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Method to simultaneously determine the optimal placement and performance of TMDs to minimize the seismic response of spatial structure buildings and study on reducing the analysis load

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Abstract

In this study, we propose an optimal design method for TMDs (Tuned Mass Damper, which is a vibration damping system composed of weights, springs, and dampers) that simultaneously determine the optimal number, arrangement, and performance of TMDs that minimize the seismic response of spatial structure buildings and examine the versatility of this method. The analysis model is a lattice dome, a cylindrical lattice shell, and an HP lattice shell. The members of each model are circular steel pipes. The optimal design algorithm of TMD is as follows. (1) Start the optimal design method from a model without TMD. (2) The modes are determined by eigenvalue analysis, and one TMD is installed at the maximum antinode of each mode, and this is used as a candidate solution for TMD installation. (3) Among the candidate solutions for TMD installation, the candidate solution with the highest effect on reducing seismic response is the TMD installation solution. The results are shown below. Compared with the randomly distributed arrangement of the same amount of TMDs, the maximum vertical displacement response is smaller in the optimal arrangement, confirming the validity of this method. When placing TMDs together considering the symmetry of the model, a higher response reduction effect is obtained than when placing TMDs one by one, but depending on the model shape, the sufficient effect could not be confirmed, so it is necessary to select the TMD placement method according to the model shape. Since the response values and TMD arrangement are different from the roof only model, it is necessary to analyze with the model designed including the substructure in the actual design. In order to shorten the analysis time, the candidate solution is determined by the response spectrum method, and the results are compared with the aforementioned method.

Keywords: spatial structure, seismic response, optimal design method, TMD, vibration control

1. Introduction

Spatial structure buildings are widely used in domes, school gymnasiums, etc., and are used as evacuation centers in times of disaster, but there are some reports of damage that ceiling materials and suspension equipment fall from the roof during an earthquake. As one of the mechanisms for reducing the response of the roof, there are some studies of vibration control using the Tuned Mass Damper (TMD), which is a vibration damping system composed of weights, springs and dampers. Since the TMD can be installed at a single fulcrum, it has a high degree of freedom of installation and is a vibration damping device suitable for spatial structure buildings. Various studies [1][2] have been conducted on the application of TMD to spatial-structured buildings. In previous studies, the number of TMDs was specified and the placement of the TMDs was determined based on a certain vibration mode. However, because the dominant mode becomes complicated depending on the shape of the spatial structure, it is difficult to obtain the optimal number, arrangement, and performance of the TMDs to be installed at the same time.

Therefore, in this study, we propose an optimal design method for TMDs that simultaneously determine the optimal number, arrangement, and performance of TMDs that minimize the seismic response of spatial structure buildings and examine the versatility of spatial structure buildings of various shapes.

2. Analysis model and analysis conditions

Figure 1-3 shows the shape of the analysis models, and Table 1-3 shows the specifications of each model. The analysis model is a lattice dome [3], a cylindrical lattice shell [1], and an HP lattice shell [4], which are the basic shapes of the spatial structure. Each model member shall be a circular steel pipe, the members shall be rigidly jointed, and the fulcrum shall be a fixed fulcrum. The fixed load is 1.18 kN/m² for the roof structure, and a mass equivalent to the fixed load is given as a concentrated mass at each node. The response analysis is a time history response analysis, the time increment is 0.02 seconds, and the seismic wave is input from the X direction of the Taft 1952EW wave. The analysis is performed by MATLAB programming.

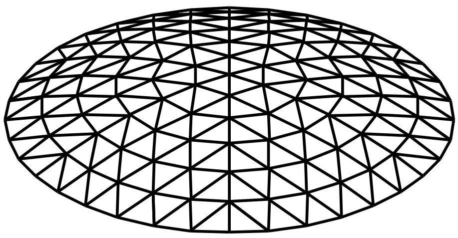


Figure 1: Lattice Dome

Table 1: Lattice Dome Specifications

Member slenderness ratio λ	100–136
Member outer diameter D (mm)	139.8
Member thickness t (mm)	3.5
Member cross-sectionl area A (cm^2)	15
Moment of inertia of area I (cm^4)	348
x-direction span L_x (m)	28
y-direction span L_y (m)	28
Rise of the roof H (m)	6.5
Total mass M_0 (kg)	341×10^3

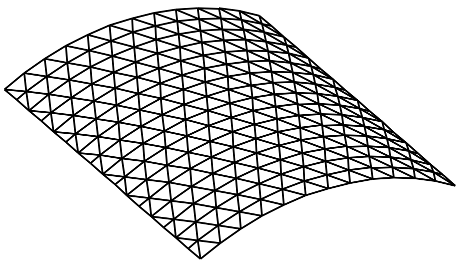


Figure 2: Cylindrical Lattice Shell

Table 2: Cylindrical Lattice Shell Specifications

Member slenderness ratio λ	21–46
Member outer diameter D (mm)	216.3
Member thickness t (mm)	9.5
Member cross-sectionl area A (cm^2)	61.7
Moment of inertia of area I (cm^4)	3306
x-direction span L_x (m)	36
y-direction span L_y (m)	48
Rise of the roof H (m)	4.8
Total mass M_0 (kg)	208×10^3

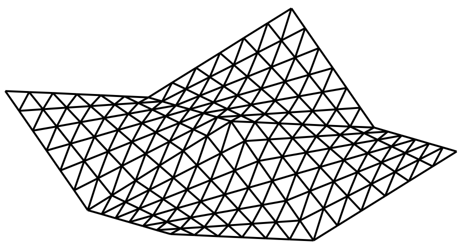


Figure 3: HP Lattice Shell

Table 3: HP Lattice Shell Specifications

Member slenderness ratio λ	41–52
Member outer diameter D (mm)	35.6, 42.3
Member thickness t (mm)	9.5, 11.3
Member cross-sectionl area A (cm^2)	103, 146
Moment of inertia of area I (cm^4)	15532, 30989
x-direction span L_x (m)	60
y-direction span L_y (m)	60
Rise of the roof H (m)	10
Total mass M_0 (kg)	432×10^3

3. TMD Optimal Design Methodology

In previous studies, the number of TMDs was determined in advance and the response reduction effect was examined. In this study, in order to investigate the effect of reducing seismic response due to changes in the amount of TMDs installed, we propose a method to track seismic response reduction while continuously installing TMDs with optimal placement and performance. In addition, since the vertical response is likely to occur in the spatial structure due to the structural characteristics, this study deals with the vertical response.

3.1. TMD Optimal Design Algorithm

The optimal design algorithm of TMD is as follows.
Step 1: Start candidate solution search without TMD.
Step 2: Determine the eigenmodes in eigenvalue analysis, the maximum antinode of each mode is the candidate solution for TMD installation.
Step 3: Determine the optimal performance (stiffness and damping) of TMD. The performance of the installed TMD is determined by the optimal condition formulas [5].
Optimal condition formulas [5]

$\dfrac{1}{1+\mu}$: Optimal synchronization ratio (stiffness)

$\dfrac{\sqrt{3}\mu}{8(1+\mu)}$: Optimal damping ratio (damping)

μ : Mass ratio of entire structure and one TMD

Step 4: One TMD is installed in the candidate solution and evaluate the response with time history response analysis. Repeat Step 3 and Step 4 for the number of the candidate solutions.
Step 5: Among the candidate solutions, the node with the smallest maximum vertical response is the installation solution.
Step 6: Install one TMD in the installation solution.
Repeat Step 1 to 6 for the number of steps of analysis.

3.2. Determination of TMD addition mass

A feature of this method is that it is possible to obtain the optimal arrangement for each different total TMD level. In this section, we examine the effect of the difference in TMD increment (added mass) per step of optimization on optimization.

Figure 4 shows the result when the TMD addition mass of 1 step is changed for a certain model and the response displacement is controlled. From Figure 4, even if the addition mass of TMD at 1 step is changed, the maximum response displacement transition is almost the same. Therefore, the mass at 1 step is set to $1{\times}10^3$kg.

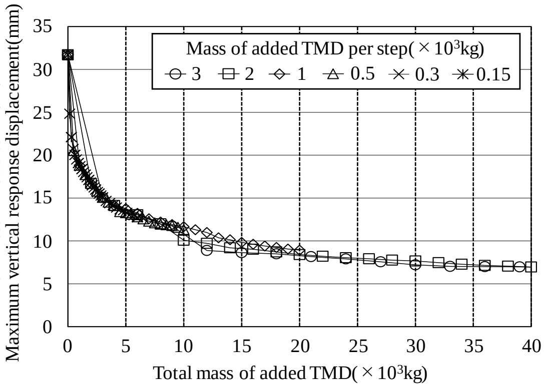


Figure 4: Maximum displacement response to the total mass of added TMD

3.3. Confirmation of the optimality of the TMD optimal design method

The validity of the optimal arrangement obtained by applying this method will be examined. Figure 5 shows a comparison of the maximum vertical response transition when the method is applied to a model and when the same amount of the same total amount of TMD is randomly distributed. From Figure 5, the response of the optimal arrangement was smaller than that of the random arrangement at any total volume level, and the validity of this method was confirmed.

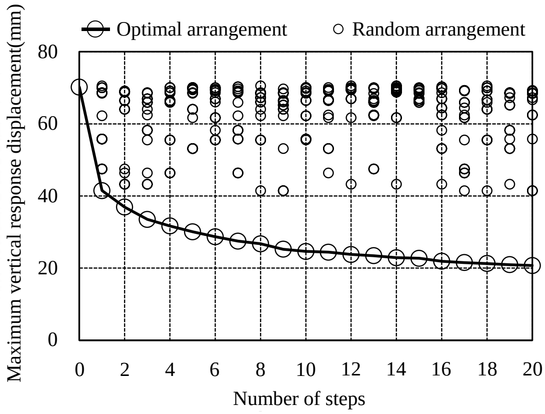


Figure 5: Comparison of optimal arrangement and random arrangement

4. Application of TMD Optimal Design Methods to Each Model

4.1. Comparison of the method of placing TMDs one by one and the method of placing TMDs in groups symmetrically

In a spatial structure building, damage to the fall of suspended objects is likely to occur, so the acceleration is reduced in the following analysis.

For each model in Figure 1-3, perform 20 steps of the optimal TMD design method to minimize acceleration. Previous studies have used a method of arranging TMDs one by one, but when considering application to building design, it is more realistic to arrange them in consideration of the symmetry of the model rather than placing them randomly. Additionally, by arranging multiple TMDs at the same time, analysis time can be shortened.

The TMD can be installed in the following two methods.

(1) Place one TMD at one node in one step, named “one by one.”

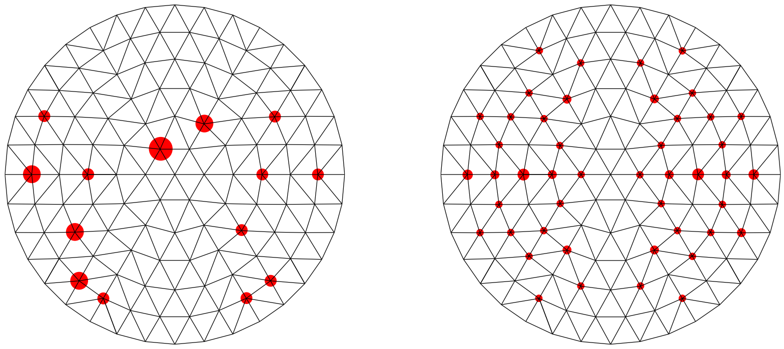
(2) Arrange multiple TMDs symmetrically on the XY axes in one step, named “group arrangement.”

Figure 6 shows the TMD arrangement, and Figure 7 shows the acceleration response reduction effect. The red circle in Figure 6 indicates the placement of the TMDs, and the size of the red circle indicates the mass of the installed TMDs.

Figure 6 shows when placing TMDs one by one, the TMDs are concentrated at some nodes, whereas when placing TMDs with symmetry in mind, the TMDs are distributed throughout the model.

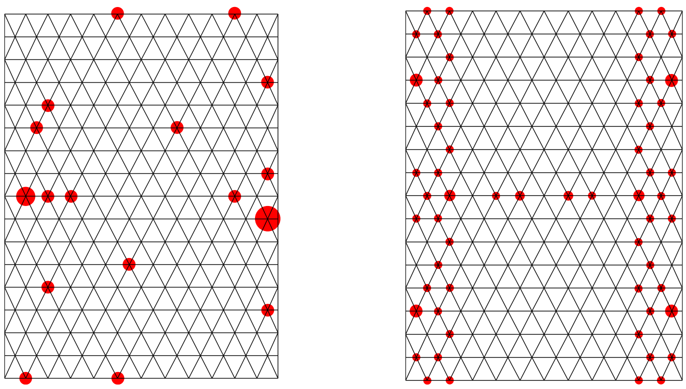
Figure 7 shows that both methods reduce the maximum vertical response acceleration for each model. For lattice domes and cylindrical lattice shells, symmetrically arranging TMDs together has a higher response reduction effect. Although the mass of the TMD per node is small, it is thought that a higher response reduction effect was obtained by arranging the TMD at more nodes.

On the other hand, in the HP shell, placing one TMD at a time has a higher response reduction effect. HP shell differs from lattice dome and cylindrical lattice shells in that the model shape has undulations, and it is necessary to select the TMD placement method according to the model shape.



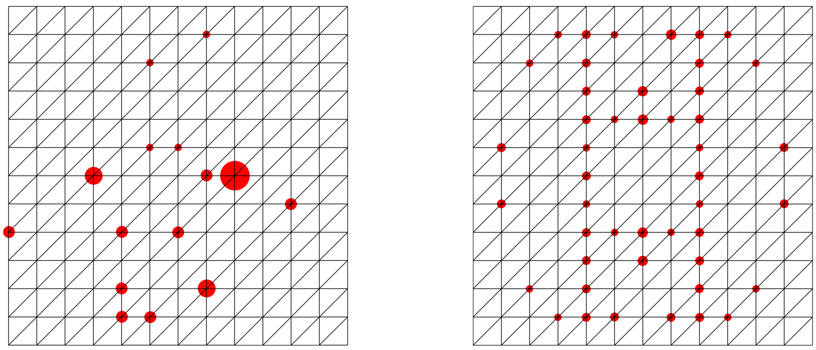
(1) one by one (2)group arrangement

(a) Lattice Dome



(1) one by one (2)group arrangement

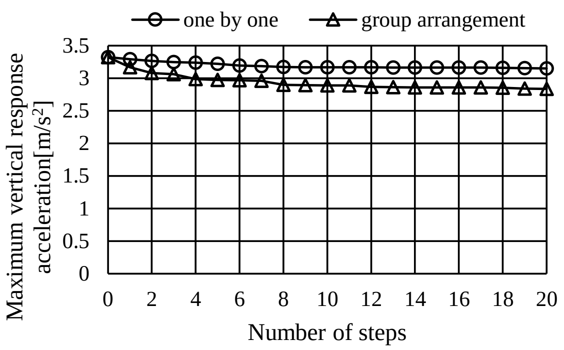
(b) Cylindrical Lattice Shell



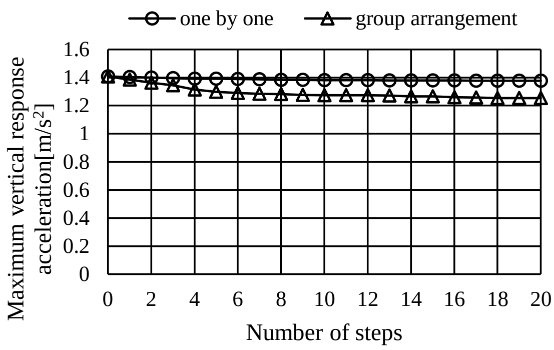
(1) one by one (2)group arrangement

(c) HP Lattice Shell

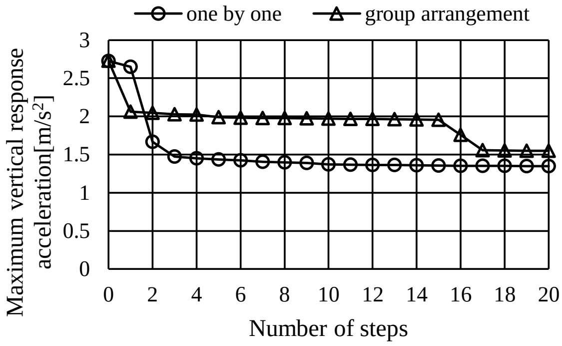
Figure 6: The placement of TMD of each model



(a) Lattice Dome



(b) Cylindrical Lattice Shell



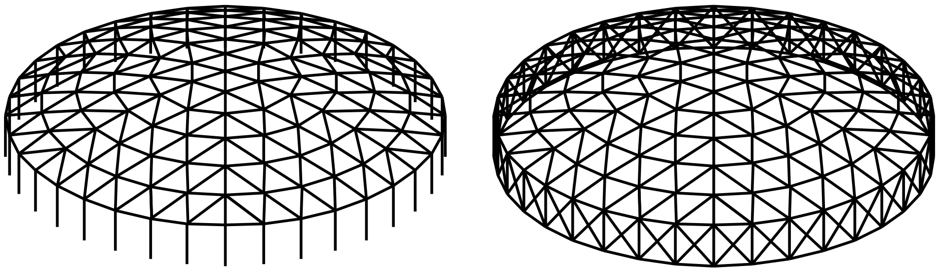
(c) HP Lattice Shell

Figure 7: Changes in maximum vertical response acceleration of each model

4.2. For models with substructures

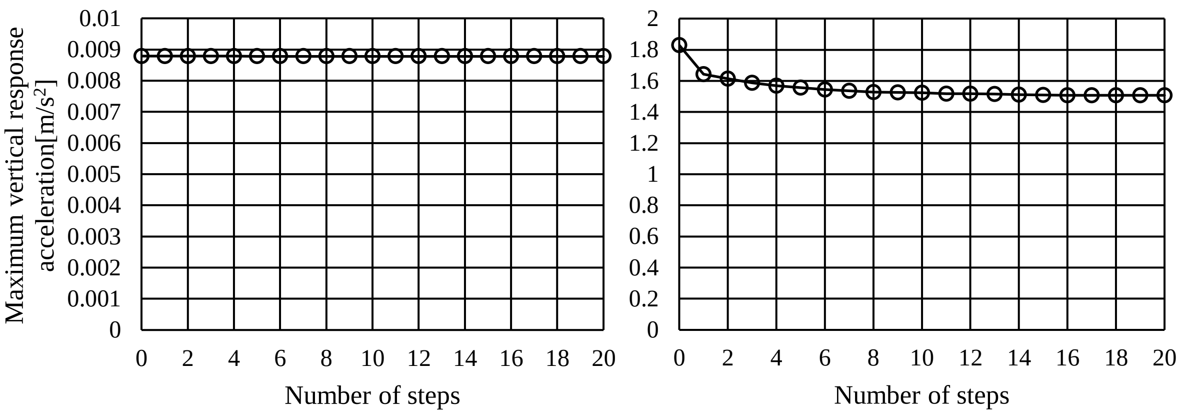
Actual spatial structure buildings have a rigid substructure. In this section, we examine the effect of the substructure on the response reduction effect of the dome model having two types of substructures shown in Figure 8. The height of the substructure is 7m, φ91.44mm×16mm round steel pipe, and the fixed load is 0.98 kN/m². The TMD arrangement method is the symmetrical arrangement.

Figure 9 shows the transition of the maximum vertical response acceleration in the model with the substructure, and Figure 10 shows the mass diagram of the TMD arrangement of 20 steps. From Figure 10, the response reduction effect by TMD is not seen in the column model having a small rigidity of the substructure because the response in the vertical direction is extremely small, but the response reduction effect by TMD is seen in the wall model. Since the response values and TMD arrangement are different from the roof only model, it is necessary to perform analysis with the model designed including the substructure in the actual design.



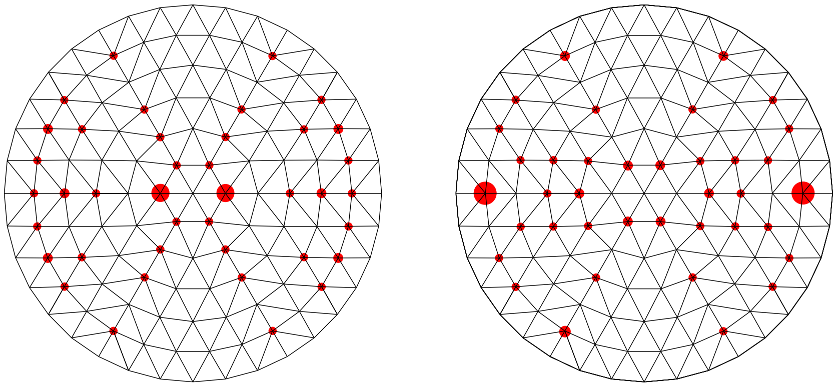
(a) Column model (b) Wall model

Figure 8: Lattice dome with substructures



(a) Column model (b) Wall model

Figure 9: Maximum vertical response acceleration of the model with substructures



(a) Column model (b) Wall model

Figure 10: The placement of TMD of model with substructures

5. Improvement of algorithm to reduce analysis load

In this method, dynamic time response analysis is performed for all candidate solutions, but as the size of the model increases, the analysis time increases and the computational load associated with the increase in the number of candidate solutions becomes an issue. Therefore, in order to shorten the analysis time, we will improve the algorithm using the response spectrum method for evaluating the response of all candidate solutions (Figure 11). As a result, the analysis time is shortened, and the accurate response value is stored by performing dynamic time response analysis with the determined TMD installation solution. We will compare the following two methods to see if it is possible to shorten the analysis time.
Method 1: Candidate resolution is determined by time history response analysis.
Method 2: Candidate resolution is performed by the response spectrum method.
The TMD arrangement method is the symmetrical arrangement. Figure 12 shows the transition of the maximum vertical response for each dome-shaped method, and Figure 13 shows a 20-step TMD arrangement diagram for each method. (a) is the acceleration when the acceleration is reduced, and (b) is the displacement when the displacement is reduced. Figure 12 shows that the solution for reducing acceleration and displacement in Method 2 using the response spectrum has not been tracked. Figure 14 shows the maximum response of each node in each response evaluation method at 20 steps in Method 2. Figure 15 shows the node number of the lattice dome. The nodes after number 92 are omitted because they are fixed ends. From Figure 14, it is considered that the difference in the TMD arrangement of each step is due to the difference in response evaluation in the response spectrum method and dynamic time analysis. Improving the accuracy of acceleration and displacement evaluation by response spectrum in Method 2 will be a future issue.

$$\delta_{i(\max)} = \sqrt{\sum_{s}^{N}\sum_{r}^{N} S_D^{(s)} S_D^{(r)} (\rho_{SS}^{(s,r)}\alpha_i^{(s)}\alpha_i^{(r)} + 2\rho_{SC}^{(s,r)}\alpha_i^{(s)}\beta_i^{(r)} + \rho_{CC}^{(s,r)}\beta_i^{(s)}\beta_i^{(r)})}$$

Maximum vertical response displacement of the i-th node

$$\alpha_{i(\max)} = \sqrt{\sum_{s}^{N}\sum_{r}^{N} S_A^{(s)} S_A^{(r)} (\rho_{SS}^{(s,r)}\alpha_i^{(s)}\alpha_i^{(r)} + 2\rho_{SC}^{(s,r)}\alpha_i^{(s)}\beta_i^{(r)} + \rho_{CC}^{(s,r)}\beta_i^{(s)}\beta_i^{(r)})}$$

Maximum vertical response acceleration of the i-th node

$\rho_{SS}^{(s,r)}, \rho_{SC}^{(s,r)}, \rho_{CC}^{(s,r)}$: Correlation coefficient of s-th mode and r-th mode

$\alpha_i^{(s)}, \beta_i^{(r)}$: Participation vector

$S_D^{(s)}$: Displacement response spectrum

$S_A^{(s)}$: Acceleration response spectrum

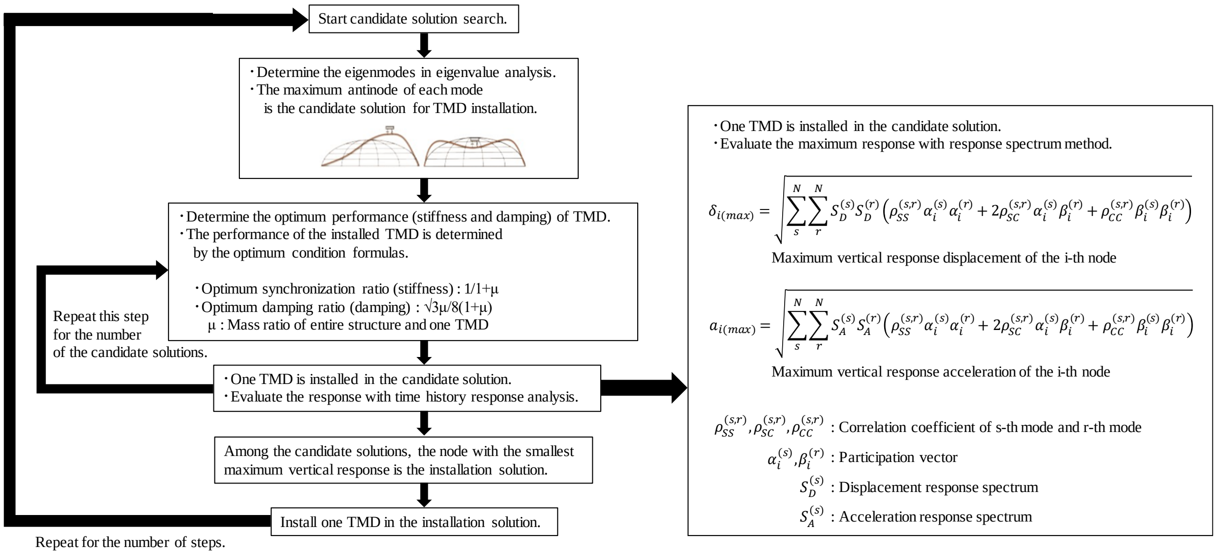
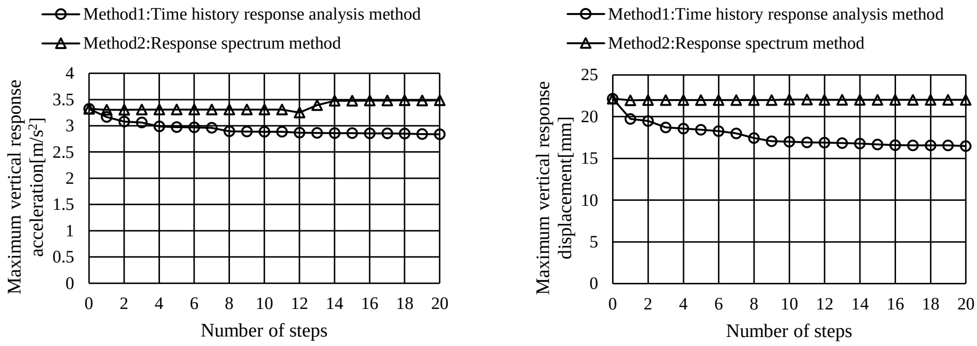
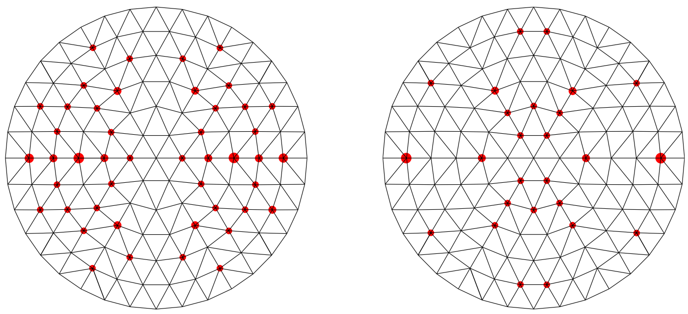


Figure 11: Improved TMD optimization algorithm



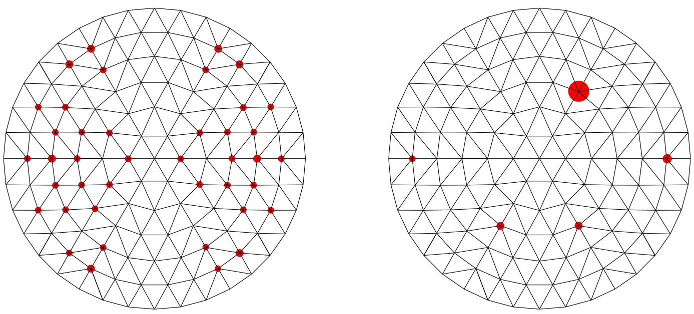
(a) Acceleration reduction (b) Displacement reduction

Figure 12: Maximum vertical response for each method



(1) Method 1 (2) Method 2

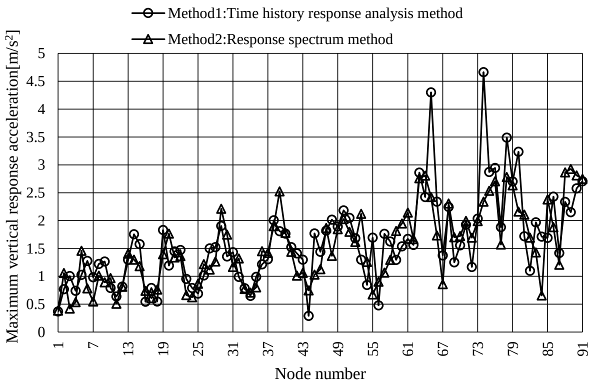
(a) Acceleration reduction



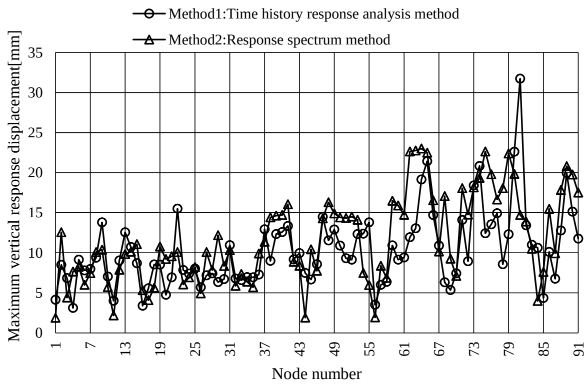
(1) Method 1 (2) Method 2

(b) Displacement reduction

Figure 13: The placement of TMD for each method



(a) Maximum acceleration of each node when acceleration is reduced



(b) Maximum displacement of each node when displacement is reduced

Figure 14: Maximum response for each node at 20 steps

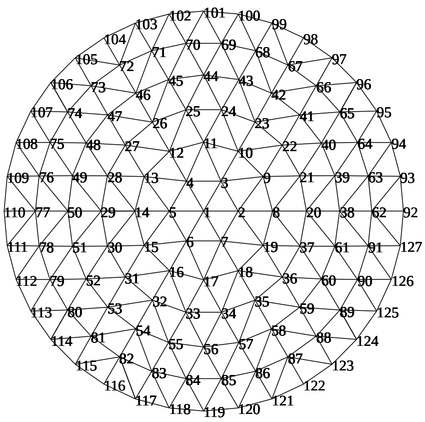


Figure 15: Node number of Lattice Dome

6. Conclusion

In this study, we proposed an optimal design method for TMD, and the main results obtained are as follows.

(1) We were able to confirm the response reduction effect and optimal placement and performance for multiple spatial structure shapes.

(2) The response reduction effect was also confirmed for the spatial structure model with a substructure, demonstrating the versatility of this study.

(3) Although the analysis time could be shortened using the response spectrum method, there are cases where the response cannot be reduced due to the deviation of the response value from the time history response analysis.

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