequencies of the staircase were identified and summarized in table II

These nature frequencies can be calculated with the dimensions of the enclosure, and described by the mode number m, n, p, present the X, Y, Z axis, respectively. There are three major dimensions in this staircase, the length, 6.19 m, the width, 2.95 m and the height between each floor, 3.43 m. Base on these three dimensions, there are three basic modes in the theoretical calculation, whose mode number (m, n, p) is (1,0,0), (0,1,0) and (0,0,1). So (1,0,0) is 27,7 Hz for the length axis, (0,0,1) is 50,2 Hz for the width axis and (0,1,0) is 58.3 Hz for the height axis. Base on these three modes, the first 12 modes have been listed in table III.

Shown in table III, experimental result are close to the theoretical nature frequencies with several modes superposed together. While the 47 Hz and 69 Hz modes have also been observed as the nature frequencies that could not be obtain in the theoretical calculation. These two modes may be the global modes that caused by the whole structure of the staircase. And the modes obtain both in experiment and calculation may be the local modes, which needs to be proved in later experiment.

Between 20 Hz to 100 Hz, the total responses of each space will be determined by certain modes since the modes are separated and retained. So the domain modes need to be found out in order to study the sound field in low frequency. Figure 7 is the room continuum spectrum responses from 20 Hz to 100 Hz in different spaces, space 2 to space 10 from the top to the bottom. In figure 7, the frequency responses of different space between 20 Hz to 100 Hz are placed together. The domain modes are identified and place the space number onto the peak.

Figure 7 indicate that each space is domain by one or several modes, presenting in table VI. All space 3, 5 and 7 are domain by 60 Hz mode and space 2, 4, 6, 8 are domain by 26 Hz. While in space 9 and 10, the frequency response become gentler and 3 modes domain the spaces. The result can partly explain the dramatic change of slope when entering space 9 and 10, shown in figure 7.

The *T*60 shows a uniform variation with the frequency in different position when frequency higher than 100 Hz, as present in figure 8. For the low frequency, 25 Hz to 100 Hz, different kinds of points present a relatively huge difference. As mentioned above, when frequency higher than 100 Hz, the modes superposed together and their individual properties were averaged to present a uniform character. For frequency lower than 100 Hz, the space was domain by several modes that their individual characters will influence the *T*60, which present a relatively variation in figure 8. The *T*60 were measured in order to taken into the SEA method to calculate the self loss factor.

## IV. THEORETICAL CONSIDERATION AND SIMULATION

The mirror image method is used for theoretical calculation to the sound response higher than 100 Hz. The source point is located at space 3, shown in figure 9. And there are 5 nearest wall with it. All the walls will generate the mirror image, which can present the effect that shows on other points. Since from figure 8, when frequency is higher than 100 Hz, the reverberation time of different points are quite similar, which means that a diffusion space has been formed when frequency is higher than 100 Hz. So the phase different can be ignored while using the mirror image method. Point 0 is the source point and point 1 to 23 is 23 different mirror points with the reflection of 5 nearest walls for calculating the space 4 and higher level space and point higher than point 8. Their coordinates were marked in table VI.

For calculating space 1, 2, 3 and point 1 to 7, other mirror points will be used to calculate. According to these coordinates, the *L*s of each space could be calculated by equation (1)



Where *r* is equal to the geometry center of each space to the source points, including the original source point and the mirror points.

Using Sabin equation, the sound absorption coefficient can be figure out that equal to 0.15. So each reflection will cause 0.7 dB sound dissipation. Figure 10 is the calculation result using the mirror image method compare with the experimental result.

Based on figure 10, the theoretical results have a good agreement with the experimental results. The Ls of two kinds of spaces decay following the different curves. The curve from space 3 to 9 decay with a constant decay rate and the curve from space 2 to 10 decay with a decreasing decay rate. The experiment result present two separate curve and so do the theoretical result presents. Besides different space can use mirror image method to simulate, the different points of the staircase can use it as well. Figure 11 present the result of the experimental data and the theoretical result.

## VI. CONCLUSIONS

## ACKNOWLEDGEMENT

## References

1Sgard F, Nelisse H, Atalla N. On the modeling of the diffuse field sound transmission loss of finite thickness apertures[J]. The Journal of the Acoustical Society of America, 2007, 122(1): 302-313.

Table I. The coordinates of every position

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| No. | 1 | 2 | 3 | 4 | S | 5 |
| (X, Y, Z) | (0.9, 0.9, 1.8) | (0.9, 1.75, 1.8) | (3.95, 1.75, 2.66) | (5.29, 1.75, 3.51) | (5.29, 0.9, 2.8) | (3.95, 0.9, 4.37) |
| No. | 6 | 7 | 8 | 9 | 10 | 11 |
| (X, Y, Z) | (0.9, 0.9, 5.23) | (0.9, 1.75, 5.23) | (3.95, 1.75, 6.09) | (5.29, 1.75, 6.94) | (5.29, 0.9, 6.94) | (3.95, 0.9, 7.80) |
| No. | 12 | 13 | 14 | 15 | 16 | 17 |
| (X, Y, Z) | (0.9, 0.9, 8.66) | (0.9, 1.75, 8.66) | (3.95, 1.75, 9.52) | (5.29, 1.75, 10.37) | (5.29, 0.9, 10.37) | (3.95, 0.9, 11.23) |
| No. | 18 | 19 | 20 | 21 | 22 | 23 |
| (X, Y, Z) | (0.9, 0.9, 12.09) | (0.9, 1.75, 12.09) | (3.95, 1.75, 12.95) | (5.29, 1.75, 13.80) | (5.29, 0.9, 13.80) | (3.95, 0.9, 14.66) |
| No. | 24 | 25 |  |  |  |  |
| (X, Y, Z) | (0.9, 0.9, 15.52) | (0.9, 1.75, 15.52) |  |  |  |  |

Table II. The nature frequencies of the staircase

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Nature frequency (Hz) | 26 | 47 | 52 | 60 | 65 | 69 | 74 | 80 | 86 | 96 |

Table III. The natural frequency of the staircase

|  |  |  |  |
| --- | --- | --- | --- |
| No. | Mode  (X, Y, Z) | Theoretical Frequency  (Hz) | Measured Frequency  (Hz) |
| 1 | (1,0,0) | 27.7 | 26 |
| 2 |  |  | 47 |
| 3 | (0,0,1) | 50.2 | 52 |
| 4 | (2,0,0) | 55.4 |
| 5 | (1,0,1) | 57.3 | 60 |
| 6 | (0,1,0) | 58.3 |
| 7 | (1,1,0) | 64.5 | 65 |
| 8 |  |  | 69 |
| 9 | (2,0,1) | 74.8 | 74 |
| 10 | (0,1,1) | 76.9 | 80 |
| 11 | (2,1,0) | 80.4 |
| 12 | (1,1,1) | 81.7 |
| 13 | (3,0,0) | 83.1 | 86 |
| 14 | (2,1,1) | 94.8 | 96 |
| 15 | (3,0,1) | 97.1 |

Table VI. Domain modes of each space from space 2 to 10.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Space No. |  | 3 | 5 | 7 | 9 |
| Domain Mode (Hz) |  | 60 | 60 | 26, 60 | 47, 52, 74 |
| Space No. | 2 | 4 | 6 | 8 | 10 |
| Domain Mode (Hz) | 26, 52, 60 | 26, 80 | 26, 52 | 26 | 60, 74, 80 |

Table V. The coordinate of the origin and mirror points

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 0 | 1 | 2 | 3 | 4 |
| (5.29, 0.9, 2.8) | (5.29, -0.9, 2.8) | (7.09, 0.9, 2.8) | (7.09, -0.9, 2.8) | (5.29, 0.9, 0.5) |
| 5 | 6 | 7 | 8 | 9 |
| (7.09, -0.9, 0.5) | (5.29, -0.9, 0.5) | (7.09, -0.9, 0.5) | (5.29, 4.9, 2.8) | (7.09, 4.9, 2.8) |
| 10 | 11 | 12 | 13 | 14 |
| (5.29, 4.9, 0.5) | (7.09, 4.9, 0.5) | (4.09, -0.9, 0.9) | (4.09, 0.9, 0.9) | (4.74, -0.9, -0.7) |
| 15 | 16 | 17 | 18 | 19 |
| (4.74, 0.9, -0.7) | (4.09, 4.9, 0.9) | (4.7, 4.9, -0.7) | (8.4, -0.9, 0.9) | (8.4, 0.9, 0.9) |
| 20 | 21 | 22 | 23 |  |
| (7.7, -0.9, -0.7) | (7.7, 0.9, -0.7) | (8.4, 4.9, 0.9) | (7.7, 4.9, -0.74) |  |

**Collected Figure Captions**

FIG. 1. The staircase in the EE building of the University of Western Australia

FIG. 2. a) The 3 dimension model of the staircase of EE building of Western Australia, with 6.190 m length, 2.95 m width and 15.420 height. The red S is the loudspeaker’s position and Numbers 1 to 25 represents the measurement positions. b) 2D simplified model of the staircase of EE building of Western Australia with 2.95 m width. Red S represent the location of the sound, Number 1 to 9 represent the different space

FIG. 3. The room 1/3 octave band frequency responses from 20 Hz to 8000 Hz at different measuring points in space 2 and space 9 and 10.

FIG. 4. The average room responses of 1/3 octave bands from 100 Hz to 8000 Hz in different spaces. The solid curve connects the room responses from the space 1, 3, 5, 9. The solid curve connects the room responses from the space 2, 4, 6, 8, 10.

FIG. 5. The average room response of 1/3 octave band from 20 Hz to 100 Hz in different spaces. The solid curve connects the room responses from the space 1, 3, 5, 9. The solid curve connects the room responses from the space 2, 4, 6, 8, 10.

FIG. 6. The continuum spectrum from 20 Hz to 100 Hz in space 4.

FIG. 7. The continuum spectrum room responses from 20 Hz to 100 Hz in 10 different spaces

FIG. 8. The *T*60 of different positions versus the frequency

FIG. 9. The mirror points of the source for calculating the upper level response

FIG. 10. The comparison of the experimental results with the theoretical calculation results of each measuring point. The dash line is the experimental result and the solid line is the theoretical one.

FIG. 11. The comparison of the experimental results with the theoretical calculation results of each space. The solid lines are the experimental result and the dash lines are the theoretical one. Square markers present line 3, 5, 7 and 9. The circle markers present line 2, 4, 6, 8 and 10.