Research Article

A Magnet-Coil-Type Bistable Vibration Energy Harvester for Random Wave Environment

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In this study, a new bistable vibration energy harvesting system is developed by originally proposing a bistable vibration model comprising a spring and a mass block and then applying a vibration generator composed of a coil and a magnet. The nonlinear equations of motion for this vibration energy harvesting system are developed and the static potential energy distribution is analyzed. The bistable vibration characteristics and the method for prediction of the periodic excitation frequency at which stochastic resonance is likely to occur are investigated theoretically, and the electromagnetic induction-based bistable vibration energy harvesting system is then developed. We predicted the excitation value that the stochastic resonance phenomenon is most likely to occur at 1.543 Hz. We also conducted experiments at 1.15 Hz, 1.50 Hz, and 1.85 Hz, which are centered on the predicted value. As a result, stochastic resonance occurred in all experimental cases. The power generation efficiency was improved by 125.03%, 149.05%, and 95.39%, respectively.

1. Introduction

In recent years, many researchers have studied vibration-based power generation methods in random vibrating environments and numerous research results have been published in this field [1–8].

The application of stochastic resonance phenomena has attracted considerable research attention as a potential method for extraction and effective use of the energy contained in random vibration environments. Stochastic resonance is a physical phenomenon in which the response of a nonlinear system operating in a random noise environment is greatly amplified by the addition of a specific periodic signal [9–14].

The stochastic resonance phenomenon was first proposed by Benzi et al. in 1981 when they examined the periodicity of the ice age of the Earth [15]. Since then, stochastic resonance has been applied to many new research fields, such as weak input signals detection [16, 17] and image sensor [18, 19].

In the mechanical field, many results have been published on the use of the stochastic resonance phenomenon to amplify the response amplitudes of nonlinear bistable systems by inputting periodic signals and noise signals simultaneously [20–24]. Among these reports, the most common system is based on a bistable vibration model that uses the opposing repulsive force that acts between a permanent magnet attached to the end of a horizontally-installed cantilever beam and a permanent magnet fixed in the vicinity of this beam [25–32]. In addition, research results have been presented on the construction of a bistable vibration model using the vertically-installed cantilever with a mass block at the tip [33–38]. Furthermore, many research has been published, including combining multiple bistable models into one vibration system [39, 40].

In addition, research results have also been published on the development of a bistable energy harvesting system in which a cantilever beam with a permanent magnet attached to its tip is installed in a wheel structure that focuses on the vibration of vehicle tires during low-speed driving [41, 42]. Since there are many low-frequency vibration sources in the natural environment, vibration power generation systems used in low-frequency vibration environments become important. The effectiveness of a bistable system consisting
of spherical magnets with a rotary-translational motion for ultra-low-frequency applications has been verified [43, 44]. Moreover, some harvesting systems using a two-degree-of-freedom vibration model were proposed, and it was verified that they could be applied to an ultra-low-frequency vibration environment [45, 46].

The authors have previously proposed a bistable vibration system that consisted of an inverted cantilever beam with a mass block attached to its tip and reproduced the stochastic resonance phenomenon. The authors also investigated the amplification effect of the stochastic resonance characteristics of the proposed system [47].

However, the bistable vibration model consisting of a cantilever beam and a mass block vibrates via elastic bending deformation of the thin cantilever beam, and there is a limit to the range within which this type of system can vibrate. In addition, the cantilever beam is often required to vibrate at very large amplitudes to pursue the required level of vibration power generation, which can pose serious problems for the durability of the vibration power generation system. Furthermore, the internal electrical resistance of the piezoelectric element used in this system is high, which means that the power available to load the external circuit is very low [48].

Therefore, it is important to develop a new bistable vibration system design that can vibrate continuously for long periods with as large an amplitude as possible and a new vibration-based power generation method that can output large quantities of power to an external circuit load rather than to piezoelectric elements to enable implementation of a practical vibration energy harvesting system.

In this study, we proposed a new bistable vibration energy harvesting system that can be applied to a random wave environment. The power generation unit of the harvesting system consists of magnets and coils. We verified the bistable vibration characteristics by using the motion equation and potential energy distribution equation. We also set out the prediction equation by using Kramer’s rate to predict the excitation frequency at which stochastic resonance is most likely to occur and developed a verification device using a water tank and vibration device in the laboratory to verify the amplification effect of vibration and the increased rate of power generation.

2. Materials and Methods

2.1. Bistable Vibration Energy Harvesting System Based on Random Waves. In this study, the bistable vibration energy harvesting system is proposed for use in a random wave environment, as shown in Figure 1, and we develop an actual device for verification experiments.

As shown in Figure 1, the experimental system comprises four parts: a water tank, a random wave generator, a bistable vibration energy harvester, and a measurement system. The vibration energy harvester is located at the center of the water tank and is fixed to the bottom of the tank using elastic springs and a support stand underneath it. A minishaker is attached to the bottom of the vibration energy harvester, and the bottom of this minishaker is then placed on the floor of an acrylic box. The acrylic box floats with half of its depth under the surface of the water, and it can be moved left and right by the action of the wave force.

To generate random waves, a wave-making plate is installed on the left side of the water tank and is fixed to the bottom of the water tank using a pin coupler that is free to rotate below the wave-making plate. The plate is then connected to a shaker via link mechanism located above the wave-making plate, and an amplifier and a signal generator are installed at the end of the shaker.

To perform the vibration energy harvesting experiment using the experimental apparatus shown in Figure 1, in order to generate stochastic resonance in the bistable vibration model, it is necessary to apply random and periodic signals as input at the same time. A random vibration signal generated by the function generator is sent to the amplifier, and the amplified vibration signal is then sent to the shaker to generate waves on the water surface in the tank. The acrylic box can be made to vibrate by the action of the random wave force and can simultaneously be made to vibrate by the action of the periodic signal from the minishaker installed at the bottom of the acrylic box.

Figure 2 shows the actual experimental apparatus used for verification of the developed bistable vibration energy harvesting system, and Table 1 lists the specifications of the system configuration.

To measure the vibration displacements of the mass block and the support point of the vibration energy harvesting model installed at the center of the tank, measurement markers are attached to both the mass block and the support point. During the measurements, a video camera is used to take motion video data for two measurement markers, and tracking software is then used to generate vibration displacement data for the mass block and the support point.

During the experiment, the relative motion of the coil and the magnet generates a voltage in the coil. The coil output lead is connected to a data logger, and this data logger records the voltage signals of the vibration generation process.

2.2. Vibration Characteristic Analysis. For the analysis, the vibration section of the vibration energy harvesting system is separated and simplified, as shown in Figure 3. In Figure 3, \( m \) is the mass of the mass block, \( x_d \) is the displacement of the mass block from the axis of symmetry, and \( x_s \) is the displacement of the support point from the axis of symmetry, including the excitation displacement composed of random wave and minishaker. In addition, \( F \) is the force of the spring, \( F_f \) is the damping force due to friction, \( l_0 \) is the initial spring length, and \( h \) is the vertical distance from the support point to the center point of the mass block. Finally, \( \theta \) is the angle between the spring axis and the horizontal direction.

When the mass block moves, electromagnetic induction damping force are generated. However, the actual experiment shows that the electromagnetic induction damping force is less than 2% of the friction damping force; therefore, we ignore the electromagnetic induction damping force in the motion equation.
Therefore, the equation of motion of the mass block moving along the straight rail is expressed as follows:

\[ m \ddot{x}_d + c (\dot{x}_d - \dot{x}_r) + F \cos \theta = 0, \]  

where \( c \) is the damping coefficient. The equation of motion (1) shown in Figure 3 can be expressed as follows:

\[ m \ddot{x}_d + c (\dot{x}_d - \dot{x}_r) + K \left( 1 - \frac{l_0}{\sqrt{(x_d - x_r)^2 + h^2}} \right) (x_d - x_r) = 0, \]  

(2)

where \( K \) is the spring constant. Here, the relative displacement between the mass block and the support point can be expressed using the following equation:

\[ x = x_d - x_r. \]  

(3)

Substitution of equation (3) into equation (2) allows the equation of motion for the relative displacement \( x \) of the mass block to be expressed in the following equation:

\[ m \ddot{x} + c \dot{x} + K \left( 1 - \frac{l_0}{\sqrt{x^2 + h^2}} \right) x = -m \ddot{x}_r. \]  

(4)

By substituting \( \ddot{x} = 0 \) and \( \dot{x} = 0 \) into equation (4), the potential energy can be expressed as shown in the following equation:

\[ U = \frac{1}{2} Kx^2 - Kl_0 \sqrt{x^2 + h^2}. \]  

(5)
To investigate the potential energy distribution characteristics, we differentiate equation (5), and the equation for the displacement $x$ can be obtained as follows:

$$K \left( 1 - \frac{l_0}{\sqrt{x^2 + h^2}} \right) x = 0. \quad (6)$$

By finding the root of equation (6), the following result can be obtained:

$$x_0 = 0,$$

$$x_1 = -\sqrt{l_0^2 - h^2},$$

$$x_2 = \sqrt{l_0^2 - h^2}. \quad (7)$$

The potential energy distribution expressed in equation (5) is shown in Figure 4, where $x_0$, $x_1$, and $x_2$ in equation (7) are the extreme of the potential energy.

As shown in Figure 3, the free length of the spring is $l_0$, which is greater than the vertical distance $h$ between the two constraint points at the ends of the spring. In addition, static equilibrium positions exist for the mass block, with positions located on each side of the vibration model corresponding to $x_1$ and $x_2$.

Depending on the excitation conditions, the mass block has the following three vibration states: (1) local vibration centered at the left extreme point $x_1$, (2) local vibration centered at the right extreme point $x_2$, and (3) global vibration spanning both of these extreme points. In this case, the local vibration centered on a single extreme point is called the monostable vibration state, while the global vibration spanning the two extreme points is called the bistable vibration state.

In the bistable vibration system, which oscillates monostably in a real vibration environment, the mass block is subjected to a weak periodic excitation, and a large amplification effect is obtained at the instant that the block overcomes the potential energy mountain at the center. This is an important point of this research.

2.3. Conditions for Occurrence of Stochastic Resonance. In a random excitation environment, a change from a monostable vibration state to a bistable vibration state results in a large amplification effect, which is called the stochastic resonance phenomenon. The most important design issue for induction of the stochastic resonance is a prediction of the frequency of the externally applied periodic signal required.

To solve this problem, McNamara–Wiesenfeld proposed an equation for the prediction of the periodic excitation frequency, as shown in equation (8), which uses Kramer’s
rate as a condition for the occurrence of stochastic resonance for a bistable vibration model [10]:

\[ f_k = \frac{w_h w_0}{4\pi q} \exp\left(\frac{-\Delta U}{D}\right), \quad (8) \]

where \( w_h \) is the natural angular frequency at local minimum potential energy point \( x_1 \) or \( x_2 \), \( w_0 \) is the natural angular frequency at the local maximum potential energy point \( x_0 \), \( q \) is the ratio of the damping coefficient to the mass, given by \( q = c/m \), \( \Delta U \) is the barrier value of the potential energy per unit mass, and \( D \) is the random signal intensity.

The angular frequency and barrier parameters above can be calculated as follows:

\[ w_h = \sqrt{\frac{U''(x_1)}{m}}, \quad (9) \]

\[ w_0 = \sqrt{\frac{U''(x_0)}{m}}, \quad (10) \]

\[ \Delta U = \frac{U(x_0) - U(x_1)}{m}. \quad (11) \]

By substituting equations (9)–(11) into equation (8), the equation for prediction of the periodic excitation frequency can be obtained, as shown in the following equation:

\[ f_k = K l_0 - h \left( l_0 + h \exp\left(\frac{K l_0 - h}{2m D}\right)\right). \quad (12) \]

In this study, a random excitation signal, as shown in Figure 5, is used for examination, and its Fourier transformed spectrum is shown in Figure 6.

The random excitation signal strength can be calculated using equation (13) after the response displacement of the support stand during excitation using random signals alone is measured and converted into a velocity:

\[ D = \frac{1}{2N} \sum_{i=1}^{N} (\dot{x}_i - \dot{x}_{\text{aver}})^2, \quad (13) \]

where \( \dot{x}_i \) is the measured response time, \( \dot{x}_{\text{aver}} \) is the average response time, and \( N \) is the number of samples included in the experiment.

3. Results

To verify the performance in terms of the stochastic resonance phenomena and vibration generation, the response displacement and voltage results were measured in three different cases: (1) random signal excitation, (2) periodic signal excitation, and (3) excitation of combined signals.

Using the periodic excitation frequency, \( f_k = 1.543 \text{ Hz} \), which was calculated using equation (12), the frequency of the periodic excitation signal used in the measurement experiment was varied within the range from 1.0 Hz to 2.0 Hz at intervals of 0.25 Hz, and the amplitude was set to be a uniform 20 mm.

Figures 7 to 12 show the results of the measurement experiments. Part (a) in each figure shows the vibration displacement and voltage results, where the blue line indicates the response vibration displacement of the support stand, the black line represents the response vibration displacement of the mass block, and the red line shows the voltage value. Parts (b) and (c) in each figure show the vibration displacement-velocity diagrams for the support and the mass block, respectively.

3.1. Vibration Excitation by Random Signal. Figure 7 shows the results of measurements of the response vibration...
displacement and the voltage obtained when the vibration is generated with random waves only. Figure 7(a) shows that the response displacement is small when shaken by random waves only and that the mass block maintains monostable vibration constantly near the right equilibrium position, which is related to the fact that the oscillator starts from the right equilibrium position. Because the amplitude of the response displacement is small, the voltage is also small, with an average voltage of 8.29 mV and a maximum value of 41.80 mV.

A comparison of Figures 7(b) and 7(c) shows that there is little difference between the amplitudes of the displacements of the support and the mass block, and the velocity of the mass block is slightly higher than that of the support.

### 3.2. Vibration by Periodic Signal

Figures 8 to 10 show the response vibration displacement and voltage characteristics generated by the periodic signals when using a minishaker.

Figure 8 shows the measurement results when excited with a periodic signal at a frequency of 1.00 Hz. The response vibration of the mass block is at almost the same frequency as the support vibration, and the response displacement of the mass block is slightly greater than that of the support; however, it can be confirmed that the mass block shows a monostable vibration state on the right side of the vibration model. The voltage is relatively small, with an average voltage of 7.59 mV and a maximum voltage of 16.30 mV.

Figures 8(b) and 8(c) show that the vibration displacement and velocity characteristics of the support and the mass block, respectively, are relatively small.

Figures 9 and 10 show the measurement results for the cases of excitation using periodic signals with frequencies of 1.50 Hz and 2.00 Hz, respectively. The figures show that, as the excitation signal frequency increases, the vibration amplitude of the support point, which is subjected to direct external excitation, remains almost unchanged, while the vibration displacement of the mass block decreases gradually. However, as the periodic excitation signal frequency increases, the voltage also gradually increases. At a frequency of 1.50 Hz, the average voltage value became 16.15 mV and the maximum voltage value was 49.60 mV. At the frequency of 2.00 Hz, the average voltage value then became 20.30 mV and the maximum voltage value increased to 51.70 mV.

The graph of the relationship between the response vibration displacement and the associated velocity shows that, as the periodic excitation signal frequency increases, the vibration velocity of the mass block remains almost constant and the block continues to vibrate on the right of the vibration model.

### 3.3. Vibration by Random and Periodic Signals

Figures 11 to 13 show the response vibration displacement and voltage measurement results obtained by excitation with a combination of random wave signals and periodic minishaker signals.

Figure 11 shows the measurement results from combined excitation with a random wave signal and a periodic signal at a frequency of 1.00 Hz. The response vibration of the mass block is greater than that of the support, and the response vibration displacement of the mass block has a random waveform, but the results confirm that it shows a monostable vibration state on the right side of the vibration model. The voltage is also random, but the average voltage is 11.25 mV and the maximum voltage is 88.80 mV.

Figures 11(b) and 11(c) show that the velocity of the mass block is higher than that of the support and confirm that the mass block shows a monostable vibration state.

Figure 12 shows the results obtained for combined excitation using random wave signals and periodic signals at frequencies of 1.50 Hz. The response vibration of the mass block intensifies, and it is confirmed that a stochastic resonance phenomenon occurs in which the bistable vibration crosses the center of the vibration model and then spans both sides. This result is consistent with the periodic excitation frequency of \( f_k = 1.543 \) Hz at which the stochastic resonance is likely to occur, as predicted using equation (12). As the response oscillation becomes increasingly intense, the voltage also increases. At 1.50 Hz, the average voltage was 28.69 mV and the maximum voltage was 184.55 mV. The response vibration displacement vs. velocity graph clearly shows that the displacement of the mass block is a bistable state, oscillating across both sides of the vibration model and thus causing a stochastic resonance phenomenon.

Figure 13 shows the measurement results for the combined excitation case with a random wave signal and a periodic signal at a frequency of 2.00 Hz. The response vibration of the mass block is again reduced, and the results show that the mass block has a monostable vibration state on the right side of the vibration model. As the response vibration displacement of the mass block decreases, the voltage also decreases, with an average voltage of 22.52 mV and a maximum voltage of 95.52 mV. Figures 13(b) and 13(c) show that the velocity of the mass block is higher than the velocity of the support, and the results confirm that the mass block shows a monostable vibration state.

### 4. Discussion

#### 4.1. Amplitude Expansion Effect Caused by Stochastic Resonance

The standard deviation of the vibration displacement, which can be expressed as equation (13), is used to evaluate the vibration response effect of stochastic resonance:

\[
S = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2},
\]

where \( x_i \) is the response displacement, \( \bar{x} \) is the average value of the vibration displacement, and \( N \) is the number of sample measurements taken in the experiment. In this section, the ratio of the standard deviations of the response displacements for the mass block and the support point is used as an evaluation index to evaluate the stochastic resonance effect:

\[
S_{\text{ratio}} = \frac{S_{\text{mass}}}{S_{\text{base}}},
\]

where \( S_{\text{mass}} \) and \( S_{\text{base}} \) are the standard deviations of the vibration displacements for the mass block and the support point, respectively.
Using equations (14) and (15), the ratios of the standard deviations are calculated for the experimental response displacement results presented in Section 3, and the calculation results are summarized in Figure 14. Figure 14 shows that the ratio of the standard deviation of the vibration displacement is obviously large when stochastic resonance occurs.

To verify the amplification effect of the stochastic resonance quantitatively, we add the results for $S_{\text{ratio}}$, which were
obtained by performing separate excitations using random and periodic signals, and then compare them with the corresponding results for $S_{ratio}$ obtained when using combined excitation for the case in which stochastic resonance occurs.

When the periodic signal is 1.15 Hz, then the sum of the separate excitations $S_{ratio}$ is $1.94 + 2.65 = 4.59$, and the result $S_{ratio}$ for the combined excitation is 6.67. The difference between these two results is $(6.67 - 4.59)/4.59 = 45.43\%$. 

Figure 9: Measured results for response vibration displacement and vibration power generation for vibration with a periodic signal at 1.50 Hz. (a) Response vibration displacement results. (b) Diagram of displacement vs. velocity of vibration for the mass block. (c) Diagram of displacement vs. velocity of vibration for the support.

Figure 10: Measured results for response vibration displacement and vibration power generation for vibration with a periodic signal at 2.00 Hz. (a) Response vibration displacement results. (b) Diagram of displacement vs. velocity of vibration for the mass block. (c) Diagram of displacement vs. velocity of vibration for the support.
When the periodic signal is 1.50 Hz, the sum of the separate excitations $S_{ratio}$ is $1.94 + 2.59 = 4.53$, and the result $S_{ratio}$ for combined excitation is 7.64. The difference between these two results is $(7.64 - 4.53)/4.53 = 68.73\%$.

When the periodic signal is 1.85 Hz, the sum of the separate excitations $S_{ratio}$ is $1.94 + 1.83 = 3.77$, and the result $S_{ratio}$ for combined excitation is 7.66. The difference between these two results is $(7.66 - 3.77)/3.77 = 103.22\%$.

Figure 11: Measured results for vibration displacement and vibration power generation for vibration with a random signal and a periodic signal at 1.00 Hz. (a) Response vibration displacement results. (b) Diagram of displacement vs. velocity of vibration for the mass block. (c) Diagram of displacement vs. velocity of vibration for the support.

Figure 12: Measured results for vibration displacement and vibration power generation for vibration with a random signal and a periodic signal at 1.50 Hz. (a) Response vibration displacement results. (b) Diagram of displacement vs. velocity of vibration for the mass block. (c) Diagram of displacement vs. velocity of vibration for the support.
Figure 13: Measured results for vibration displacement and vibration power generation for vibration with a random signal and a periodic signal at 2.00 Hz. (a) Response vibration displacement results. (b) Diagram of displacement vs. velocity of vibration for the mass block. (c) Diagram of displacement vs. velocity of vibration for the support.

Figure 14: Verification result of the amplification effect caused by stochastic resonance.

Figure 15: Verification results for the effect of stochastic resonance on power generation.
These comparisons show that the amplification effect when the stochastic resonance occurs with combined excitation is higher than the corresponding amplification effect when the excitations are performed separately using the random and periodic signals.

4.2. Expansion Effect of Vibration Power Generation by Stochastic Resonance. In this section, we use the average electrical work rate, which is calculated using the following equation, to evaluate the amount of vibration power generation:

\[
W_{\text{aver}} = \frac{1}{T} \int \frac{V^2}{R} \, dt = \frac{\Delta T}{TR} \sum_{i=1}^{N} V_i^2,
\]

where \( V \) is the voltage, \( V_i \) is the measured voltage, \( R \) is the electric load resistance, \( T \) is the measurement time, and \( N \) is the number of samples. In this study, these parameters are set as follows: \( R = 3.6 \, \text{Ohm}, \ T = 60 \, \text{s}, \) and \( N = 10000 \).

The average electric work rate \( W_{\text{aver}} \) is calculated using equation (16) for each of the vibration power generation measurements given in the previous section, and the calculated results are summarized in Figure 15. The blue graph in Figure 15 shows \( W_{\text{aver}} \) for vibration with a periodic signal, and the red graph shows \( W_{\text{aver}} \) for vibration with the combined signal.

Figure 15 shows that, as the periodic signal frequency increases, the amount of vibration power generated via the periodic excitation tends to increase; however, in the cases of combined excitation using the random signal and periodic signals at frequencies of 1.15 Hz, 1.50 Hz, and 1.85 Hz, the \( W_{\text{aver}} \) values obtained are higher than those of other single stable motion states because of the occurrence of the stochastic resonance of the bistable vibration.

To investigate the effect of stochastic resonance further on the amount of power generated via vibration, we compared the results of the addition of the \( W_{\text{aver}} \) values obtained from separate excitations using random and periodic signals with the \( W_{\text{aver}} \) values obtained from combined excitation.

When the periodic signal is 1.15 Hz, the sum of the separately excited \( W_{\text{aver}} \) values is \( 72.89 + 291.89 = 364.78 \mu \text{W} \), and the result for the combined excitation \( W_{\text{aver}} \) is \( 686.85 \mu \text{W} \), giving a difference between the two results of \( (686.85 - 364.78)/364.78 = 149.05\% \).

When the periodic signal is 1.50 Hz, the sum of the separately excited \( W_{\text{aver}} \) values is \( 72.89 + 231.97 = 304.86 \mu \text{W} \), and the result for the combined excitation \( W_{\text{aver}} \) is \( 686.85 \mu \text{W} \), giving a difference between the two results of \( (686.85 - 304.86)/304.86 = 125.30\% \).

When the periodic signal is 1.85 Hz, the sum of the separately excited \( W_{\text{aver}} \) values is \( 72.89 + 366.82 = 439.72 \mu \text{W} \), and the result for the combined excitation \( W_{\text{aver}} \) is \( 800.55 \mu \text{W} \), giving a difference between the two results of \( (800.55 - 409.72)/409.72 = 95.39\% \).

These comparisons show that the amount of power generated using the stochastic resonance generated by the combined excitation approach is on average 100% more than the amount of power generated via separate excitation using the same random and periodic excitation signals.

5. Conclusion

In this study, we have developed a new vibration power generation system that can be applied in random wave environments by combining an electromagnetic induction-type power generator composed of a magnet and a coil with a bistable vibration model. A detailed investigation of the proposed system was conducted, and the following conclusions were obtained.

First, we proposed the equations of motion for the vibration model and analyzed the model theoretically. It was concluded that the proposed vibration system has bistable vibration characteristics over a wide range of amplitudes caused by the mass block, which is the basic condition required to generate the stochastic resonance for the proposed bistable vibration energy harvesting system.

Second, we used Kramer’s rate to propose a prediction equation for the periodic excitation frequency at which the stochastic resonance phenomenon of the proposed bistable vibration system was most likely to occur, and the excitation frequency obtained was confirmed to be in good agreement with the frequency from the actual excitation experiment. Therefore, the most important design problem for the practical application of the proposed bistable vibration system has been resolved.

Third, we developed the bistable vibration energy harvesting system and conducted excitation experiments to simulate a random wave environment. We have confirmed the occurrence of the stochastic resonance phenomenon, in which the response vibration of the mass block definitely changes from a monostable vibration state into a bistable vibration state, and the amplification effect is shown to be quite large on average.

Finally, we measured the actual voltage and average power generated by the oscillator with and without the stochastic resonance and found that the oscillator with stochastic resonance based on the bistable vibration generated more than 100% power on average than an oscillator in which the random and periodic signals were applied separately.

Data Availability

The data that support the findings of the study are available from the author by the e-mail (zhaoxilu@sit.ac.jp) upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest associated with this paper.

Authors’ Contributions

W. Zhao contributed to the study concepts, study design, and manuscript preparation; X. Zang and N. Kawada contributed to the experiment, data acquisition, and manuscript editing; X. Zhao contributed as the guarantor of integrity of the entire study.
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