Optimization of multiple dynamic vibration absorbers for reduction of low frequency vibration of joist floor structures

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Abstract

A dynamic vibration absorber (DVA) can be used to reduce the vibration of a joist floor structure. This is achieved by tuning the natural frequency of the DVA to match the frequency of the host structure, as a large amount of structural vibration energy can be transferred to the DVA and is then dissipated by the DVA's damping. The parameters mass, damping, stiffness, and location, need to be tuned for an optimal vibration control. In this paper, an optimization procedure for the design parameters of multiple dynamic vibration absorbers (DVAs) is proposed to reduce the low-frequency vibration of joist floor structures. First, the vibration of the joist floor structure is calculated by an analytical model combining the motion of a plate and beams. The absorbers are then modeled as SDOF mass-spring-damper systems attached to the floor structure. The optimal DVA solution is analyzed and compared with traditional improvement measures. The result shows that, with the same increase in the floor weight, the DVAs can be more effective than conventional improvement methods in reducing floor vibration in the target low-frequency bands.

Keywords: joist floor, vibration absorbers, low frequency, optimization, vibration reduction.

1 Introduction

A dynamic vibration absorber (DVA), consisting of a mass, damper and spring, can effectively provide vibration control on a vibrating system by suppressing undesirable vibration. When the natural frequency of a DVA is tuned in resonance with the dominant mode of the host structure, a large amount of the structural vibration energy is transferred to the DVA and then dissipated by the damping in the DVA [1].

The basic concept of a DVA is simple, but the design of a DVA often needs to be optimized using a certain criteria to maximize its performance. The fixed-point theory was the first theory to be used for optimizing the damping and tuning frequency of a DVA on an undamped single degree of freedom system [2]. The optimization process is aimed at minimising the amplitude of the system resonance. This optimization method is known as the H_∞ optimization, and was more recently applied for the DVA attached to a multi-degree-of-freedom damped linear system [3~6]. Another criterion, the H_2 method, was proposed for DVA optimization by minimizing the total vibration energy of the host system [7]. The transfer function of the host system was used to predict the effect of a single DVA on vibration suppression when subjected to random excitation and thus to optimize the parameters of the DVA [8, 9]. Recent studies on the DVA optimizations based on the two methods can be found in [10, 11].

The performance of a single DVA is sensitive to the vibration characteristics of the host structures. A deviation in the parameters can result in the drop in its vibration reduction performance. Also, some researchers have pointed out that the multiple distributed DVAs are more effective than the single DVA in achieving the robust, broadband and large scale vibration reduction on continuous structures, such as plates and beams [5, 12]. However, there are very few easy-to-use optimization theories for the multiple DVAs. Considering the complexity of the vibration systems consisting of continuous structures carrying multiple DVAs, researchers usually solve this optimization problem by utilizing optimization algorithms such as the linear quadratic regulator-based optimization method [13] and the genetic algorithm [14].

In this paper, the objective is to investigate the performance of multiple DVAs to reduce the vibration of a wooden joist floor in a low frequency range. The parameters of the DVAs, including their natural frequency, damping and position, are optimized by using the genetic algorithm. The performance of the DVAs is evaluated by an analytical model of a joist floor combined with multiple SDOF spring mass dampers, which calculates the reduction of the floor vibration energy induced by point excitations at random positions. The effectiveness of the multiple DVAs on suppressing the floor vibration is discussed by comparing the results with those of some conventional measures.

The paper is organized as follows: Section 2 presents the methodology of the optimization procedure. Section 3 introduces a case study and the results. Discussions are given in section 4, and conclusions are drawn in section 5.

2 Optimization methodology

The performance of a DVA is affected by its parameters as well as the parameters of the host floor. In order to apply the DVAs more efficiently, optimizations for obtaining their positions, vibration frequencies, and damping values are needed.

In this study, the performance of the DVAs were optimized for frequencies below f_t. f_t is the given upper limit of the interest frequency range. A lightweight joist floor usually has multiple modes in the low frequency range of human hearing. The optimization procedure needs to address these floor modes and searches for the suitable parameters of the DVAs to suppress the dominant modes.

2.1 Optimization strategy

Based on studies in distributed DVAs on a rectangular plate in [5] and the application of the genetic algorithm on the DVAs' optimization in [14], the strategies for the DVAs' optimization in this research have been developed as follows:

1. The DVAs are divided into *p* groups so that each group can target a particular mode of the host floor. Each group consists of four SDOF mass-spring-damper type of absorbers having the same parameters. Considering that the low-frequency mode shapes of a rectangular floor tend to be (anti-)symmetric, the four absorbers are installed symmetrically on the host floor.

2. Considering that the DVAs should not largely change the weight of the host floor, the total mass of the DVAs was specified to be no more than 10% of the mass of the host floor. The masses of all absorbers are equal and the mass of each needs to be specified according to the number of the groups. For example, if the floor mass is 200kg, the maximum allowable mass is 20kg. If p=5, that means each group will weigh 4 kg. Since each group contains 4 DVAs, each DVA will then weigh at maximum 1kg.

3. To optimize the DVAs' parameters, the vibration energy of the floor reduced by the DVAs is evaluated by an objective function. The parameters of the DVAs are constrained in the chosen value ranges and the genetic algorithm is applied to search for the best suited values for the parameters.

In the genetic algorithm, a population of candidate solutions (individuals) to the optimization problem is evolved toward better solutions [15]. Each candidate solution has a set of properties which can be mutated. The evolution starts from a population of randomly generated individuals, and is an iterative process, with the population in each iteration called a generation. In each generation, the fitness of every individual in the population is evaluated; the fitness is usually the value of the objective function in the optimization problem being solved. The more fit individuals are stochastically selected to be the 'parents' of the next generation, and the properties of the new generation are based on those of the parents and modified (recombined and possibly randomly mutated) according to the crossover and mutation operators. Then, the new generation of candidate solutions is then used in the next iteration of the algorithm. Lastly, the algorithm terminates when the relative change (local gradient) of the objective function has become less than the given 'Function tolerance'.

The flowchart of the optimization strategy for the DVAs is shown in Figure 1. The optimization process is the implemented with the GA function in the global optimization toolbox of the software Matlab. The main properties of genetic algorithm are listed in Table 1.

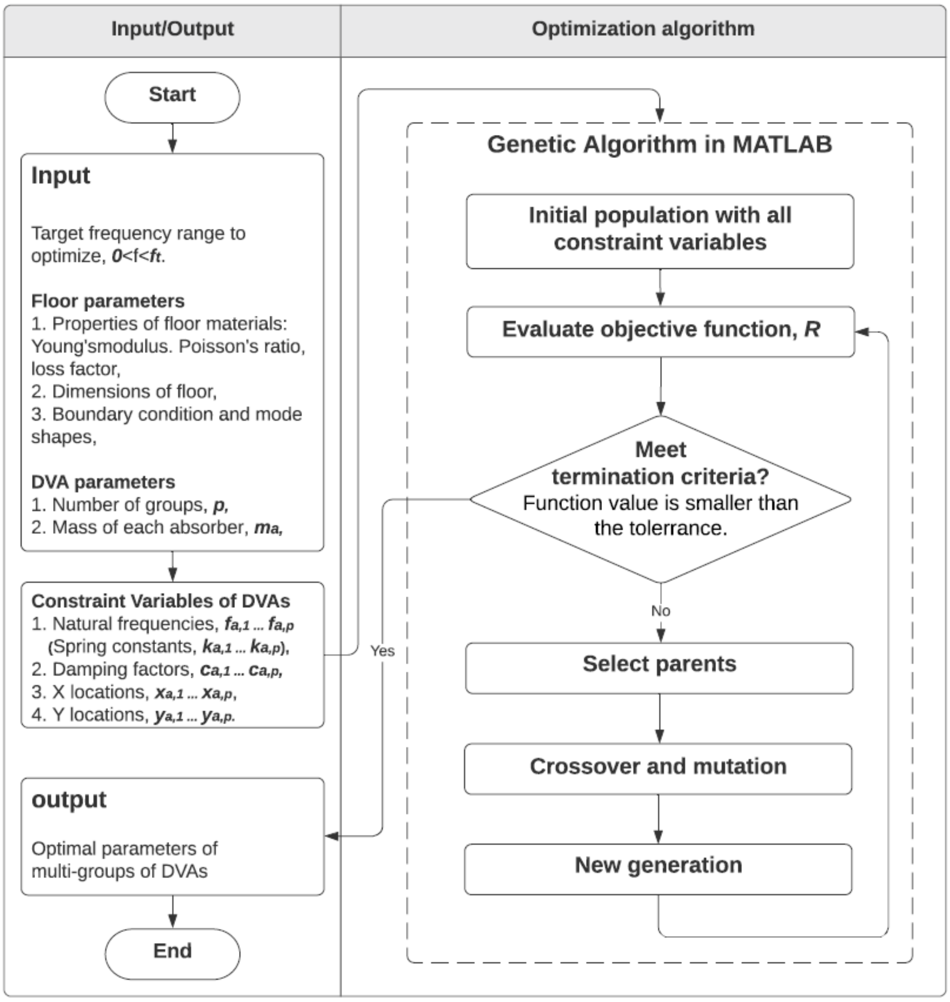


Figure 1 – Flowchart of the optimization strategy.

Table 1 – Property values applied in genetic algorithm.

Properties	Values
Population size	200
Maximum generations	100
Crossover fraction	0.8
Constraint tolerance	0.1
Function tolerance	0.1

2.2 Objective function

The calculation of the objective function is based on the analytical model of the joist floor [19, 20]. The model computes the transfer function of the joist floor by applying the modal superposition method. The DVAs are modelled as SDOF spring-mass systems and their displacements are coupled with that of the floor at the attaching positions. The equations of the coupled motions between the floor and the DVAs are expressed as

$$\sum_{n=1}^{N}\sum_{m=1}^{M}\left(K_{floor}-M_{floor}\omega^2\right)u_{mn}+\sum_{r=1}^{R}k_{a,r}\left(1+j\eta_{a,r}\right)\left(w_{a,r}-w_{floor,r}\right)=F, \tag{1}$$

$$m_{a,r}\omega^2 w_{a,r}+k_{a,r}\left(1+j\eta_{a,r}\right)\left(w_{floor,r}-w_{a,r}\right)=0, \qquad r=1,2\ldots R, \tag{2}$$

in which K_{floor} and M_{floor} are the modal stiffness and modal mass of the host structure, $k_{a,r}$, $m_{a,r}$ and $w_{a,r}$ are the spring constant, mass and displacement of the rth vibration absorber. $\eta_{a,r}$ is the loss factor of the rth vibration absorber given by

$$\eta_{a,r}=c_{a,r}\sqrt{k_{a,r}/m_{a,r}} \tag{3}$$

u_{mn} is the modal coefficient of the floor displacement and $w_{floor,r}$ *is* the displacement of joist structure at the DVA's attaching position ($x_{a,r}$, $y_{a,r}$). The displacement of joist floor at any position can be calculated by

$$w_{floor}(x,y)=\sum_{n=1}^{N}\sum_{m=1}^{M}u_{mn}\phi_m(x)\psi_n(y) \tag{4}$$

in which ϕ_m and ψ_m are the mode shape functions of the floor mode (m,n) along x and y directions. For the joist floor simply-supported at four boundaries, the mode shape functions are given by

$$\phi_m(x)=\sqrt{\frac{2}{l_x}}\sin\left(\frac{m\pi x}{l_x}\right),\ \ \psi_n(y)=\sqrt{\frac{2}{l_y}}\sin\left(\frac{n\pi y}{l_y}\right) \tag{5}$$

where l_x and l_y are the lengths of the floor in x and y directions. For more detailed formulations, please see [16]. The objective function, the index of the vibration energy reduction in the floor, can be calculated by [17]

$$R=10log_{10}\left(\frac{E_0}{E_1}\right) \tag{6}$$

where E_1 and E_0 are the averaged kinetic energy of the floor with and without DVAs in the given frequency range. For a frequency range from 0 to f_t, the values of the averaged kinetic energy are calculated as

$$E=\int_0^{f_t}\frac{1}{2}M\langle v^2\rangle df \tag{7}$$

where M is the mass of the floor. The averaged quadratic velocity of the floor, $\langle v^2\rangle$, over S receiving positions is computed by

$$\langle v^2 \rangle = \frac{(2\pi f)^2}{S} \int_{s=1}^{S} w(x_s, y_s)\, w^*(x_s, y_s) ds \tag{8}$$

where the asterisk denotes complex conjugate.

To exhibit the optimization results, the 1/3-octave-band velocity levels and the vibration level reductions of the floor are frequently used. $L_{v,floor+DVA}$ and $L_{v,floor}$ denote the 1/3-octave-band velocity levels of the floor with and without the DVAs calculated with a reference velocity value of 10^{-6}m/s. The vibration level reductions ΔL_v is calculated by

$$\Delta L_v = L_{v,floor} - L_{v,floor+DVA}. \tag{9}$$

2.3 Constrained variables

The DVAs are divided into p groups. Then, there are p sets of variables to be optimized. For each group, the constrained variables include:

1. Natural frequency of the absorber, f_a.

As the interested frequency range for the vibration reduction is below f_t, the natural frequencies of the DVAs are constrained between 0 and f_t. The mass of each absorber, m_a, is predetermined according to the mass of the host floor and the number of the DVA groups. Thus, by assuming the host structure to act as a rigid material with respect to the vibration absorber, the spring constant, k_a, of absorber can be calculated by

$$k_a = m_a (2\pi f_a)^2 \tag{10}$$

2. Damping factor of the absorber, c_a.

In order to provide a mechanism for energy dissipation and to enlarge the effective bandwidth of the absorber, damping can be introduced into the DVA. Figure 2 shows the vibration of a SDOF host system reduced by an absorber having different loss factors. The absorber with lower damping transfers the energy of the floor's vibrations at the natural frequency to the nearby frequencies, while the one with higher damping can suppress the energy of the mode in a broader frequency range. In this study, the damping value of each DVA c_a is constrained between 10^{-3} and 10^3 Ns/m.

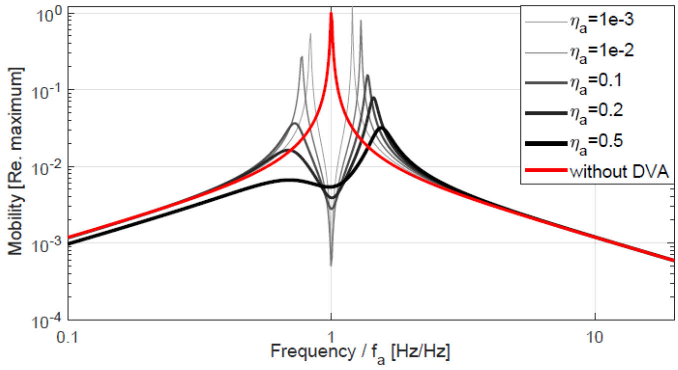


Figure 2 – Flowchart of the optimization strategy.

3. Attachment locations of the absorbers.

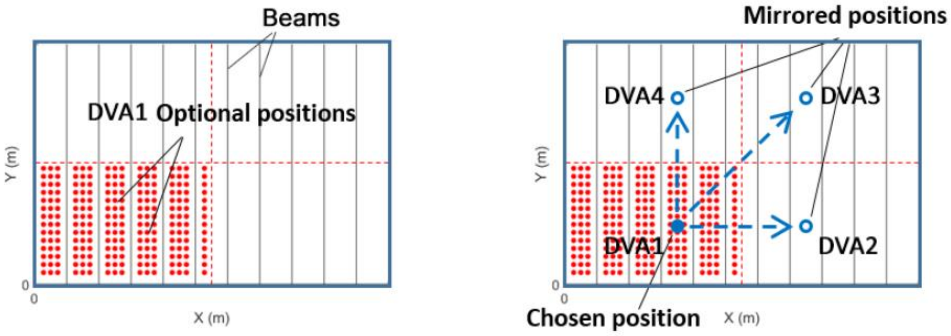
The principles for the locations of the DVAs are specified as follows:

- As low-frequency mode shapes of the rectangular floor are (anti-)symmetric, the 4 DVAs of each group are distributed symmetrically on the floor.

- The DVAs are avoided to be located on the beams and close to the floor edges. Their positions are at least 0.15m away from the beams and floor edge, and at least 0.1m from each other.

- To simplify the selection of the DVAs' positions, possible locations of a DVA on the 1/4 floor area are predetermined according to the above principles, as shown in Figure 3a. The position of one absorber in each group is selected from the optional positions, then mirrored against the central axes for the positions of the other 3 absorbers in the same group (Figure 3b).

- Any two absorbers cannot be installed on the floor at the same position.



(a) Optional positions (red dots) for one absorber in the 1/4 floor area

(b) Determination of the other absorbers for a DVA group

Figure 3 – Positioning of the DVAs in each group

3 Case study

3.1 Optimization configuration

In this case study, a 3.35 x 3.35m wooden joist floor is used as the host floor. The floor consists of a wooden top layer ribbed by seven joists with an equal distance of 413 mm in the *x*-direction. The material properties of the floor components are given in Table 2.

Table 2 – Material properties of the floor components.

	Plate	beams
Material	Plywood	Spruce
Average density (kg/m^3)	522	452
Modulus of elasticity (GPa)	6.0	6.1
Poisson's ratio	0.4	0.4
Loss factor	$0.02 + 0.0003\,f$	$0.013 + 0.0003\,f$

f is the frequency for calculation.

In the optimization, the objective function was calculated for 16 excitation positions and 17 x 9 receiver positions, as shown in Figure 4. Some dominant modes of the floor can be observed in Figure 5 and 6. To analyse the effect of the target frequency range on the optimization results, f_t was set to be 50 and 100Hz, respectively.

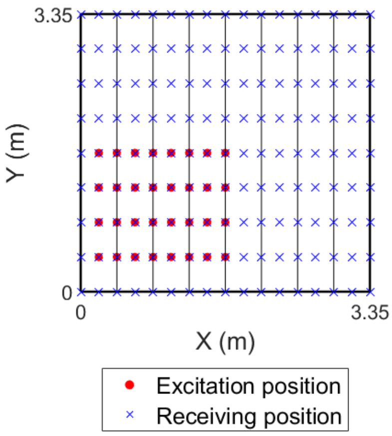


Figure 4 – Excitation and receiver positions on the joist floor.

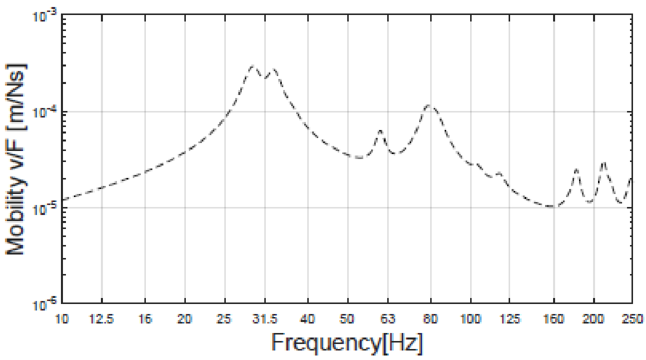
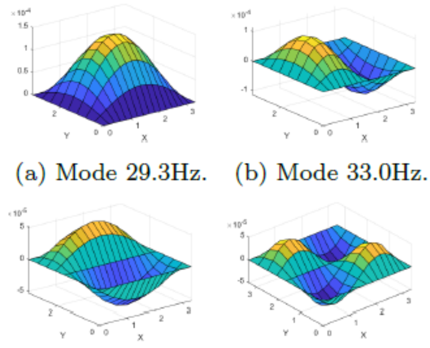


Figure 5 – Averaged mobility of the host joist floor.



(a) Mode 29.3Hz. (b) Mode 33.0Hz.

(c) Mode 78.7Hz. (d) Mode 82.1Hz.

Figure 6 – Mode shapes of some dominant modes of the host joist floor.

The floor has a mass of 196kg, thus, the total mass of the DVAs should not be over 19.6kg. In the optimization, the DVAs were applied in 1, 2 and 4 groups to compare between their performances. Correspondingly, the masses of each absorber were predetermined as 4, 2 and 1 kg, respectively.

3.2 Result

Figure 7 shows the velocity levels of floor with different DVA solutions targeting 0~50Hz. All DVA solutions achieved a 10dB velocity reduction in the 31.5Hz 1/3-octave-band. As the floor modes are close to each other, even the 1-group DVAs solution can suppress all floor modes in the target frequency range. Also shown in the figure are the locations of the DVAs of different solutions. No matter how many groups the DVAs are divided into, the absorbers are basically distributed along the centre line of the floor in y-direction. Table 3 shows the optimized DVA parameters of different solutions. The natural frequencies of the DVAs mainly correspond to the dominant modes below 50Hz.

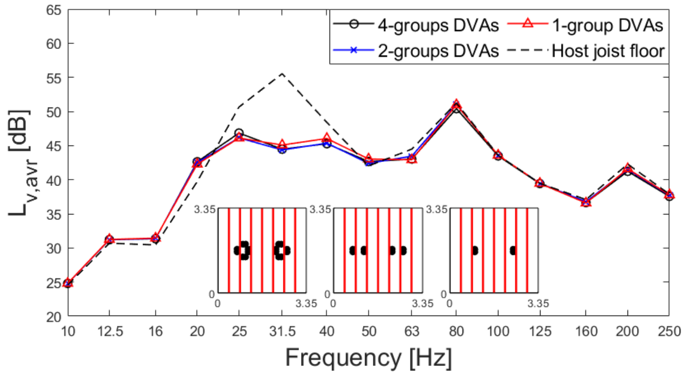


Figure 7 – Floor vibration level with and without the DVAs targeting 0-50Hz.

Table 3 – Optimal parameters of the DVAs targeting 0-50Hz.

Group	Natural frequency, f_a, Hz	Damping, c_a N·s/m	Mass, m_a kg	DVA1 location m	Objective function, R, dB
4–groups DVAs					
1	28.3	55.3	1	(1.15,1.63)	6.1
2	28.5	83.1	1	(0.73,1.63)	
3	34.7	120.3	1	(0.95,1.43)	
4	43.7	306.8	1	(1.05,1.43)	
2–groups DVAs					
1	28.2	157.4	2	(1.15,1.63)	6.2
2	31.1	242.3	2	(0.73,1.63)	
1–group DVAs					
1	29.3	517.7	4	(0.95,1.63)	5.8

Figure 8 shows the velocity levels of floor with different DVA solutions targeting 0~100Hz. Due to the large frequency gap between the floor modes, 1-group DVAs solution cannot reduce the floor vibration over the full frequency range, but only shows a good performance (10dB) in the 31.5 Hz band. The 2-groups DVAs solution is also less effective on reducing the vibration of the 80Hz band (around 2dB), as the second natural frequency of the absorbers is 41 Hz, which is far from the 80Hz band. In contrast, the 4-groups DVAs solution gives good results covering the two bands, 10dB for 31.5Hz band and 5dB for 80Hz band. Comparing to the DVA solutions targeting 0~50Hz, the DVAs for the vibration control over a broader bandwidth has moved along the y-direction towards the floor edges. Their positions are seemingly corresponding to the 78.7Hz mode of the host floor.

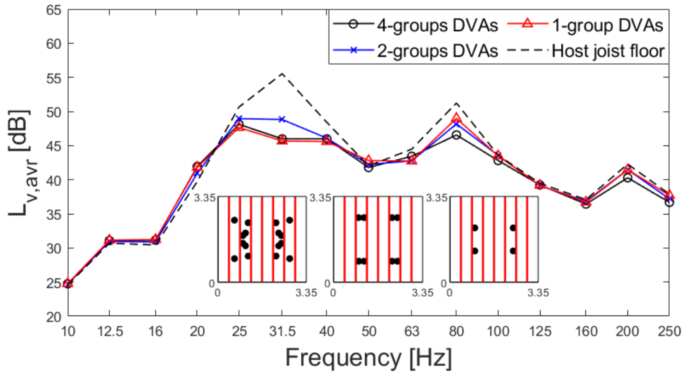


Figure 8 – Floor vibration level with and without the DVAs targeting 0-100Hz.

Table 4 – Optimal parameters of the DVAs targeting 0-100Hz.

Group	Natural frequency, f_a, Hz	Damping, c_a N·s/m	Mass, m_a kg	DVA1 location m	Objective function, R, dB
4–groups DVAs					
1	28.4	60.4	1	(1.05,1.43)	4.6
2	33.4	87.3	1	(0.95,1.53)	
3	46.2	345.9	1	(1.15,1.03)	
4	84.3	226.5	1	(0.63,0.93)	
2–groups DVAs					
1	28.8	199.6	2	(1.15,0.83)	3.6
2	41.0	499.8	2	(0.95,0.83)	
1–group DVAs					
1	30.3	591.7	4	(0.95,1.63)	4.2

4 Discussion

4.1 The effectiveness of DVA solution compared to other measures

To reduce the floor vibration level and impact sound, it is common to increase the floor mass or add a floating floor system. Usually, a large weight needs to be added on the floor to achieve a good result, and, the reduction of the vibration and the impact sound are more noticeable at high frequencies. Compared with these commonly used methods, the DVA approach can be more effective in reducing floor vibrations at low frequencies.

As shown in Figure 9, when the measures increase the floor mass by around 10%, the DVA approach targeting 0-100Hz can provide a higher reduction in the floor vibration (10dB at 31.5Hz and 5dB at 80Hz) compared to the 1dB reductions by the measure of increasing the floor mass. For a lightweight floating floor system, its ability to reduce the low-frequency vibration of the floor is also limited by the mass. In the figure, the floating floor used for the comparison consists of a 4mm plywood plate and 1cm mineral wood layer. The mass of the floating floor is around 10% of the bass floor's mass, and the cut-off frequency is 210Hz due to its light weight. Comparing to the DVA approach, the measure of the floating floor system can only provide a less than 3dB reduction in the low-frequency floor vibration.

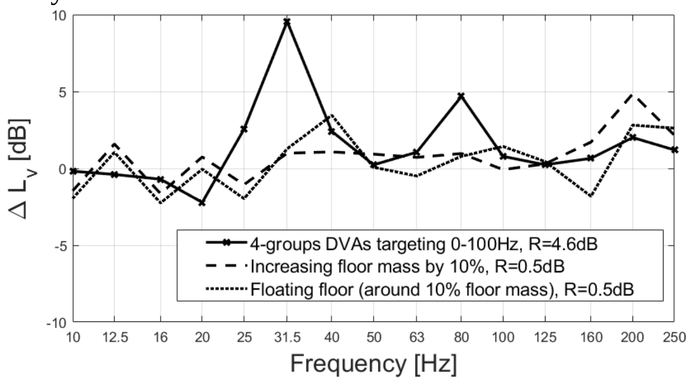
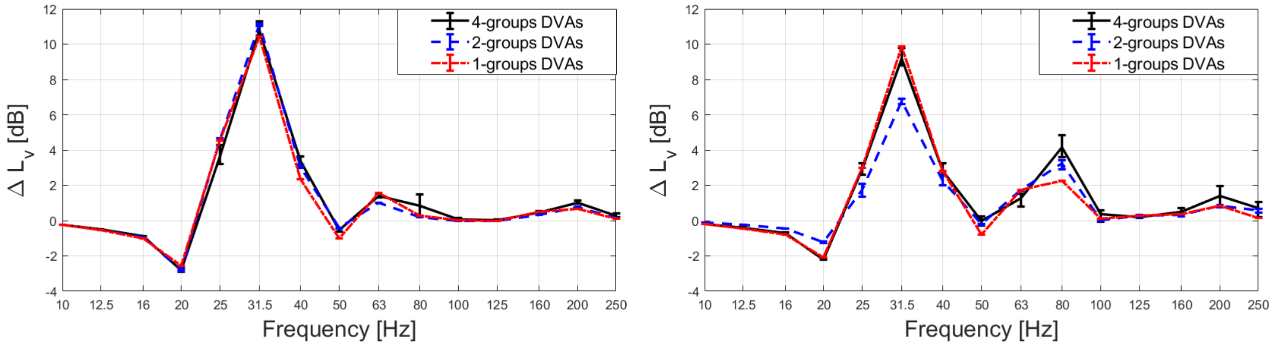


Figure 9 – Comparison of the performances of different measures on reducing the floor vibration. The result for the floating floor is calculated according to [18].

4.2 The non-uniqueness of the optimal DVA solutions

Due to the randomly generated candidate solutions and the tolerance used to stop the optimization in the genetic algorithm, the optimization processes do not lead to a unique optimal solution, but to several solutions with similar results. In this study, the optimization for the DVA solutions with different number of groups was run three times for each DVA scheme, and the deviation were compared between the solutions for different runs.



(a) ΔL_v of the DVAs targeting 0-50Hz (b) ΔL_v of the DVAs targeting 0-50Hz

Figure 10 – Optimization results vs. Runs. Lines show the mean value and the error bars show the extreme values of the three results.

In Figure 10, the 1–group DVAs solution shows a best repeatability. The results of both the vibration level reduction and the optimal DVA parameters are very close for the different runs. In contrast, the 4–groups DVAs solutions had a worst repeatability. No matter for the target frequency of 0~50Hz or 0~100Hz, three runs of the optimization lead to different results of the DVA parameters. This is because the optimization with 4-groups DVAs has four times as many variables as the optimisation with 1-group DVAs. The increase in the number of variables results in an increase in the combination of variables and, thus, a decrease in the likelihood of obtaining a unique solution to the optimisation.

However, the difference in vibration reduction value between solutions is usually only less than 1 dB and the different DVA solutions can offer a wide range of options for the implementation of floor vibration control, such as more suitable DVA locations.

4.3 The impact of the furniture loads on DVAs' performance

Lightweight floors are subjected to furniture loads when they are in use. This can result in the changes in the dynamic mechanical properties of the floor and thus, the low-frequency floor modes [19]. Therefore, with the presence of furniture loads, the DVAs will show different performances on the floor.

In this discussion, a 100kg furniture was modelled by 11×11 point masses covering an area of 1×1m on the floor (Figure 11). In Figure 12, the performances of the DVAs (4-groups targeting 0~100Hz) with and without furniture loading are compared.

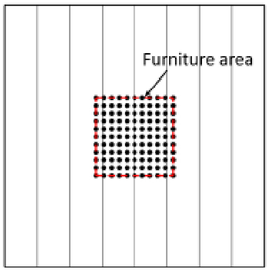
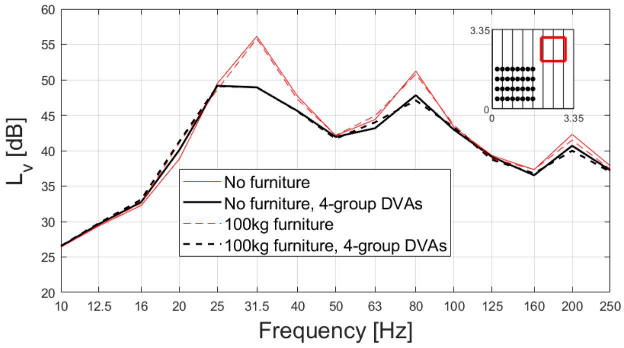
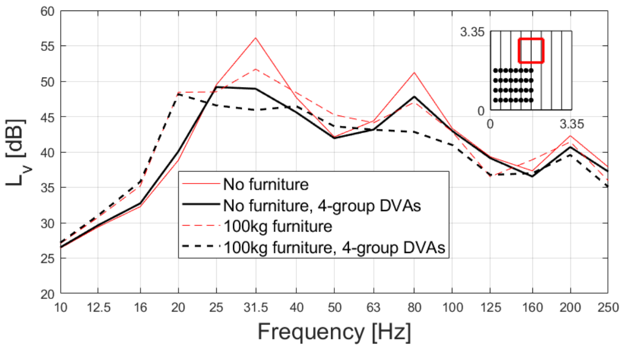


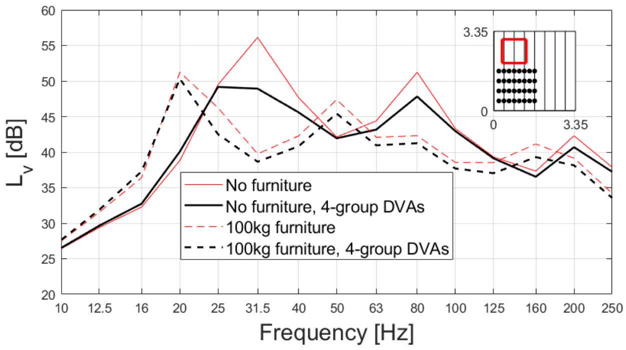
Figure 11 – A 100kg furniture is modelled as 11 x 11 point masses (black dots).



(a) Case 1, Furniture on far beams.



(b) Case 2, Furniture in the middle of the floor.



(c) Case 3, Furniture on near beams.

Figure 12 – Effect of the furniture loading on the performance of the DVAs. The small maps in (a), (b) and (c) show the impact positions (black dots) and furniture positions (red squares).

In Case 1, the furniture is located at the corner far from the excitation positions, the floor vibration and the performance of the DVAs are barely affected by the presence of the furniture. When the furniture is moving closer to the impacts, its effect on the performance of the DVAs becomes larger. In Case 3, the furniture and the impacts are located on the same beams, the DVAs can still give a reduction in the floor vibrations to a certain extent, but this reduction has been largely reduced by the furniture loading.

This lower impact of the DVAs is because the excitation cannot excite much modes below 100 Hz as their positions are in a region that is stiffened due to the added mass. But, with the presence of furniture, the vibration level of the floor is already lower than that without the furniture. Based on the full analysis of the vibration reduction for all excitation positions, DVAs still contribute to vibration reduction at low frequencies when furniture are present on the floor.

5 Conclusions

In this study, multiple DVAs are applied to reduce the vibration of lightweight floors, and an optimization process is designed to obtain the parameters of the DVAs, including the natural frequencies, damping values and locations. In a case study on a wooden joist floor, the optimal DVAs solutions can effectively reduce the vibration in the dominant frequency bands, the reduction levels are around 10dB in 31.5Hz band and 5dB in 80Hz band. When the DVAs are divided into more groups and more natural frequencies are assigned to the DVAs in the optimization, the optimal solution can have an effect over a wider frequency, but there may be multiple solutions to the optimization. Compared to other measures, such as increasing floor thickness and adding a floating floor system, the DVA approach is more effective in reducing the floor vibration at low frequencies with a small amount of mass. The performance of the DVAs can be influenced by the position of excitation positions and furniture loadings. When the furniture loads and impacts locate on the same beams, the effect of the DVAs on the floor vibration will be largely reduced.

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