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# Subsystems' Layout Change Method based on Analytical SEA for Vibration Reduction; Utilization for an Injection Pump of an Engine

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## ABSTRACT

**Conventionally, noise and vibration problems arise in the latter stages of design or manufacturing, but it is necessary to develop a robust design process for low noise and vibration, especially in the early stage. To achieve this, the present authors have proposed a two-step design process based on energy propagation analysis. The first step focuses on the baseline (average) frequency response behavior of structures, and the second step focuses on the peak behavior of the frequency response. Because conventional approaches such as the finite-element method and the boundary-element method can be used for the second step, the authors have focused more on developing the first design step, especially using analytical statistical energy analysis (SEA) and an optimization package. In the first step, using analytical SEA makes it possible to predict the noise and vibration response by mathematical expressions, and low noise and vibration can be realized at the initial design stage without the detail like. However, in previous reports the design flexibility was limited; the shape of each subsystem could be designed but the layout of each unit could not be changed. In this paper, an initial design step is proposed that is applicable to an arbitrary layout. The proposed use of analytical SEA enables one to change and set each subsystem, including the input subsystem and the vibration source, at optimal**

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**locations in terms of SEA for low vibration. As an example, the proposed method is used to reduce the vibration of a mock-up of an injection-pump structure, and the feasibility is examined through numerical simulation. Consequently, each subsystem including the input is located at its optimal position and the vibration of the target subsystem is reduced.**

**Keywords:** Low-Vibration, Analytical SEA, Layout Change
**I-INCE Classification of Subject Number:** 43

## 1. INTRODUCTION

In recent years, high-frequency noise and vibration have become more apparent because of the electrification of mechanical products, an example being automobiles. Consequently, there is a need to reduce such high-frequency noise and vibration. Conventionally, vibration modes are analyzed and countermeasures are taken to reduce noise and vibration. However, countermeasures based on modes affect only the frequency of interest and do not work in broadband. Worse still, there are many modes in the high-frequency range, so it difficult to specify the target mode to be measured by conventional numerical methods such as the finite-element method (FEM). Therefore, it is expected that statistical methods such as statistical energy analysis (SEA) will be used instead to assess the mean behavior of the frequency response. Also, the need to limit development costs makes it necessary to develop a non-iterative design procedure for low noise and vibration.

Against this background, we have previously proposed a two-step design process based on energy propagation analysis for problems involving broadband noise and vibration [1]. In particular, the initial design (i.e., the first design step) is intended to be a robust design that is focused on the average behavior (baseline) of the frequency response characteristics of the target product. We use analytical SEA for this first design step because the mathematical expressions of SEA are suitable for the initial structural design; the basic equation contains physical parameters such as the Young's modulus and the approximate size of each subsystem [1–3]. Because vibration energy and physical parameters are directly correlated, it can be used to obtain an outline of the structural design. However, the design flexibility of the previous research was limited; the shape of each subsystem could be designed but the layout of each unit could not be altered.

In this paper, we propose an initial design step that is applicable to an arbitrary layout. The proposed method enables one to change and set each subsystem, including the input subsystems and vibration source, at their optimal locations from an SEA perspective for low vibration.

First, this paper explains the initial design step based on analytical SEA with optimization manipulation. Next, the procedure for changing the design layout is proposed and demonstrated, and how the layout changes when the input subsystem is either included or excluded is discussed. Finally, the proposed method is applied to a mock-up of the initial design stage for the casing of an injection fuel pump, and FEM is used to examine the vibration reduction.

## 2. INITIAL DESIGN STEP BASED ON ANALYTICAL SEA

### 2.1. Basic SEA Equations

SEA is an analysis method based on balancing the vibration energy between a few or many subsystems. In the SEA model, the system is regarded as an assembly of subsystems. It is assumed that the energy dissipation of a subsystem is proportional to the vibration energy thereof, and the transfer energy between subsystems is also taken to be proportional to the vibration energy between two subsystems. Considering the power balance leads to a set of equations, the basic SEA equation being

$$\mathbf{P} = \omega \mathbf{L} \mathbf{E} \tag{1}$$

where **P** is the external power input, **E** is the subsystem vibration energy vector, and $\omega$ is the band center angular frequency. The matrix **L** is the matrix of loss factors and is written as

$$\mathbf{L} = \omega \begin{bmatrix} \eta_1 + \eta_{12} + \eta_{13} + \cdots & -\eta_{21} & \cdots \\ -\eta_{12} & \eta_2 + \eta_{21} + \eta_{23} + \cdots & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \tag{2}$$

where $\eta_i$ is the internal loss factor (ILF) of subsystem $i$ and $\eta_{ij}$ is the coupling loss factor (CLF) from subsystem $i$ to subsystem $j$. The loss factors are dependent on the frequency. In analytical SEA, the CLF is evaluated using either Equation (3) if the subsystem is like a thin plate or Equation (4) if it is a three-dimensional solid [4]:

$$\eta_{ij} = \frac{2L_{ij}\tau_{ij}}{\pi S_i} \sqrt{\frac{h_i}{\omega}} \sqrt[4]{\frac{E_i}{12\rho_i(1-\nu_i^2)}} \tag{3}$$

$$\eta_{ij} = \frac{S_{ij}\tau_{ij}}{2\pi\omega V_i} \sqrt{\frac{E_i}{\rho_i}} \tag{4}$$

Here, $S_i$, $V_i$, $E_i$, $\rho_i$, and $\nu_i$ are the surface area, volume, Young's modulus, mass density, and Poisson's ratio, respectively, of subsystem $i$, and $L_{ij}$, $S_{ij}$, and $\tau_{ij}$ are the coupling length, coupling area, and energy transmission efficiency, respectively, between subsystem $i$ and subsystem $j$.

### 2.2. Method for Initial Design Step based on Analytical SEA

The method for the initial design step based on analytical SEA is described. First, the target structure is divided into $N$ subsystems as SEA subsystems, and the CLFs are calculated from Equations (3) and (4) using the approximate size and material properties of each subsystem. Next, an $N$-dimensional matrix **L** of loss factors is constructed from the calculated CLFs and ILFs. By using the constructed **L** and the input power **P**, the energy of each subsystem is predicted from Equation (1). This subsystem energy prediction is repeated to complement the objective function using an optimization method. The optimization is performed under various constraints generally concerning the design variables (e.g., plate thickness, surface area, coupling length). Finally, the design variables are determined by the mathematical optimization algorithm with the objective of minimizing the vibration. Such optimization is normal when seeking a low-vibration version of an existing structural layout, but change in the structure layout (subsystem layout) is not taken into consideration.

## 3. METHOD FOR CHANGING THE SUBSYSTEM LAYOUT BASED ON ANALYTICAL SEA

In this section, an initial design step is proposed that is applicable to an arbitrary layout, then the feasibility of the proposed method is demonstrated with analytical SEA. We also discuss how the layout design differs with and without the input subsystem.

### 3.1. Layout Change Design of Low Vibration Subsystems

The layout of the target mechanical system is determined as follows. Each process is described in detail in the remainder of Section 3.

1) Divide the target structure into subsystems.
2) Select the output subsystem and the subsystems whose layout is to be changed.
3) Conduct analytical SEA modeling.
4) Conduct optimization.
5) Determine the optimal subsystem layout.

#### 3.1.1. Dividing Target Structure into Subsystems

The target structure is divided virtually into $N$ subsystems as SEA subsystems before determining the location of each part. In general, the subsystem division is based on the boundaries of the member units having structural discontinuity [5].

#### 3.1.2. Selecting Output Subsystem and Subsystems whose Layout is to be Changed

After the subsystem division, the subsystem whose vibration to be reduced is determined arbitrarily as the output subsystem, which is the objective function. Next, to reduce the vibration of the output subsystem, the subsystems whose layout is to be changed are determined by the optimization that is done using the analytical SEA model.

#### 3.1.3. Analytical SEA Modeling

The CLFs are calculated from Equations (3) and (4) using the properties of each subsystem. Next, the $N$-dimensional matrix $\mathbf{L}$ of loss factors is constructed from the calculated CLFs and the given ILFs. However, in the layout design, the space in which there are no subsystems must also be considered in the design space. In this case, the values of the ILF and CLF concerning the subsystem in $\mathbf{L}$ are treated as zero. Therefore, the rank of $\mathbf{L}$ decreases, and the matrix calculation cannot be performed because the subsystem division number of the design space and the subsystem division number of the structure are different. Thus, we set only the CLF concerning the non-existent subsystem to zero, leaving the ILF of that subsystem, so that the rank of $\mathbf{L}$ does not fluctuate [2]. The presence or absence of a subsystem is represented only by the CLF. Consequently, it is possible to predict the subsystem energy of each subsystem including the present and absent subsystems.

#### 3.1.4. Determine Optimal Subsystem Layout

Here, we identify the layout that minimizes the vibration energy of the output subsystem in the constructed SEA model. For this, we perform mathematical optimization using Microsoft Excel. A layout in which the subsystem energy of the output subsystem is minimized is the design value.

### 3.2. Demonstration of Layout Design with Analytical SEA

#### 3.2.1. Layout Design Including Input Subsystem

The layout of the input subsystem is changed for a simplified structure for which the subsystem division corresponds to seven plates with a thickness of 1 mm, as shown in Figure 1. Each subsystem is made of SUS304 steel (Young's modulus: 200 GPa; Poisson's ratio: 0.3; density: 7930 kg/m$^3$). The input subsystem to be rearranged is subsystem 1, and the output subsystem whose vibration is to reduced is subsystem 6. Subsystems 2–7 are the design parameters that are connected by the input subsystem (subsystem 1). Here, the number of connected subsystems is considered to be just one.

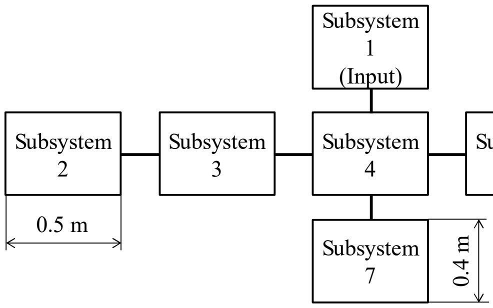



*Figure 1: Simplified structure*

Consequently, the layout optimization is determined as shown in Figure 2. Subsystem 1 (input subsystem) was located to subsystem 2, which is farthest from subsystem 6 (output subsystem). This is because the power input to the input subsystem decreases gradually through each subsystem, thereby decreasing the subsystem energy of the output subsystem. Figure 3 compares the subsystem energy of subsystem 6 (output subsystem) before and after the optimization. This confirms that the energy of subsystem 6 is decreased by the latter being the farthest subsystem from subsystem 1 (input subsystem).

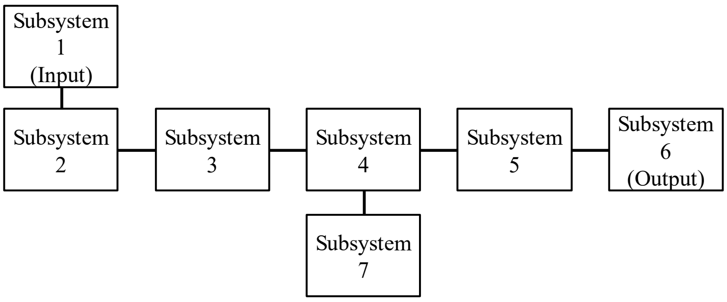



*Figure 2: Result of changing the layout of subsystem 1 (input subsystem)*

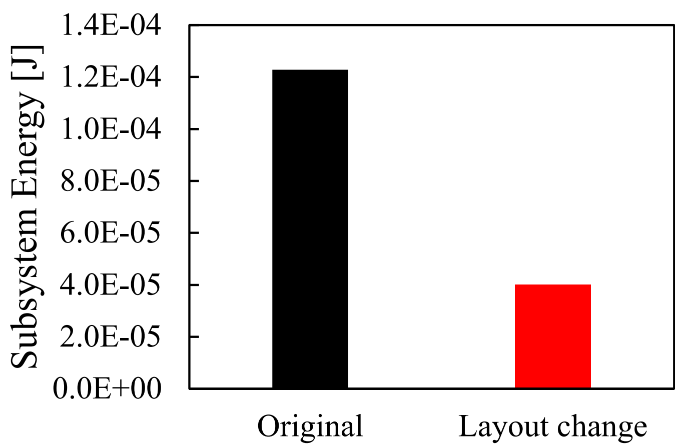



*Figure 3: Comparison of energy of subsystem 6 (output subsystem) before and after changing the layout of subsystem 1 (input subsystem)*

### 3.2.2. Layout Design Excluding Input Subsystem

As in section 3.2.1., the location of the subsystem is optimized to reduce the energy of the output subsystem shown in Figure 1. Here, another subsystem, namely, subsystem 7, is considered as the subsystem whose location is to be changed to reduce the energy of the output subsystem (subsystem 6). Again, we connect just one subsystem with this output subsystem.

The result of this layout optimization is shown in Figure 4. Now, subsystem 7 is connected to subsystem 6 (output subsystem), which as in Ref. [3] is understood because the former absorbs the energy of the latter directly. Figure 5 compares the energy of the output subsystem before and after optimization as estimated by the analytical SEA model. This confirms that the energy of the output subsystem is reduced by attaching subsystem 7. Moreover, we see that the layout change for the input subsystem has large vibration reduction compared with that shown in Figures 3 and 5.

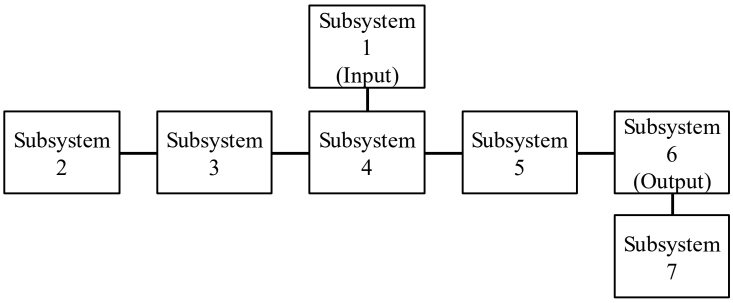



*Figure 4: Result of changing the layout of subsystem 7*

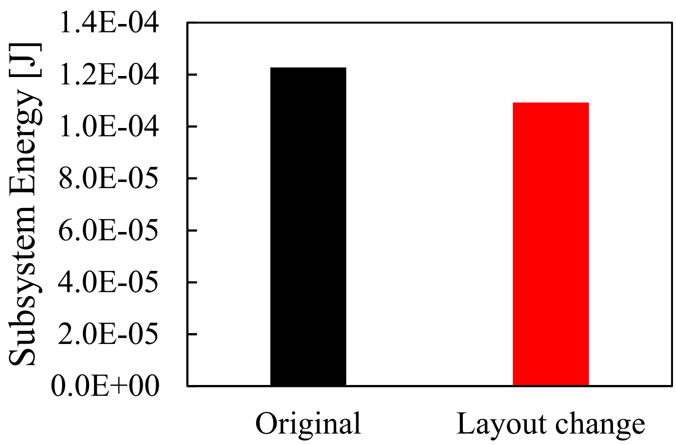



*Figure 5: Comparison of energy of subsystem 6 (output subsystem) before and after changing the layout of subsystem 7*

### 3.2.3. Verification of Low-Vibration Structure by FEM

Thus far, we have described two cases of determining a low-vibration layout based on analytical SEA with optimization, and we have shown that changing the layout of the input subsystem is better than doing so for another subsystem. Here, we verify those results by using FEM calculations.

We built three FEM models, namely one of the original structure shown in Figure 1, one of that shown in Figure 2, and one of that shown in Figure 3. Each subsystem is a flat plate, and their connections are continuous at the nodes on the boundary.

We conducted frequency response analysis under point excitation of the input subsystem (subsystem 1). The kinetic energy of the output subsystem (subsystem 6) was calculated from the spatial average throughout the subsystem based on the responses at several nodes thereon.

Figure 6 compares the kinetic energy of the output subsystem in the original case in Figure 1 with that in the case of the changed input-subsystem layout in Figure 2. The response after the layout change is clearly smaller over a wide frequency range. Meanwhile, Figure 7 compares the kinetic energy of the output subsystem in the original case in Figure 1 with that in the case of the redesigned normal-subsystem layout in Figure 3. Again, the response after the layout change is smaller, but by less than in Figure 6.

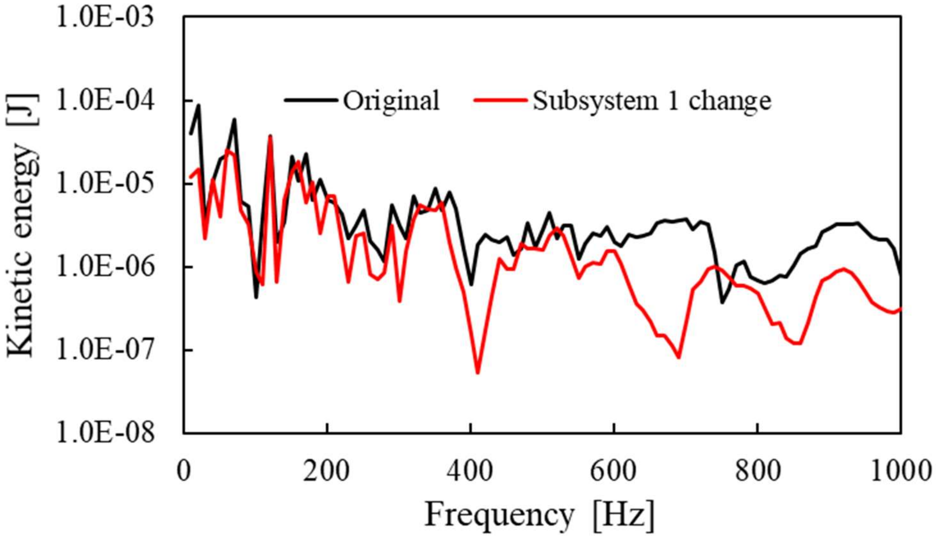



*Figure 6: Comparison of kinetic energy before and after changing the layout of subsystem 1 (input subsystem)*

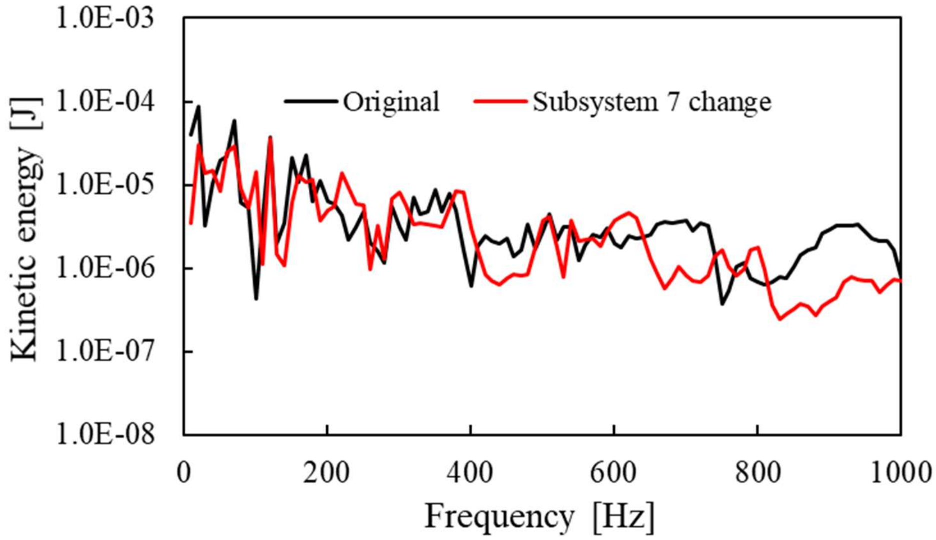
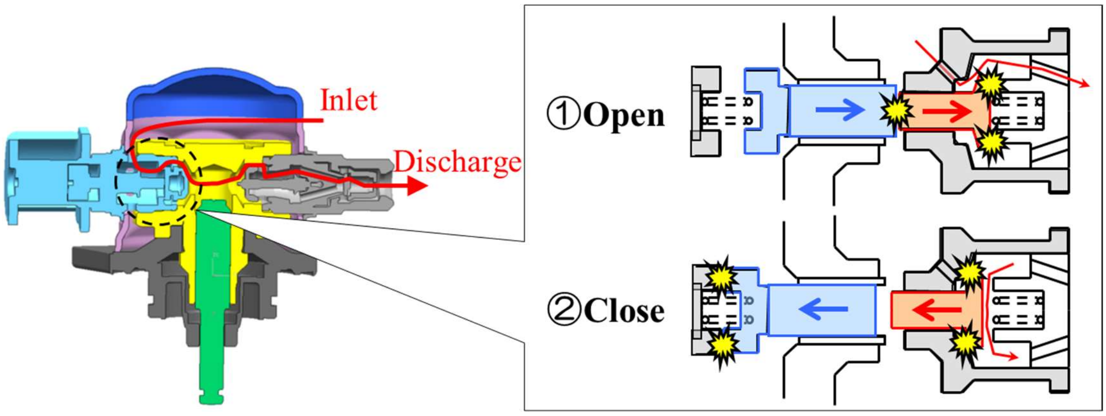



*Figure 7: Comparison of kinetic energy before and after changing the layout of subsystem 7*

## 4. DESIGN OF LOW-VIBRATION LAYOUT FOR INJECTION PUMP

In this section, we apply the proposed design method to a target structure that simulates the casing of a fuel injection pump, and we use FEM to verify the vibration reduction. The fuel injection pump of an automobile engine works by alternately opening and closing a solenoid valve, as shown in Figure 8. When working, the valve hits the wall, creating an impact force that is the source of noise and vibration over a wide frequency range, including high frequencies. To reduce this annoying noise from the pump, countermeasures must be taken against the high-frequency vibration.




*(a) Component drawing* *(b) Valve condition*

*Figure 8: Mechanism of fuel injection pump*

### 4.1. Subsystem Division and Target Structure

Figure 9 shows the target structure, which is a mock-up of the injection-pump casing. It has 15 parts, nine housing plates, three valves (solenoid valve, inlet valve, discharge valve), a cylinder head, a flange, and a bench. All parts are made of SUS304 steel. In the SEA modeling, this structure was subdivided into 15 SEA subsystems. Figure 10 shows the subsystem subdivision and the connection diagram.

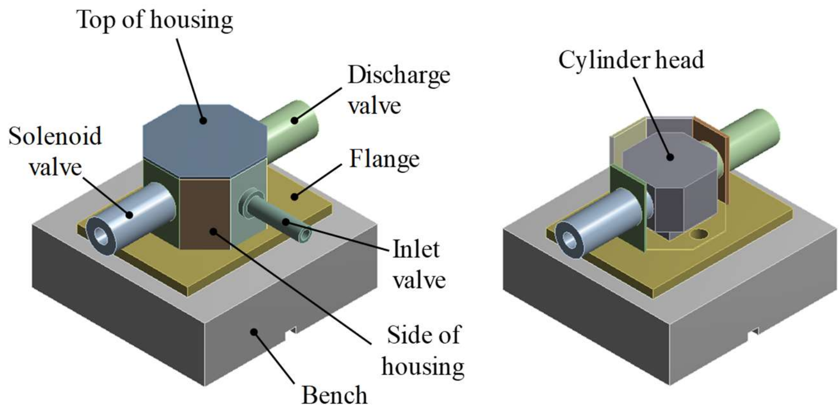



*Figure 9: Target mock-up injection-pump structure*

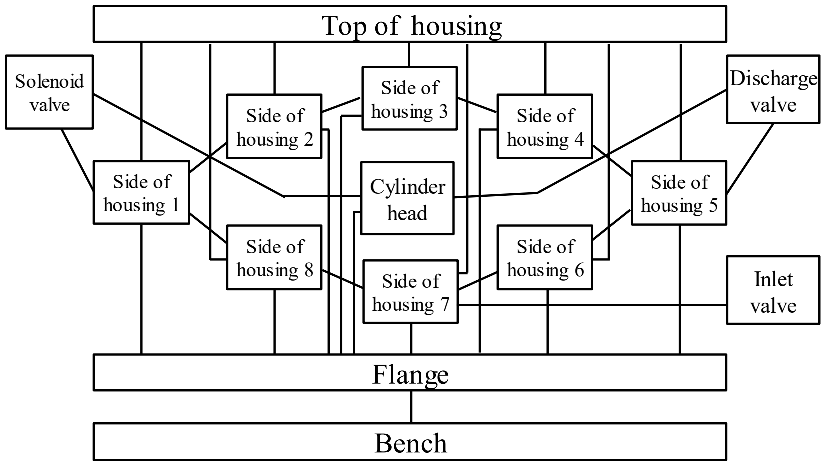



*Figure 10: Subsystem division of target structure*

### 4.2. Selection of Output Subsystems and Subsystems to be Rearranged

For the target injection-pump casing, the solenoid valve causes vibration that propagates to the housing and then is radiated as sound. The top of the housing has the largest surface area, and therefore this was selected as the output subsystem for vibration reduction. The design parameters for changing the layout were the arrangements of the three valves, namely the solenoid valve (input subsystem), the discharge valve, and the inlet valve.

### 4.3. Analytical SEA Modeling

To construct the SEA model, the CLFs of the target structure were obtained from Equation (4); each subsystem of the target structure is considered as a three-dimensional solid. In this paper, the energy transmission efficiency in Equation (4) is set to unity for convenience, and the ILF is assumed to be 0.01 for all subsystems.

### 4.4. Identify Optimal Subsystem Layout

#### 4.4.1. Optimization Conditions

Optimization was performed under the following conditions. The input subsystem is the solenoid valve and the output subsystem is the top of the housing. The objective function is to minimize the subsystem energy of the top of housing (output subsystem), the design variables are the arrangements of the solenoid valve, the discharge valve, and the inlet valve, and the constraints are that (i) each valve is connected to just one subsystem and (ii) none of the valves are connected to each other.

#### 4.4.2. Optimization Results

The results of the layout optimization are shown in Figures 11 and 12. The solenoid valve (input subsystem) is located farthest from the top of the housing (output subsystem), and the discharge valve and inlet valve are arranged to disperse energy from the top of housing (output subsystem). This result is similar to that in Section 3. Figure 13 compares the subsystem energy of the top of the housing before and after the optimization by analytical SEA, and the vibration reduction due to the layout change is approximately 20%.

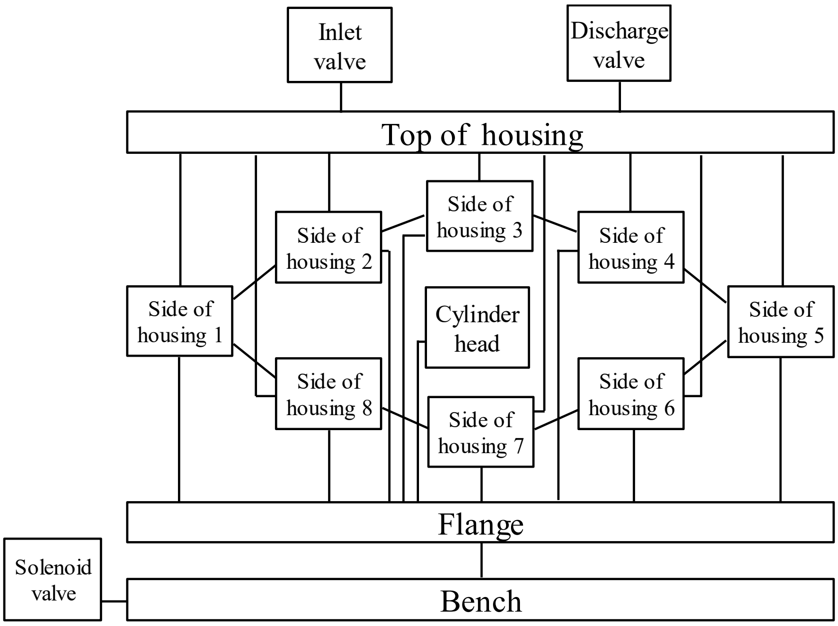



*Figure 11: Subsystem division of the target structure after layout change*

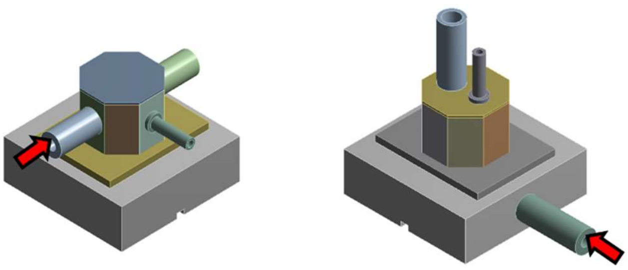


*Figure 12: Apparatus of the target structure before and after layout change*

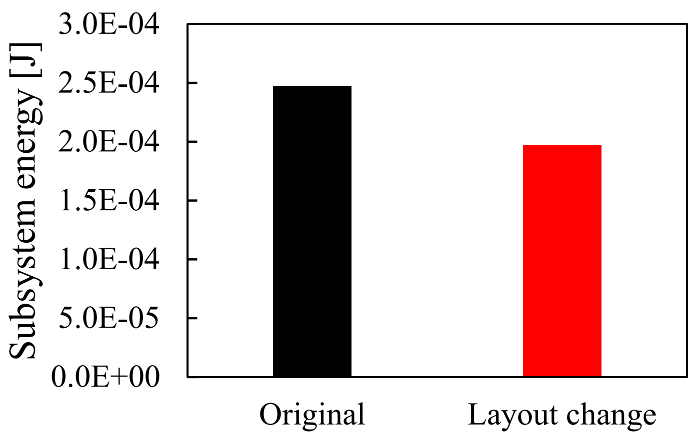



*Figure 13: Comparison of energy of top of housing (output subsystem) before and after layout change*

### 4.5. Verification of Low Vibration by FEM

Using the design policy specified in section 4.4., we built FEM models of the structure before and after the optimization, as shown in Figure 12. We conducted frequency response analysis to examine the extent of vibration reduction by changing the layout in a practical manner. A sinusoidal excitation force of 1 N was applied where indicated by the red arrow in Figure 12, and the average kinetic energy was evaluated at multiple points on the top of the housing. Figure 14 compares the kinetic energy of the top of the housing before and after the layout change, suggesting that the proposed layout-change method achieved vibration reduction over a wide range of frequencies, includes high frequencies.

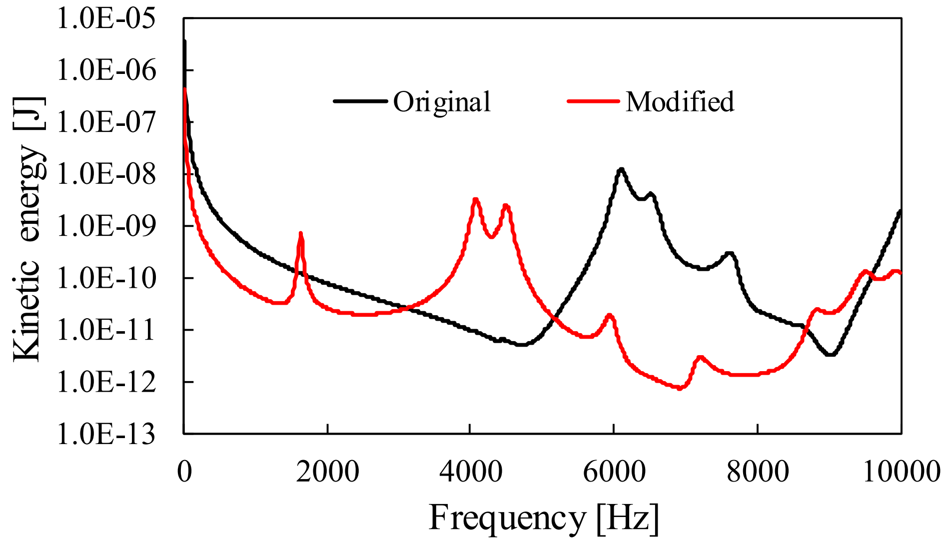



*Figure 14: Comparison of kinetic energy of top of housing (output subsystem) before and after layout change*

### 5. CONCLUSIONS

In this paper, a method was proposed for designing a low-vibration layout based on analytical SEA. The design method was applied to a mock-up of the casing of an injection pump, and its effectiveness was shown. The specific remarks are as follows.

1) A method for designing a low-vibration layout based on analytical SEA was proposed, and its effectiveness was demonstrated with a simplified structure.
2) As a result of the layout change, the input subsystem was located farthest from the output subsystem, and the subsystems excluding the input subsystem were arranged to disperse the energy of the output subsystem. The extent of vibration reduction was larger in the case in which the location of the input subsystem was changed.
3) The proposed design method was applied to a target structure, namely a mock-up of the casing of an injection pump, and the reduction of vibration was confirmed by FEM.

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