WOOD RESEARCH
63 (5): 2018
855-870

EFFECT OF CONSTITUTION ON SOUND INSULATION PERFORMANCE OF WOOD-FRAME WALLS

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(Received July 2017)

ABSTRACT

This paper aims at investigating the influence of constitution and sound insulation materials on the sound insulation of wood-frame walls. The effects of stud sizes, stud spacing, layers of sheathing and sound insulation materials on the sound insulation were analyzed and discussed. The results showed that the sound insulation property was influenced by layers of sheathing, stud sizes and spacing, density and thickness of sound insulation materials. The regression model was established with six sets of data and five sets of data were used to verify it. The recommended design scheme of wood-frame wall was determined according to the frequency of daily noise.

KEYWORDS: Wood-frame wall, sound insulation performance, sheathing, the mass law.

INTRODUCTION

The use and variety of available materials for sound insulation has greatly increased over the past few years, mostly due to both technological advancements and increasing public concern regarding noise pollution and the environment (Arenas et al. 2014). Although sound insulation in wood frame buildings can be achieved using heavy screens, vibration isolation, and using floating slabs, one way is to maintain the best possible sound insulation performance of the building envelope, which is achieved both by using of suitable materials and their proper combination and wall constitution. When used in practice innovative concept will improve the sound insulation performance of the construction (Blazek et al. 2016), avoid the noise caused by human activities in the building and the traffic out the building interfering with people's life. As a vital component of building envelope, minimizing sound transmission and maximizing sound absorption of wood-frame wall have remarkable influences on sound insulation and energy consumption of buildings.

A large number of wood-frame wall sound insulation studies have been performed in the world (Hongisto 2006). One of the first prediction models was proposed by Beranek and Work (1949). The model assumed perpendicular incidence of acoustic waves, which allowed to describe the propagation of through double walls by means of the structural impedance approach. An extension of the model to the diffuse sound field, involving oblique angles of incidence, was introduced by London (1950). White and Powel (1966) introduced a model for bounded panels, taking into account the resonance effects caused by their dimensions. They analyzed the power flow response between two or more coupled multi-resonant systems to random excitation, determining the coupling between a reverberant acoustic field and a structure by means of a radiation resistance approach. Cummings and Mulhoulland (1968) took acoustic wave reflections between double walls by raytracing approaches to calculate the acoustic insulation performance of cavities. Heckl (1981) evaluated the influence on the sound transmission of the mass per unit area, the bending stiffness and damping. Further work on sound insulation and sound transmission in the presence of rigid construction joints was done. The influence on the sound transmission of plasterboard double walls was evaluated using a statistical prediction approach by Green and Sherry (1982). Urbán et al. (2016) evaluated sound insulation of naturally ventilated double skin facades by measuring in situ and laboratory, a new model was proposed that predicted the sound insulation of naturally ventilated double walls.

From airborne sound insulation point of view, the composition with whole-excelsior dimensions of particles gave better sound insulations values. Porous materials could be useful for high frequency sound absorption while perforated wood panels were useful to obtain good absorption values at medium frequency. Asdrubali et al. (2017) analyzed that by making wooden battening or holes in wooden surface, a perforated resonator could be created that also efficiently dampened medium-to-high-pitched sounds, and the footstep insulation of wooden floor could be improved by increasing the mass of the floor. With an experimental campaign Zhou et al. (2007) studied the influences of building details on the sound insulation of wood structure walls. He found that factors influencing the sound insulation were panel's surface density, stud sizes and spacing, density and thickness of glass fiber batts, and he suggested that 600 mm should be selected as wall stud spacing. Hiramitsu (2008) reported the results of measurement of the airborne sound insulation performance of separation walls of a full-size four-story building. The performance of the wall with staggered studs was the highest and with common stud placement was hardly any difference, even though there were differences in thickness of the air layer or the wall. Reichelt et al. (2016) confirmed that elastomers were a suitable way to meet acoustic requirements as well as structural demands, they were more and more commonly used in wood constructions to reduce disturbing sound transmission over the flanking parts and to provide a good acoustical performance over the lifetime of the building. Monteiro et al. (2017) evaluated the adequacy of performing translations based on the geometrical relation between the sound reduction index R and the standardized level difference D_{nT}, and the effect of the frequency range extension on such translations was studied for two typical building systems such as heavy and lightweight walls. Santoni et al. (2017) presented a prediction model to evaluate the sound transmission loss provided by the external thermal insulation composite systems, also considering the sound bridges that connect the insulating slabs to the basic wall.

In order to provide theoretical basis of sound insulation performance used in wood-frame wall, this paper took an experimental study on sound insulation properties of different structural parameters walls. Attempting to develop cost-effective and practical retrofit systems to reinforce existing wooden construction for specific stud-wall deficiencies of sound insulation. The result is expected to offer reference for the future design and calculation of prefabricated wood-frame walls, especially in the acoustic insulation properties.

MATERIAL AND METHODS

Wall structure design and materials

Wall structure design

At present, no ready-made design table of wood-frame wall structure can be adopted in China. In this test, non-load bearing partition wall structures were designed and referred to Canada Wood-frame House Construction, thus, the safety calculation of wall structure was omitted. Based on GB50005-2003- (2004) and GB/T50361-2005- (2006), the walls were designed by a single-row-of-wood-stud and external sheathing structure, filled with sound insulation materials. The thickness of sound insulation layer was determined according to the heat transfer coefficient U of wall according to the national standard, wood-frame wall structures were shown in Fig. 1.

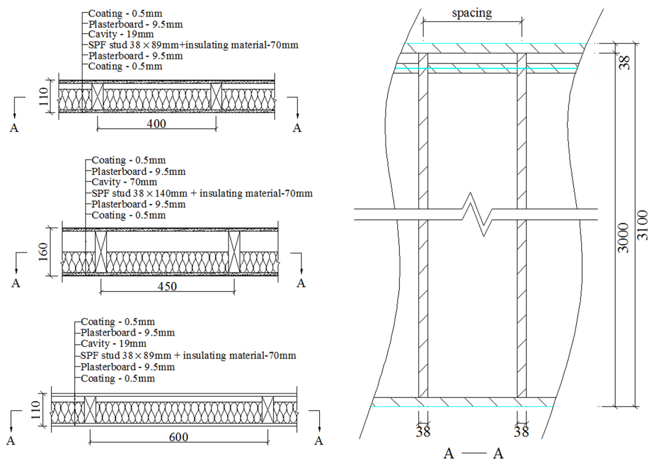

Fig. 1: Structure design of partition walls.

Wall materials

The cross-section sizes of wall studs with Canadian SPF (spruce-pine-fir) dimension lumber were 38 × 89, 38 × 140 mm, respectively, No. 2 grade specification of SPF. Sheathing was fireproof plasterboard with areal density 8.0 $kg \cdot m^{-2}$, and its dimension was 3000 × 1200 × 9.5 mm. Mineral wool, glass wool and polyester were employed as acoustic insulation materials, their densities were 50 $kg \cdot m^{-3}$, 16 $kg \cdot m^{-3}$, 28 $kg \cdot m^{-3}$, respectively. Different wall materials and constitutions were shown in Tab. 1.

Tab. 1: Orthogonal experimental table.

Factors	Stud sizes (mm)	Stud spacing (mm)	Plasterboard layers	Insulation materials
1	38×89	400	I + I	Mineral wool
2	38×89	450	I + II	Glass wool
3	38×89	600	II + II	Polyester
4	38×140	400	I + II	Polyester
5	38×140	450	II + II	Mineral wool
6	38×140	600	I + I	Glass wool
7	38×140	400	II + II	Glass wool
8	38×140	450	I + I	Polyester
9	38×140	600	I + II	Mineral wool

Note: I + I = single-layer plasterboard on both sides; I + II = single-layer plasterboard on one side and double-layer on the other side; II + II = double-layer plasterboard on both sides.

Tab. 2: Simplified table of orthogonal experiment.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	2	1	3	2
8	2	2	1	3
9	2	3	2	1

Wall construction

The size of wall is 5000 (width) × 3100 (height) mm with a solid wood door 865 × 1980 × 40 mm on it. The walls were constructed at the test site in order to avoid the damage caused by material handling and structural deformation. The other walls in test room were designed in concrete structure, the thickness of the concrete wall and floor were 300 mm. The size of the emitting room and receiving room were 5000 × 3600 × 3975 or 5000 × 3600 × 3770 mm, respectively. Plasterboards were vertically laid, and all seams were filled with sticky mud, stuck firmly and smoothly with bandages.

Test methods and calculation principles

Test equipment and methods

AWA6290M type double channel acoustic measuring system was applied as the main test equipment, including AWA6290M type double channel signal analyzer, the microphone, sound power amplifier, the dodecahedron loudspeakers system and sound-level calibrator etc. The measure points and equipment of sound insulation measurement were laid as illustrated in Fig. 2.

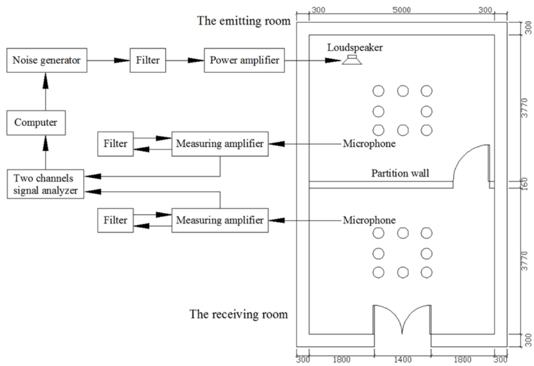

Fig. 2: The layout of acoustic measuring system.

In accordance with the specification of GBJ75-84-(1985). The signal generator generated narrow-band random noise by the filter, including the 1/3 octave bands white noise or pink noise, altogether 18 central frequency: 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150Hz. The dodecahedron loudspeakers system made noise by the signal passing power amplifier in the sound source room, then measured the respective sound pressure level L1 of the emitting room and L2 of the receiving room by the microphone, and reverberation time T60 in the receiving room.

Calculation principles

Based on the reverberation time T60, the sound absorption A of the receiving room can be obtained by the W. C. Sabine formula:

$$A = \frac{0.161V}{T_{60}}$$

where: V - volume of receiving room (m^3),
T_{60} - the reverberation time (S).

The characterization of airborne sound insulation performance of the wall was evaluated by the sound transmission loss R, which can be obtained by the following formula:

$$R = L_1 - L_2 + 10\lg\frac{S}{A}$$

where: L_1 and L_2 - represent, respectively, the average sound pressure level of emitting room and receiving room (dB),
S - area of the specimen (m^2),
A - sound absorption of receiving room (m^2).

The value of weighted sound insulation R_w was used to represent the wall sound insulation performance in comparison. Weight sound insulation was the decibel by comparing sound insulation curve each centre frequency position drawing and reference curve to meet the specific conditions. Compared with the average sound transmission loss, R_w could better represent the effect of sound insulation wall components, thus assuring a certain comparability between different components.

RESULTS

Analysis of factors affecting sound insulation performance

Range and variance analysis method were combined to analyze the results of orthogonal design experiments. Comparing the size of range, range analysis method had some limitations, and it was competent in identifying the main and secondary factors, though inferior to variance analysis method, which was capable to distinguish whether differences between experimental results and their counterpart levels of each factor resulted from changes in levels or experimental errors. But, variance analysis method could make up for those limitations, this was the very reason why two analysis methods were adopted together in this study.

When frequency is 100 Hz, orthogonal experimental results are shown in Tab. 3 and 4.

It can be seen from Tab. 3 and 4 that at the frequency of 100 Hz, the significant factor affecting the airborne sound insulation performance is stud sizes, while stud spacing, sound insulation materials and plasterboard layers exert little effect. The best combination of the sound insulation performance was stud size 40 × 140 mm, stud spacing 600 mm, with single-layer plasterboard on both sides and insulation material polyester.

Tab. 3: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	15.900	22.467	23.133	23.633
Mean value 2	28.117	23.867	24.767	23.400
Mean value 3	/	25.800	24.233	25.100
Range analysis	12.217	3.333	1.634	1.700

Tab. 4: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	298.494	1	143.429	18.500	*
Stud spacing	16.809	2	4.038	19.000	
Plasterboard layers	4.162	2	1.000	19.000	
Insulation materials	5.096	2	1.224	19.000	
Error	0.042	1			

When frequency is 125 Hz, orthogonal experimental results are shown in Tab. 5 and 6. We can see from Tabs. 5 and 6 that at the frequency of 125 Hz, effect of stud sizes on the sound insulation performance of the wall is significant, while slight effect is exerted by stud spacing, sound insulation materials and plasterboard layers. The best combination of the sound insulation performance was stud size 40 × 140 mm, stud spacing 450 mm, with double-layer plasterboard on both sides, and insulation material polyester.

Tab. 5: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	24.033	26.533	28.067	27.700
Mean value 2	29.550	28.400	26.700	26.800
Mean value 3	\	28.200	28.367	28.633
Range analysis	5.517	1.867	1.667	1.833

Tab. 6: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	60.867	1	24.144	18.500	*
Stud spacing	6.302	2	1.250	19.000	

When frequency is 160Hz, orthogonal experimental results are shown in Tab. 7 and 8.

It can be seen from Tab. 7 and 8 that at the frequency of 160 Hz, effect of stud sizes on the sound insulation performance of the wall is significant, while slight effect is exerted by stud spacing, sound insulation materials and plasterboard layers. The best combination of the sound insulation performance was witnessed when stud size was 40 × 140 mm, stud spacing 600 mm, single-layer plasterboard on both sides, and insulation material using mineral wool. Based on the range analysis table, it can be seen that although the sound insulation performance of mineral wool is the best at this point, polyester is very similar.

Tab. 7: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	15.233	19.833	21.300	21.367
Mean value 2	23.400	21.033	20.000	19.567
Mean value 3	\	21.167	20.733	21.100
Range analysis	8.167	1.334	1.300	1.800

Tab. 8: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	133.389	1	104.66	18.500	*
Stud spacing	3.236	2	1.270	19.000	
Plasterboard layers	2.549	2	1.000	19.000	
Insulation materials	5.662	2	2.221	19.000	
Error	2.55	2			

When frequency is 200 Hz, orthogonal experimental results are shown in Tabs. 9 and 10.

We can see from Tab. 9 and 10 that at the frequency of 200 Hz, it is at the first resonance frequency range, and sound transmission loss is minimum, which indicates it is ideal to enlarge air layer in certain thickness space in order to reduce the resonance frequency on wood-frame wall design, and lower the first resonance frequency than the commonly used audio frequency range, so as to improve the sound insulation performance of the wall. Effects of various factors on the airborne sound insulation of wall are not significant except sound insulation materials. The best combination of the sound insulation performance was witnessed when stud size was 40 × 140 mm, stud spacing 400 mm, single-layer plasterboard on both sides, applying polyester as insulation material.

Tab. 9: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	21.633	28.600	28.433	20.667
Mean value 2	27.550	25.133	26.733	26.933
Mean value 3	\	23.000	21.567	29.133
Range analysis	5.917	5.600	6.866	8.466

Tab. 10: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	70.014	1	2.922	18.500	
Stud spacing	47.929	2	1.000	19.000	
Plasterboard layers	76.736	2	1.601	19.000	
Insulation materials	115.796	2	2.416	19.000	
Error	47.93	2			

When frequency is 250 Hz, orthogonal experimental results are shown in Tabs. 11 and 12.

We can see from Tab. 11 and 12 that at the frequency of 250 Hz, the effects of various factors on the airborne sound insulation of wall are not significant, and among them, stud spacing, sound insulation materials and plasterboard layers are three factors which have a remarkable effect on sound insulation, while stud sizes have minimal impact. The best combination of the sound insulation performance was stud size 40 × 140 mm, stud spacing 400 mm, single-layer plasterboard on both sides, and with glass wool as insulation material.

Tab. 11: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	28.933	30.333	29.900	28.867
Mean value 2	29.200	28.867	29.433	29.900
Mean value 3	\	28.133	28.000	28.567
Range analysis	0.267	2.200	1.900	1.333

Tab. 12: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	0.142	1	1.000	161.000	
Stud spacing	7.529	2	26.511	200.000	
Plasterboard layers	5.882	2	20.711	200.000	
Insulation materials	2.936	2	10.338	200.000	
Error	0.140	1			

When frequency is 315 Hz, orthogonal experimental results are shown in Tabs. 13 and 14.

It can be seen from Tab. 13 and 14 that at the frequency of 315 Hz, stud sizes and sound insulation materials are the two factors which exert distinct influence on sound insulation performance, especially sound insulation materials, which are the most significant influencing factors. Plasterboard layers and stud spacing have minimal effect on sound insulation. The best combination of the sound insulation was stud size 40 × 140 mm, stud spacing 450 mm, single-layer plasterboard on both sides, and insulation material for mineral wool.

Tab. 13: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	28.100	29.700	30.467	33.667
Mean value 2	30.617	30.000	29.733	27.100
Mean value 3	\	29.633	29.133	28.567
Range analysis	2.517	0.367	1.334	6.567

Tab. 14: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	12.667	1	110.629	18.500	*
Stud spacing	0.229	2	1.000	19.000	
Plasterboard layers	2.676	2	11.686	19.000	
Insulation materials	71.282	2	311.275	19.000	*
Error	0.230	2			

When frequency is 400 Hz, orthogonal experimental results are shown in Tabs. 15 and 16.

It can be seen from Tab. 15 and 16 that at the frequency of 400 Hz, stud sizes and sound insulation materials have a significant influence on sound insulation performance, while plasterboard layers and stud spacing have less influence. The best combination of the sound insulation performance was stud size 40 × 140 mm, stud spacing 400 mm, single-layer plasterboard on both sides, and insulation material for mineral wool.

Tab. 15: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	27.933	31.667	31.200	33.267
Mean value 2	32.117	30.000	30.433	29.100
Mean value 3	\	30.500	30.533	29.800
Range analysis	4.184	1.667	0.767	4.167

Tab. 16: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	35.001	1	67.180	18.500	*
Stud spacing	4.389	2	4.212	19.000	
Plasterboard layers	1.042	2	1.000	19.000	
Insulation materials	29.869	2	28.665	19.000	*
Error	1.040	2			

When frequency is 500 Hz, orthogonal experimental results are shown in Tabs. 17 and 18.

It can be seen from Tab. 17 and 18 that at the frequency of 500 Hz, sound insulation materials exert a significant influence on sound insulation performance, stud spacing and plasterboard layers have less influence. The best combination of the sound insulation performance was stud size 40 × 140 mm, stud spacing 450 mm, single-layer plasterboard on both sides, and insulation material for mineral wool.

Tab. 17: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	29.900	30.533	31.633	34.267
Mean value 2	31.767	31.733	30.267	29.333
Mean value 3	\	31.167	31.533	29.833
Range analysis	1.867	1.200	1.366	4.934

Tab. 18: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	6.969	1	6.447	18.500	
Stud spacing	2.162	2	1.000	19.000	
Plasterboard layers	3.482	2	1.611	19.000	
Insulation materials	44.242	2	20.463	19.000	*
Error	2.160	2			

When frequency is 630 Hz, orthogonal experimental results are shown in Tabs. 19 and 20.

The range and variance analysis show when the frequency is 630 Hz, the effects of various factors on the wall sound insulating properties are not significant, among them, stud spacing and sound insulation materials have a relatively outstanding effect, while the influence of plasterboard layers is slight. When stud size was 40 × 140 mm, stud spacing 450 mm, single-layer plasterboard on both sides, and applying mineral wool as insulation material, it was the best combination against sound insulation.

Tab. 19: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	31.233	32.200	33.700	35.033
Mean value 2	34.067	35.100	33.633	32.700
Mean value 3	\	32.067	32.033	31.633
Range analysis	2.834	3.033	1.667	3.400

Tab. 20: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	16.056	1	6.011	18.500	
Stud spacing	17.629	2	3.300	19.000	
Plasterboard layers	5.342	2	1.000	19.000	
Insulation materials	18.142	2	3.396	19.000	
Error	5.340	2			

When frequency is 800 Hz, orthogonal experimental results are shown in Tabs. 21 and 22.

Range and variance analysis show when the frequency is 800 Hz, sound insulation materials, stud sizes and spacing have a notable influence on sound insulation performance, while the influence of plasterboard layers is the least. When stud size was 40 × 140 mm, stud spacing 450 mm, single-layer plasterboard on both sides, insulation material for mineral wool, it was the best combination on sound insulation.

Tab. 21: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	32.667	32.567	34.333	36.967
Mean value 2	34.583	35.900	33.667	32.700
Mean value 3	\	33.367	33.833	32.167
Range analysis	1.916	3.333	0.666	4.800

Tab. 22: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	7.347	1	20.352	18.500	*
Stud spacing	18.169	2	25.165	19.000	*
Plasterboard layers	0.722	2	1.000	19.000	
Insulation materials	41.529	2	57.519	19.000	*
Error	0.720	2			

When frequency is 1000 Hz, orthogonal experimental results are shown in Tabs. 23 and 24.

Range and variance analysis show when the frequency is 1000 Hz, the effects of various factors on the wall sound insulation performance are not significant, among them, sound insulation materials have a greater impact on sound insulation property while the influence of plasterboard layers is the least. The best combination of the sound insulation effect was stud size 40 × 140 mm, stud spacing 450 mm, single-layer plasterboard on one side and double-layer on the other side, and insulation material for mineral wool.

Tab. 23: The table of range analysis mean value.

Factors	Stud sizes	Stud spacing	Plasterboard layers	Insulation materials
Mean value 1	34.600	36.667	35.867	38.967
Mean value 2	36.750	36.833	36.800	35.267
Mean value 3	\	34.600	35.433	33.867
Range analysis	2.150	2.233	1.367	5.100

Tab. 24: The table of variance analysis.

Factors	sum of the squares	Degree of Freedom	F ratio	Critical F value	Significance
Stud sizes	9.245	1	6.317	18.500	
Stud spacing	9.287	2	3.173	19.000	
Plasterboard layers	2.927	2	1.000	19.000	
Insulation materials	41.660	2	14.233	19.000	
Error	2.930	2			

DISCUSSION

The airborne sound insulation of wall components with noise frequency between 1250 and 3150 Hz is similar with those between 160 and 400 Hz in the transmission loss-frequency curve, but the former is higher than that of 9~12 dB in sound transmission loss. Fig. 3 shows that noise frequency between 100 and 125 Hz is in the stiffness controlled region, which controls the size of the wall sound insulation starting from the low frequency, and the stiffness of wall is proportional to the transmission loss, in which the sound transmission loss of wall decreases with the increase of frequency.

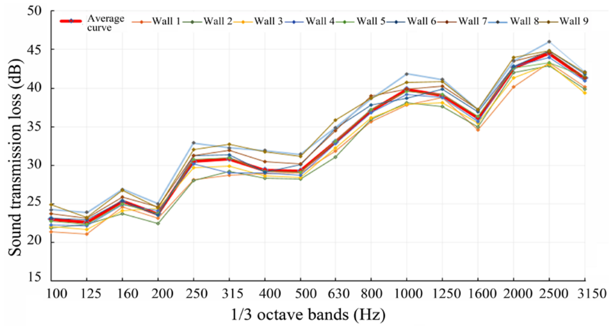

Fig. 3: The transmission loss versus frequency curve.

Damping (resonance) controlled region is located between 125 and 500 Hz, and when the noise in this frequency range, the natural frequency of components resonates with its incident sound at the same frequency, which resulted in the minimum sound transmission loss, the first resonance frequency F0 produces the greatest effect. Therefore, damping controlled region should be as narrow as possible when walls are designed. When noise frequency varies between 500 and 1000 Hz, each additional band increases 3~5 dB in sound transmission loss, which accords with the mass law in mass controlled region, where the mass plays the most important law in soundproofing. The mass law says that each time the mass per unit area of a single layer wall is doubled or the frequency of a sound is doubled, the transmission loss is increased by about 6 dB. In other words, low frequencies always penetrate even through a thick wall, whereas high frequencies can be blocked with a thin blanket. When noise frequencies are above 1000 Hz, noise frequency falls into coincidence controlled region. The wavelengths of bending waves match those created it at one frequency, the critical frequency, and effects of the mass and bending stiffness are offset, it gives a far more efficient transfer of sound energy from one side of the wall to the other, hence the coincidence dip at the critical frequency, which lead to little acoustic impedance of the wall. The trough will appear when the critical frequency is about 1600 Hz, the coincidence effect will be produced and the sound transmission loss of the wall will notably reduce.

Influence of stud sizes on sound insulation performance

From the measurement data it was found that the sound insulation performance of walls was substantially affected by stud sizes and acoustic resonances of the cavity. In the low and high frequency range, stud sizes had a significant effect on the sound insulation of the wall, while in the middle frequency range, no significant effect could be observed. In the whole frequency range, the larger stud size the higher sound insulation performance. The mass law said that if the cross-sectional area of studs was increased, the stiffness and transmission loss of the wall was increased too, which mainly occurred in 100-200Hz. In addition, the sound transmission loss would increase with the thickness of the cavity increased (Yang et al. 2017). Based on the measured data, it could be inferred that increasing the width of the cavity had a positive impact on the sound insulation (when the cavity increased 51 mm, insulation increased to about 5 dB), because the insulation deteriorating cavity resonance shifted to lower frequencies, which were less audible (Urbán et al. 2016). In the whole frequency range, stud size 38 × 140 mm was used, which showed to have a better sound insulation performance than 38 × 89 mm, it also verified the conclusion of Cremer et al. (1975).

Influence of stud spacing on sound insulation performance

The results depicted the variation of sound insulation performance with different stud spacing, the general trend was that larger stud spacing performed better at lower frequencies (100-160 Hz), the sound insulation property was the best when stud spacing was 600 mm, although the difference was not distinct. While at mid-high frequencies (500-1000 Hz), when stud spacing was 450 mm, the sound insulation was superior to the other two kinds of spacing. There was no significant effect in high frequency range. This result was consistent with the view of Zhou et al. (2006) that stud spacing 600 mm was a superior choice at lower frequencies because of sound bridges (studs) lowered the sound transmission loss of wall.

Influence of insulation materials on sound insulation performance

Sound insulation materials can be characterized in terms of their ability to lower sound transmission and absorb impinging sound waves. Sound absorption defines the part of the acoustic energy dissipated inside the materials because of friction or thermal loss or resonance phenomena. While porous insulation materials are usually good sound insulators. The airborne sound insulation is strongly dependent on the mass and fluffy structure of the materials, lightweight materials are commonly poor sound insulators (Schiavoni et al. 2016). Therefore, in the low frequency range, sound insulation of polyester with fluffy structure was better than mineral and glass wool. In the mid-high frequency range, mineral wool with the maximum density (50 $kg \cdot m^{-3}$) had a great effect on sound insulation obeying the mass law. The presence of insulation materials in the cavity of wall limited cavity resonances and consequently to increase the sound insulation of the wall.

Influence of sheathing on sound insulation performance

There was no significant influence of sheathing's layers on sound insulation performance of the wall, generally single-layer plasterboard on both sides could meet sound insulation requirements of the national standards. Double-layer plasterboard could be used on both sides of the wall if the sound insulation requirements were higher. The staggered arrangement of double-layer sheathings had a great effect on the sound insulation, which could cover the gaps of the inner sheathings and consequently to improve the sound insulation of the wall (Wang 1981). In addition, the door was the weakest part of building envelope in term of acoustic performances (Asdrubali et al. 2017) and 1.7 m^2 door would reduce the sound transmission loss of wall about 5 dB. But layers of sheathing had a comparatively great effect when applying polyester as sound insulation material.

The establishment of regression model

The above analysis revealed the relationship between the sound insulation performance of wall and the mass of sheathings, stud sizes, stud spacing, the characteristics of sound insulation materials. On the basis of Zhou's (2006) calculation model of wood frame partition wall without filling acoustic insulation material, and the mass law and principle of the correction term, empirical formulas for calculating can be obtained by weighted sound insulation R_w of wood-frame wall, which still need further examination in practice:

$$R_w = 10 \times (\lg m_1 + \lg m_2) + 60 \times C + 0.074 \times D + 44.26 \times T + 5 \times S + 12$$

Where m_1 and m_2 represent, respectively, the mass of plasterboard on one side and the other side of wall ($kg \cdot m^{-2}$), C is the depth of cavity (m), D is the density of insulating material ($kg \cdot m^{-3}$), T is the thickness of insulating layer (m), S is stud spacing (m).

CONCLUSIONS

Major conclusions can be drawn based on the above study and analysis as following:

1. In the low and high frequency range, stud sizes had a significant effect on the sound insulation performance of wood-frame wall, while in the middle frequency range, no significant effect could be observed. In the whole frequency range, the larger stud size the higher sound insulation performance.
2. In the low frequency range, stud spacing had a distinct effect on the sound insulation performance of the wall, while in the mid-high frequency range, when stud spacing was 450 mm, the sound insulation property was superior to the other two kinds of spacing. There was no significant effect in the high frequency range.
3. In the low frequency range, sound insulation of polyester with fluffy structure was better than mineral and glass wool. In the mid-high frequency range, mineral wool with the maximum density had a great effect on sound insulation obeying the mass law.
4. Influence of sheathing's layers on the sound insulation performance of the wall was not remarkable, generally single-layer plasterboard on both sides could meet acoustic requirements of the national standards. But layers of sheathing had a significant effect when applying polyester as sound insulation material.
5. In the daily life with noise frequency range (200-2000 Hz), it is recommended to design wall structure in this way: stud spacing is 450 mm, stud size is 40 × 140 mm, sound insulation material for mineral wool, sheathing's layers for single-layer plasterboard on both sides, which can achieve the requirements of residential sound insulation standards.
6. A regression model was established to evaluate the sound insulation performance of wall.

ACKNOWLEDGMENTS

The authors wish to acknowledge the National Nature Science Foundation of China (Grant No. 031020138) and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

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