Research Article

Study on Electrical Parameter Matching of Piezoelectric Stack Periodic Strut for Helicopter Cabin Noise Control

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The gear meshing noise generated by the helicopter main reducer is one of the important sources of noise in the helicopter cabin. By improving the isolation performance of the struts supporting reducer to the gear meshing vibration, the purpose of reducing the gear meshing noise in the helicopter cabin can be achieved. Piezoelectric stack periodic strut (PSPS) composed of piezoelectric stacks and passive materials periodically arranged is an original type of strut with active and passive hybrid isolation characteristics. Piezoelectric stacks and passive materials form a periodic structure, which makes PSPS have a unique stopband characteristic. The propagation of elastic waves in the stopband frequency range is attenuated, which can improve the broadband passive vibration isolation capability of the PSPS; The piezoelectric stacks can adjust the elastic wave propagation in the PSPS and improve the single-frequency or multifrequency active isolation performance of the PSPS. Since the driving voltage and current range of the piezoelectric stacks significantly affect the isolation performance of the PSPS, this article focuses on the relationship between the isolation performance of the PSPS and the voltage and current required by the piezoelectric stacks. Firstly, based on the passive material periodic structure transfer matrix model, the driving voltage and current of the piezoelectric stacks are introduced into the model, and a PSPS electromechanical coupling model based on the transfer matrix form is established. Secondly, the correctness of the model is verified by the finite element software. Based on the model, the design process of PSPS parameters is proposed. The optimal isolation performance of PSPS is predicted under the limitation of maximum driving voltage and current. The effects of damping loss factor, exciting force, period number and passive material on the requirements of electrical parameters for active control are studied. A three-period PSPS strut composed of piezoelectric stack actuator and PV strut is used for experimental research, and the matching of electrical parameters of this PSPS in the test is analyzed.

1. Introduction

A dominant source of noise in a helicopter cabin is the meshing of the main gearbox [1–5]. Figure 1 shows the noise spectrum in the S-76 helicopter cabin [4]. As can be seen from the figure, the harmonic noise generated by the gear meshing is mainly distributed in the frequency of 500–2000Hz, which is the sensitive noise frequency range to human ears. The gear meshing noise of the reducer mainly includes two parts [6]. One part is the noise that is directly transmitted into the air during the gear meshing process; The other part is the structural-borne noise because the gear meshing vibration is transmitted to the body through the connection structure between the main gearbox and the body(such as the gearbox strut), which causes the vibration of the fuselage structure. The main object of noise reduction in this study is the structural-borne noise, which can be controlled by the isolation design of the gearbox strut.

Szefi [7] and Asiri [8] et al. first proposed to apply the gearbox strut with a periodic structure to reducing helicopter cabin noise. Whether an active periodic structure or a passive periodic structure, they are all connected by the same substructure or cell in the same way [9]. Due to the unique
The main content of this paper includes the following parts. In chapter 2, based on the piezoelectric constitutive equation and the differential equation of the strut vibration, the electromechanical coupling dynamic model of PSPS is established in the form of the transfer matrix. In chapter 3, the geometric parameters of the PSPS are designed based on the EH101 helicopter main reducer strut. The force transmissibility rate is simulated by the electromechanical coupling dynamic model of the PSPS firstly, through which the optimal vibration isolation performance of the PSPS can be estimated when the active and passive hybrid vibration isolation control is performed. Secondly, to guide the design of the electrical parameter matching of the active structure or the active and passive structure, this study analyzes the influence of the excitation force, the damping loss factor, and periodic number on the voltage and current of the piezoelectric material required for the active control.

To deeply study the relationship between the driving voltage and current required by the piezoelectric stacks and the isolation performance of the PSPS when the active control is applied, in this paper, a simplified active and passive hybrid vibration isolation control system model piezoelectric stack periodic strut(PSPS) is proposed, that is, the smart strut with a periodic arrangement of piezoelectric stacks and passive materials, as shown in Figure 2. For PSPS, the periodic arrangement of the piezoelectric stacks and the passive materials makes the strut have the unique mechanical filtering characteristics of the periodic structure; at the same time, by controlling the voltages of the piezoelectric stacks to change the dynamic stiffness of the piezoelectric material, the strut can effectively suppress the disturbing vibration.

When the material, structure, boundary conditions, driving voltage, and current range of the piezoelectric stacks are determined, it is also determined that the optimal isolation performance. The optimization of all active vibration control algorithms is only to approach the optimal isolation performance infinitely, and can not change the optimal isolation performance. However, the existing research literature on active vibration isolation control applied to the struts of helicopter main reducer mostly focuses on active control algorithm innovation [12–15], and does not discuss the effect of piezoelectric driving voltage and current range on isolation performance, in which the designs of the active structures have the problem of electrical parameter matching. In the active control experiments [12–15], by imposing a tiny excitation force load, there is no insufficient electric power in these experiments, and the active control can also obtain obvious vibration attenuation. However, in practical engineering applications, the active control structure is subject to a large boundary load, and insufficient electric power of the piezoelectric material will make a fatal mistake in electrical matching so that the active control cannot achieve a significant vibration isolation effect. Therefore, it is necessary to evaluate the optimal vibration isolation performance of active vibration isolation structures based on electrical parameters. This article focuses on this problem. To this end, it is necessary to establish the electromechanical coupling dynamic model of the PSPS firstly, through which the optimal vibration isolation performance of the PSPS can be estimated when the active and passive hybrid vibration isolation control is performed. Secondly, to guide the design of the electrical parameter matching of the active structure or the active and passive structure, this study analyzes the influence of the excitation force, the damping loss factor, and periodic number on the voltage and current of the piezoelectric material required for the active control.
coupling dynamic model, and the simulation result is compared with the finite element software COMSOL Multiphysics to verify the correctness of the model. Chapter 4 presents the design process of the PSPS. The optimal vibration isolation performance of the PSPS is estimated, and the influence of the important parameters of the PSPS on the driving current and voltage of the piezoelectric stacks under active control is analyzed. In chapter 5, the active and passive hybrid control capability and electrical parameter matching of the PSPS are verified by experiments.

2. Electromechanical Coupling Dynamic Model of the PSPS in Transfer Matrix Form

To establish the PSPS electromechanical coupling dynamic model in transfer matrix form, this chapter establishes the transfer matrix dynamic model of a one-dimensional passive strut and an electromechanical coupling dynamic model of piezoelectric stack actuator in the form of the transfer matrix. Based on the passive strut model and piezoelectric stack actuator model, the electromechanical coupling dynamic model of PSPS is derived in transfer matrix form.

2.1. Transfer Matrix Dynamic Model of the One-Dimensional Passive Strut. The transfer matrix dynamic model of the passive strut is determined only by the dynamic properties of the system itself, regardless of the structures and excitations at both ends of the system. Therefore, the transfer matrix form is particularly suitable for application in the analysis of the dynamic of the system with several substructures. For a linear elastic strut, if there is only one input and one output end, the transfer matrix dynamic model is shown in Figure 3.

In the frequency domain, the longitudinal transfer relation between the input end and the output end of the strut is

\[
\begin{bmatrix}
F_1 \\
V_1
\end{bmatrix} = T_p
\begin{bmatrix}
F_2 \\
V_2
\end{bmatrix}
\]

\[
= \begin{bmatrix}
\cos(kL) & \frac{E A k}{j \omega} \sin(kL) \\
\frac{j \omega}{E A k} \sin(kL) & \cos(kL)
\end{bmatrix}
\begin{bmatrix}
F_2 \\
V_2
\end{bmatrix}
\]  

(1)

In the formula, the input \( F_1, V_1 \) and the output \( F_2, V_2 \) are all complex amplitude with amplitude and phase information. \( k \) is the longitudinal wavenumber and \( k = \omega \sqrt{\rho / E} \), \( \rho \) and \( E \) are the mass density and Young’s elastic modulus of the material respectively, the length of the strut is \( L \), and the cross-sectional area is \( A \). It can be seen from the formula that according to Young’s modulus \( E \) of the material, the wavenumber \( k \), and the geometric parameters of the structure, the transfer matrix \( T_p \) of the strut can be obtained. Then according to the boundary conditions of the system (the velocity at the fixed end is \( 0 m/s \); the force at the free end is \( 0 N \) ), the response of the system can be solved without solving the differential equations of motion.

2.2. Electromechanical Coupling Dynamic Model of Piezoelectric Stack Actuator in Transfer Matrix Form. Compared with the piezoelectric plate, the piezoelectric stack actuator has a larger displacement along the electric field direction (in the d33 mode), the piezoelectric stack actuator is more widely used in practice. The piezoelectric stack actuator can be regarded as composed of multiple piezoelectric plates connected in series on the mechanical structure and in parallel on the electrical circuit, as shown in Figure 4.

For the electromechanical coupling dynamic model of piezoelectric material, the most widely used model is Mason’s equivalent circuit [16], but this model can only be used for modeling the single-layer piezoelectric plate. To obtain the whole piezoelectric stack actuator, it is necessary to multiply the model of the piezoelectric plate in Mason’s equivalent circuit, which requires a lot of calculation. To reduce the amount of calculation, this paper refers to Zhang’s piezoelectric stack actuator model [17–19] and establishes a dynamic piezoelectric stack actuator model in the form of a transfer matrix that is applied to the PSPS with multiple piezoelectric stack actuators.

First of all, the electromechanical coupling dynamic model of the piezoelectric stack actuator is established. The physical model is shown in Figure 5. The piezoelectric stack actuator in the figure consists of \( n \) layers of piezoelectric plates connected in series.

In Figure 5, the subscript ‘in’ represents the input end of the piezoelectric stack actuator, and the subscript ‘out’ represents the output end of the piezoelectric stack actuator. \( f_{in} \) and \( v_{in} \) are the force and velocity at the input end respectively; \( f_{out} \) and \( v_{out} \) are the force and velocity at the output end respectively; \( u \) and \( i \) are the driving voltage and current of the piezoelectric stack respectively. According to the piezoelectric constitutive equation, the longitudinal vibration differential equation of the strut, and the assumption that the electric field in each layer of the piezoelectric plates in the actuator is uniformly distributed, the current, normal velocity, and normal force of the piezoelectric stack actuator can be deduced as follows [17–19]:

\[
i(t) = A \left( e^{V_{out} - V_{in}} \frac{\alpha}{f_p} \frac{\partial u(t)}{\partial t} \right),
\]

(2)

\[
v(x, t) = i \omega (a_1 \sin(kx(t)) + a_4 \cos(kx(t))),
\]

(3)
\[ f(x, t) = A \left[ c' \left( a_1 k \cos(kx) - a_2 k \sin(kx) \right) e^{j \omega t} - e^{j \omega t} \right], \]

where \( v \) is the normal velocity; \( t_p \) is the thickness of the piezoelectric layer; \( n \) is the number of piezoelectric plates in the piezoelectric stack actuator; \( \epsilon' \) represents the dielectric constant under zero strain; \( a \) is the wavenumber of the piezoelectric stack; \( a_1 \) and \( a_2 \) are the two constants; \( c' \) is the elastic modulus of the piezoelectric material in the short circuit; \( e' \) is the ratio of the strain to the electric displacement in the short circuit. The velocities at both ends of the piezoelectric stack actuator are defined as \( v_{in} = V_{in}e^{j \omega t} \) and \( v_{out} = V_{out}e^{j \omega t} \); The normal forces at both ends are defined as \( f_{in} = F_{in}e^{j \omega t} \) and \( f_{out} = F_{out}e^{j \omega t} \); The current and voltage are defined as \( i(t) = I e^{j \omega t} \) and \( u(t) = U e^{j \omega t} \). Put the above equations into the current equation (2), normal velocity equation (3), and normal force equation (4), and turn them into matrix form in the frequency domain:

\[
\begin{bmatrix}
F_{in} \\
F_{out} \\
U \\
V_{in} \\
V_{out} \\
I
\end{bmatrix} =
\begin{bmatrix}
A \left( \frac{e'^2}{j \omega \epsilon' t_p} + \frac{c' a}{\tan(aL)} \right) & -A \left( \frac{e'^2}{j \omega \epsilon' t_p} + \frac{c' a}{\sin(aL)} \right) & \frac{e'}{j \omega \epsilon'} \\
A \left( \frac{e'^2}{j \omega \epsilon' t_p} + \frac{c' a}{\sin(aL)} \right) & -A \left( \frac{e'^2}{j \omega \epsilon' t_p} + \frac{c' a}{\tan(aL)} \right) & \frac{e'}{j \omega \epsilon'} \\
\frac{e'}{j \omega \epsilon'} & -\frac{e'}{j \omega \epsilon'} & t_p \\
\frac{e'}{j \omega \epsilon'} & -\frac{e'}{j \omega \epsilon'} & t_p \\
V_{in} & V_{out} & I
\end{bmatrix}.
\]

It can be seen from the above equation that there is a coupling relation between the mechanical parameters (force, velocity) on both ends of the piezoelectric stack actuator and the electrical parameters (voltage, current) of the piezoelectric stack actuator. Modify the above equation to the following matrix form:
\[
\begin{bmatrix}
F_{\text{out}} \\
V_{\text{out}} \\
U \\
I
\end{bmatrix}
= T_a
\begin{bmatrix}
F_{\text{in}} \\
V_{\text{in}} \\
U \\
0
\end{bmatrix},
\]
(6)

where, a particular solution of \( T_a \) is \( T_{ad} \):

\[
T_{ad} = \begin{bmatrix}
\cos(aL) & -Ac' \sin(aL) & Ae' (\cos(aL) - 1) & 0 \\
\sin(aL)j\omega & \cos(aL) & e'j\omega \sin(aL) & 0 \\
0 & 0 & 1 & 0 \\
e'j\omega \sin(aL) & Ae' (\cos(aL) - 1) & j\omega A \left( n \frac{e'}{t_p} + \frac{e'^2 \sin(aL)}{t_p c' a} \right) & 1
\end{bmatrix}.
\]
(7)

The matrix \( T_a \) is a piezoelectric stack electromechanical coupling matrix. Since formula (6) is equivalent to formulas (2)–(4), the electromechanical coupling dynamic problem of the piezoelectric stack can be solved by determining only three parameters of mechanical boundary conditions (velocity and force) and electrical boundary conditions (driving voltage and current of the piezoelectric stacks). Since formula (6) is derived from three equations (2)–(4), there are infinite solutions for \( T_a \). For the convenience of description, the particular solution \( T_{ad} \) is used to represent the electromechanical coupling matrix of the piezoelectric stack.

The electromechanical coupling dynamic model in this paper is derived from the constitutive equation of piezoelectric material and the vibration equation of the strut, which is independent of the control method. Therefore, this model can be applied not only to active control [12–15], but also to semiactive control like the shunt circuit [20–23].

When no driving signal is applied, the model is a passive model of piezoelectric stack.

2.3. Electromechanical Coupling Dynamic Model of PSPS in Transfer Matrix Form. Figure 6 is the electromechanical coupling dynamic model of PSPS with \( m \) periods, and the driving voltage and current of each piezoelectric stack are independent respectively. In order to express the electromechanical coupling dynamic model of PSPS by using the transfer matrix of passive material and the electromechanical coupling transfer matrix of the piezoelectric stack, the model of passive material and piezoelectric stack need to be rewritten.

According to the principle that passive materials do not affect the voltage and current of the piezoelectric stack, the transfer matrices of all passive materials \( T_p \) Figure 6 can be modified as \( T_{pd} \):

\[
T_{pd} = \begin{bmatrix}
\cos(kL) & -Ac'k\sin(kL) & 0 & \cdots & 0 \\
\sin(kL)j\omega & \cos(kL) & 0 & \cdots & 0 \\
0 & 0 & 1 & \cdots & 0 \\
\vdots & \ddots & 0 & \ddots & 0 \\
0 & \cdots & \cdots & \cdots & 0 & 1
\end{bmatrix}.
\]
(8)

\[ (2m+2)\times(2m+2) \]
Since the $i$th piezoelectric stack does not affect the voltage and current of the other $m-1$ piezoelectric stack, the expression $T_{ad}^i$ can be written according to (7). For example, the first piezoelectric stack transfer matrix $T_{ad}^1$ and the $m$th piezoelectric stack transfer matrix $T_{ad}^m$ can be expressed as:

$$T_{ad}^1 = \begin{bmatrix}
\cos(aL) & -A'e \sin(aL) / i\omega & -A'e (\cos(aL) - 1) / t_p & 0 & \cdots & 0 \\
\sin(aL)i\omega / Ac'k & \cos(aL) & -\epsilon i\omega \sin(aL) / t_p c' a & 0 & \ddots & 0 \\
0 & 0 & 1 & 0 & \ddots & \cdots & 0 \\
\epsilon i\omega \sin(aL) / t_p c' a & A'e (\cos(aL) - 1) / t_p & -i\omega A \left( n e' / t_p + e'^2 \sin(aL) / t_p c' a \right) & 1 & \ddots & \cdots & 0 \\
0 & 0 & \ddots & \ddots & \ddots & \ddots & 0
\end{bmatrix}_{(2m+2)\times(2m+2)}$$

$$T_{ad}^m = \begin{bmatrix}
\cos(aL) & -A'e \sin(aL) / i\omega & 0 & \cdots & 0 & A'e (\cos(aL) - 1) / t_p & 0 \\
\sin(aL)i\omega / Ac'k & \cos(aL) & 0 & \cdots & 0 & \epsilon i\omega \sin(aL) / t_p c' a & 0 \\
0 & 0 & 1 & \ddots & 0 & 0 & 0 \\
\epsilon i\omega \sin(aL) / t_p c' a & A'e (\cos(aL) - 1) / t_p & 0 & \cdots & 0 & i\omega A \left( n e' / t_p + e'^2 \sin(aL) / t_p c' a \right) & 1 \\
0 & 0 & \ddots & \ddots & \ddots & \ddots & \cdots & 0
\end{bmatrix}_{(2m+2)\times(2m+2)}$$

Figure 6: Electromechanical coupling model of PSPS.
The electromechanical coupling transfer matrix relation of the PSPS in Figure 6 is as follows:

\[
\begin{bmatrix}
F_0 \\
V_0 \\
U_1 \\
0 \\
U_2 \\
0 \\
\vdots \\
U_{2m} \\
0
\end{bmatrix}
= T_{psps}
\begin{bmatrix}
F_{2m} \\
V_{2m} \\
U_1 \\
I_1 \\
U_2 \\
I_2 \\
\vdots \\
U_{2m} \\
I_{2m}
\end{bmatrix},
\]

where the electromechanical coupling transfer matrix of PSPS with \( m \) periods is

\[
T_{psps} = \prod_{i=1}^{m} (T_{ad} \ast T_{pd}),
\]

4. Design Process and Simulation Analysis of PSPS

In this section, according to the PSPS model, the design process of PSPS parameters is given. In order to evaluate the optimal active and passive hybrid vibration isolation performance of PSPS and guide the parameters adjustment in the design process, the PSPS in Figure 7 is taken as the object to study these two problems. However, due to a large number of parameters in the model, it is impossible to comprehensively study the interaction between parameters. To observe the influence of main parameters, it is mainly studied that the influences of passive material damping, excitation force and cell number of the PSPS on active control voltage and current when the driving voltage of each piezoelectric stack actuator is identical. In addition, when the driving voltage of the piezoelectric stack actuator is independent, the optimal force transmissibility of the PSPS is obtained by nonlinear optimization, which takes the range of the driving voltages and currents as the constraint conditions.

4.1. Parameter Design Process of PSPS. According to the electromechanical coupling dynamic model of PSPS in the form of transfer matrix established in this paper, passive materials and piezoelectric materials, the geometry parameters of PSPS, the driving capacity of the piezoelectric stack, and the boundary conditions of PSPS are all important factors affecting the vibration isolation performance of PSPS. In addition to satisfying the vibration isolation performance, the strength and stiffness requirements of the helicopter reducer strut should also be met. Therefore, the design method of PSPS is given, as shown in Figure 9.

In the parameter design process of PSPS, the driving capacity and boundary conditions of the piezoelectric actuator can be measured, and the strength and stiffness of PSPS can be verified by the finite element method. Therefore, the Parameter adjustment method of PSPS and the evaluation of the active and passive hybrid vibration isolation performance are the research focuses in this section. For these two problems, the optimal vibration isolation performance is estimated, and the influence of the main passive parameters on the driving voltage and current of the piezoelectric stack is analyzed. In this section, PSPS in Figure 7 is taken as the object to study the influence of parameters.

4.2. Optimal Vibration Isolation Performance of PSPS. In order to compare the optimal vibration isolation performance, the band structure of the PSPS (the damping loss factor of rubber material is set as 0.05) and its passive vibration isolation performance (Since the band diagram and force transmissibility of PSPS are almost the same in the short-circuit and open-circuit condition, only the band diagram and force transmissibility in short-circuit condition are given here) are shown in Figure 10.

The yellow area in Figure 10(a) corresponds to the bandgap of the PSPS. As can be seen from Figure 10(b),
vibration propagation in the bandgap frequency range is attenuated obviously.

When the amplitude of excitation force is 100 N, the maximum driving voltage amplitude of the piezoelectric stack actuator is 200 V, and the maximum driving current is 10 A (the values of the maximum driving voltage and current will vary with the frequency, and the actual values need to be measured). Taking the minimum force transmissibility rate as the optimization objective, the maximum driving voltage and current are the constraint conditions, the driving voltages and currents of four piezoelectric stack actuators as the optimization variables, the MATLAB optimization toolbox is used to solve the optimization problem, and the nonlinear optimization problem could be expressed as:

$$\min_{T_F(U_1, U_2, U_3, U_4, I_1, I_2, I_3, I_4)}$$

subject to

$$0 \leq \text{abs}(U_i) \leq 200, \quad i = 1, 2, 3, 4,$$

$$0 \leq \text{abs}(I_i) \leq 10, \quad i = 1, 2, 3, 4.$$

After nonlinear optimization, the minimum force transmissibility is obtained, and the minimum force transmissibility rate of the PSPS is shown in Figure 11. As can be seen from Figure 11(a), when the frequency of excitation force is greater than 237 Hz, the force transmissibility can be attenuated to −150 dB. In fact, the active vibration control can attenuate the reaction force to 0 N, the small force transmissibility in the figure is due to the tiny numerical error remaining in the optimization calculation. Of course, in practical application, due to the existence of various interference factors, active control is difficult to attenuate the reaction force to 0 N. Figure 11(b) is the low-frequency part of Figure 11(a). It can be seen that, within the range of 120 – 220 Hz, the force transmissibility can be further reduced by 1 – 3 dB, and the limited low-frequency control ability can be realized within this frequency range.

However, below 50 Hz, the minimum force transmissibility rate and the force transmissibility rate of piezoelectric stacks in short-circuited (passive mode) are almost unchanged. To study the reasons for limiting the optimal vibration isolation capacity of PSPS, it is necessary to check the driving voltages and currents of PSPS, as shown in Figure 12.

As can be seen from Figure 12, the driving voltages of the four piezoelectric stacks all reach their maximum values when below 236 Hz. In the meanwhile, the following reaction forces blow 236 Hz cannot be attenuated to 0 N in Figure 11, which indicates that the upper limit of the driving voltage limits the vibration isolation performance of PSPS at the frequency below 236 Hz. In the frequency range above 237 Hz, the driving voltage and current of the four piezoelectric stacks do not reach the maximum value at the same time. In theory, PSPS can attenuate the reaction force to 0 N. This result is also shown in Figure 11. It can also be seen from Figure 12 that when PSPS obtain the optimal vibration isolation effect below 236 Hz, the driving voltage of the piezoelectric stack required for active control reaches the upper limit, while the driving current does not. Therefore, it is the upper limit of the driving voltage, not the current, that limits the vibration isolation performance of PSPS.

In the study of literature [14], three piezoelectric stacks were used in parallel with the main reducer struts to isolate the vibration of the first rotor passing frequency (19.8 Hz). The problem of electrical parameter matching of the active structure was not considered in the study, and the optimal
vibration isolation performance of the active structure was not estimated. In fact, the driving voltage and current of the piezoelectric stacks can hardly meet the power requirement in the low frequency. It should be noted that the optimal force transmissibility in Figure 11 is obtained without considering the control error and noise interference. Figure 13 shows the force transmissibility with the control voltage error taken into account.
Figure 11: Minimum force transmissibility of PPS by optimizing the voltages and currents. (a) Minimum force transmissibility of PPS within 1500 Hz. (b) Minimum force transmissibility of PPS within 220 Hz.

Figure 12: Continued.
The vibration isolation performance with control error in Figure 13 is not as dramatic as that in Figure 11 under the ideal driving signal. In general, the vibration isolation performance becomes worse with the increase of control error.

4.3. Influence of Main Design Parameters of PSPS on Driving Voltage and Current Required for Piezoelectric Stacks

4.3.1. Influence of Passive Material Damping Loss Factor on Driving Voltage and Current Required for Piezoelectric Stacks. In a periodic structure, the damping loss factor of material has a great influence on the vibration isolation performance of the structure. To study the effect of the damping loss factor in the PSPS on the driving voltage and current required for active control, the following simulation analysis is performed. In the PSPS and boundary conditions in Figure 7, the excitation force amplitude is set to 20N, and the reaction force value is 0N, which means that the vibration is fully attenuated. The rubber damping loss factor is set to 0, 0.05, 0.15, respectively. The voltages and currents required for active control in these conditions are obtained in Figure 14. In the meanwhile, Figure 15 shows the force transmissibility rate of PSPS with different damping loss factors under passive control (piezoelectric stacks are short-circuited).

As can be seen from Figures 14 and 15, as the damping loss factor of rubber increases, the piezoelectric stack actuators in active control mode need less voltage and current to reduce the reaction force to 0 in Figure 14. When the damping loss factor increases, the force transmissibility of the periodic structure will decrease in Figure 15 so that the voltages and currents required for active control will decrease too. On the other hand, although the loss factor increases and the resonance peak of vibration decreases, the value of voltage and current required by the piezoelectric stack actuators below 250Hz are still very high. In this example, when the vibration in 150Hz is controlled, the voltage signal required under active control can be reached
to $10^4$ V, while the current signal is exceeded 200A. Such a driving power is difficult to achieve in practical application. Therefore, the application of piezoelectric materials in low-frequency vibration control is limited by the driving power.

The range of feasible and infeasible zones are determined by the performance of actuators and piezoelectric materials in engineering applications. Here, it is assumed that the maximum driving voltage is 1000V, and the maximum driving current is 100A; then, the feasible and infeasible zones are shown in Figure 14.

According to the force transmissibility in Figure 15 and the required voltage and current in Figure 14, it can be seen that the peak frequencies of voltage and current required for active control are not completely consistent with those of force transmissibility. Therefore, when designing the vibration isolation structure with active and passive hybrid vibration control, in order to obtain a better vibration isolation effect, not only the resonant frequency of the structure should be far away from the frequency of excitation force for a smaller vibration response but the maximum driving voltage and current frequency of active control also should be far away from the frequency of excitation force for less power required in active control. In other words, when designing the structure of active and passive hybrid vibration control, it is necessary to consider not only the structural dynamic characteristics but also the influence of the piezoelectric driving power on the vibration isolation ability.

4.3.2. Influence of Excitation Force on Driving Voltage and Current Required for Piezoelectric Stacks. This section discusses the influence of harmonic excitation force on the voltage and current required for active control in PSPS. In the model and boundary conditions in Figure 7, the amplitude of the excitation force is set as 1N, 10N, 100N respectively, the damping loss factor of rubber is 0.05, and the voltage and current required to attenuate the reaction force to 0N are calculated. It is shown in Figure 16 that the the required voltage and current for active control in the conditions of different harmonic excitation forces.

It can be seen from Figure 16 that, the voltage and current required for active control increase exponentially as the excitation force increases exponentially. In the stopband of the PSPS, the active control only requires a very small voltage and current because the reaction force has been greatly attenuated. From the general trend, the lower the controlled frequency, the greater the voltage and current required for active control. When there is a design requirement for active control in low frequency, the boundary

![Figure 14: Voltages and currents of PSPS with different damping loss factors, (a) Required voltages of the piezoelectric stacks under active, (b) Required currents of the piezoelectric stacks under active control.](image)

![Figure 15: Force transmissibility of PSPS with different damping loss factors under short-circuit.](image)
conditions such as excitation force should be considered in the structure design process. Otherwise, the piezoelectric stack actuator and its driving equipment may not be able to meet the huge voltage and current requirements for active control.

From the perspective of the relationship between the vibration isolation potential of the active structure and the excitation force, it can also be deduced that: when evaluating the effect of active control, the ratio of the force or acceleration under active control and no active control cannot fully represent the isolation effect of active control. It is necessary to supplement the mechanical boundary conditions (such as the excitation force), or to compare the real values of force or acceleration after and before the active control. For example, if the steady-state error of reaction force in a control system is 0.01 N, that is, it is assumed that the active control algorithm cannot attenuate this part of the signal by continuing adjusting in any way. When the reaction force is 10 N without the active control, after vibration isolation of the PSPS or other active control structures, the reaction force can only attenuate to 1 N because of the limitation of the active structure control ability, then the attenuation rate of the force is 20 dB. But when the excitation force is lowered to make the reaction force be 1 N without the active control, using the same active control structure and algorithm, the active control system has enough potential to make the reaction force close to the steady-state error 0.01 N, and the force attenuation rate obtained will be close to 40 dB. That is to say, when the force boundary is changed, the vibration reduction effect of the same active control system is evaluated differently by the attenuation rate. Especially when the value of the excitation force is the upper limit of the excitation force that can be controlled by the active structure totally, and the steady-state error is small enough, the active vibration control effect evaluated by the force attenuation rate will reach the maximum.

4.3.3. Influence of Periodic Number on Driving Voltage and Current Required for Piezoelectric Stacks. In a periodic structure, the cell number of a periodic structure determines the stopband attenuation rate of a periodic structure. To study the effect of the cell number on the voltage and current of the piezoelectric stacks under active control, the boundary condition in Figure 7 (one end is fixed and the other end is excited) is used. The cell number of the PSPS is selected as 2, 4, 10, respectively, and the damping loss factor of rubber material is 0.05. The amplitude of excitation force is 20 N, and the voltage and current required for active control are calculated when the reaction force is attenuated to 0 N. Figure 17 shows the voltage and current required by piezoelectric stack actuators with different periodic numbers. Figure 18 shows the force transmissibility rate of PSPS with the different periodic numbers.

As can be seen from Figure 17 and 18, within the stopband range, the greater the periodic number, the smaller the voltage and current required for active control of the piezoelectric stack actuators. On the one hand, the greater the periodic number, the greater the attenuation, and the smaller the reaction force within the stopband range; On the other hand, increasing the periodic number also increases the number of the piezoelectric plates, to achieve the same vibration reduction effect, only requires a smaller driving signal. However, in practical application, the total length of the PSPS is limited, so it is necessary to design the periodic number of the PSPS reasonably according to the actual situation.
4.3.4. Influence of Passive Materials on Driving Voltage and Current Required for Piezoelectric Stacks.

The passive materials that make up the periodic structure have a great influence on transmissibility. In this section, the influence of passive materials on the driving voltage and current during active control is studied. It is assumed that the passive materials of PSPS in Figure 7 are rubber, aluminum, and steel respectively, and the material parameters of aluminum and steel are given in Table 3. The amplitude of excitation force is 20 N, and the damping loss factor of rubber material is 0.05. When the amplitude of reaction force is attenuated to 0 N, the voltage and current required for active control are calculated. The results are shown in Figures 19 and 20 is the force transmissibility rates of PSPS composed of three passive materials under passive control.

As can be seen from Figures 19 and 20, when active control is carried out below 300 Hz, the PSPS with passive materials of steel or aluminum has the lower requirements on the driving ability of piezoelectric stack actuators, and can easily meet the output power requirements for active control. In the second and third stopband range of the periodic structure composed of the piezoelectric stack actuators and rubber material, the driving voltage and current required by the PSPS with rubber are lower than those required by the PSPS with aluminum or steel, which is due to the periodic structure composed of piezoelectric stack and rubber produces a bandgap in this frequency range. In general, PSPS with different passive material has different vibration responses, which affect the driving voltage and current required for active control of piezoelectric stacks. The PSPS made of rubber as the passive material has the bandgap effect, but also has the vibration response peaks. Therefore, compared with the steel and aluminum PSPS without a bandgap, the driving signal for active control is smaller in the bandgap range, but a larger driving signal is required in the peak range of the PSPS with rubber.

Based on the above analysis, it can be seen that if only single or multiple frequency active vibration control is required, it is more suitable to use steel or aluminum as passive materials. If only broadband control is required, rubber is selected as a passive material to form a periodic structure with broadband vibration reduction capability. If multiple frequencies and broadband vibration control are needed, it is recommended to use steel or aluminum.
carried out at the same time, it is necessary to make a reasonable compromise in the selection of passive materials. Therefore, there is a tradeoff problem in the design of PSPS. The tradeoff problem can be analyzed by using the method of calculating the optimal vibration isolation performance in this paper. For example, when the maximum driving voltage amplitude is 20V and the maximum current amplitude is 5A, the optimal force transmissibility curves for the three PSPSs with different passive materials are as shown in Figure 21.

Figure 21 clearly shows the vibration isolation frequency range and ability of the three PSPSs when applying active control, so as to solve the tradeoff problem between the active and passive control. The solution to the tradeoff problem of active and passive control potential can effectively guide the design of PSPS and other active vibration isolation systems using piezoelectric materials.

5. Experimental Study

The PSPS is used to carry out active and passive hybrid vibration control in this experiment, and the control effect of the active and passive hybrid vibration and the electrical parameters matching are studied. However, due to the limitation of test conditions, the proposed PSPS adapted to helicopter conditions was not used in the experimental study, but the three-period PSPS composed of piezoelectric...
stack actuators and PV strut were used as a simplified PSPS for the study.

5.1. Experiment Setup. In the experiment, the piezoelectric stack actuator and the PV strut are arranged periodically to form a three-period PSPS. The piezoelectric stack actuator and the PV strut are shown in the Figure 22.

The experiment set-up and schematic diagram of the set-up are as shown in Figures 23 and 24.

As can be seen from Figure 23 and Figure 24, the PSPS specimen is suspended by several thin wires and kept in a horizontal state. The vibrator is excited longitudinally along the PSPS specimen and the an impedance head and an acceleration sensor are used to measure the acceleration at the left and right ends of the specimen. Three piezoelectric stack actuators are excited by the same shaker channel so that the driving voltages of the three piezoelectric stacks are consistent. The driving voltage and total driving current of the three piezoelectric stacks are measured by the voltage probe and current probe. The controller DSP6747 takes the acceleration signal on the right side as the target signal and uses ASAC frequency domain control algorithm to drive three piezoelectric stacks for active control. The control flow of ASAC is shown in Figure 25.

In Figure 25, where $Z_0$ is the complex response amplitude of the right acceleration caused by the shaker when no control is applied to the piezoelectric stack, $Z$ is the complex response amplitude when active control is applied to the piezoelectric stack, $\theta$ is the complex control amplitude of the voltage input to the piezoelectric stack, and $T$ is the frequency response matrix of the control channel. More detailed information on ASAC is available in the literature [24].

5.2. Experiment Results and Analysis

5.2.1. Active and Passive Hybrid Vibration Control Effect. White noise and harmonic excitation of 100Hz were applied to the shaker. After 5s, ASAC was applied to suppress the harmonic excitation of 100Hz. The time-domain diagram of the acceleration signal on the right side before and after the ASAC control and the frequency domain diagram of the acceleration transmissibility are shown in Figure 26.

As can be seen from the time-domain diagram of acceleration at the right end of Figure 26(a), the active control is applied after 5s, and the active control is in a stable state at 20s. As can be seen from Figure 26(b), the acceleration transmissibility of active and passive hybrid vibration control can attenuate to below −20dB at 100Hz. In other frequency ranges, the acceleration transmissibility of hybrid vibration control is almost exactly the same as that of passive control, and also has the bandgap characteristics of periodic structure.

Although the above experiment can reflect the hybrid vibration control effect, in order to study the electrical parameters matching problem, it is necessary to obtain the vibration isolation performance, driving voltage and current at different frequencies.

5.2.2. Electrical Parameter Matching in the PSPS. When studying the electrical parameter matching problem, it is necessary to ensure that the mechanical boundaries of active control at different frequencies remain consistent after stability and the left end acceleration is adjusted to 0.5m/s² in this experiment. The experiment process is shown in Figure 27:

In Figure 27, the above process can ensure that the left acceleration is 0.5m/s² after active control is stabilized. According to the ASAC active control algorithm mentioned above, active control in frequency domain is performed at 600 Hz, 700 Hz, 725 Hz, 750 Hz, 775 Hz, 800 Hz, 900 Hz, 1000 Hz, 1100 Hz, 1200 Hz, 1300 Hz, 1400 Hz, 1500 Hz, and 1600 Hz, respectively. And the acceleration transmissibility on these frequencies are as shown in Figure 28.

As can be seen from Figure 28, the acceleration transmissibility of the PSPS with active control (active in Figure 28) can continue to go down on the basis of the passive curve (passive in Figure 28). However, active control has
**Figure 23:** Experiment setup.

**Figure 24:** Schematic diagram of the setup.

**Figure 25:** ASAC control flow chart.
almost no attenuation effect at 600 Hz and 700 Hz, which is because the left acceleration of the specimen is 0.5 m/s² and the piezoelectric stack driver cannot provide sufficient driving voltage and current for active control. The passive transmissibility calculated theoretically (passive in theory in Figure 28) is almost consistent with the measured passive transmissibility (passive in Figure 28) below 1500 Hz. Based on the theoretical model, the influence of active control error on vibration isolation performance is analyzed. The active + 1% error and active + 10% error in the figure are the acceleration transmissibility when the driving voltage amplitudes are 1% and 10% less than the optimal voltage amplitude and driving voltage phases are 1% and 10% less than the optimal voltage phase, respectively. It can be seen from the figure that the acceleration with 10% control error is close to the measured result. However, at 1500 Hz and
1600 Hz, there is a large error between the simulation results and the measured results, mainly because the electromechanical coupling dynamic model in this paper only considers the longitudinal vibration, but does not consider the transverse deformation and bending torsion. At high frequencies, the transverse deformation mode and bending torsion mode are obvious, and the assumption that the adjacent piezoelectric plates in the piezoelectric stack are parallel to each other is no longer satisfied.

Then the driving voltage and current under active control are compared with the theoretical optimal driving voltage and current (Figure 29).

As can be seen from Figure 29, although there is a gap between the actual driving voltage and current obtained by the ASAC algorithm and the theoretical optimal driving voltage and current due to the existence of errors and interference, the variation trend of actual voltage and current is similar to that of theoretical optimal voltage and current. The driving voltage and current in actual control do not simultaneously exceed the theoretical optimal driving voltage and current. The driving voltage at 700 Hz exceeds the optimal driving voltage, but the driving current does not exceed the optimal driving current. The analysis of driving voltage and current also shows the correctness of electromechanical coupling dynamic model of PSPS and the electrical parameters matching phenomenon in the PSPS.

6. Conclusions

Based on the research background that the strut supporting the reducer suppress the gear meshing noise in the helicopter cabin, aiming at the needs of broadband vibration control and multifrequency harmonic isolation control, a PSPS suitable for active and passive hybrid vibration control is proposed, and an electromechanical coupling model in the form of transfer matrix is established. Because this model is determined by all the parameters of PSPS struts including material, geometric dimensions, mechanical boundaries (force and velocity) and electrical boundaries (current and voltage), the electrical parameter matching problem can be studied using this model, and experimental studies have been carried out. The conclusions of the research on electrical parameter matching for PSPS mainly include the following three parts:

1. When the range of driving voltage and driving current are determined, the optimal vibration isolation performance can be obtained by using the proposed PSPS model. Because of the interference noise in the control system, the optimization of active control algorithm can only make the vibration isolation effect infinitely close to the optimal vibration isolation performance, but cannot change the optimal vibration isolation performance. Improving the driving ability for piezoelectric material in the vibration isolation system, especially the range of driving voltage, can enhance the vibration isolation ability of the vibration isolation system.

2. When the damping factor of the passive material increases and the cell number of PSPS increases, the driving voltage and current required for active control will decrease because the attenuation rate of the PSPS in passive mode increases. As the excitation force increases, the driving voltage and current required for active control of PSPS also increase. When selecting passive materials in the PSPS, there is a tradeoff effect between passive control and active control, which can be solved by the electromechanical coupling dynamic model of the PSPS to get the optimal vibration isolation capacity.

3. Three-period PSPS composed of piezoelectric stack actuators and polyester struts were used as a simplified model for experimental study. The active and passive hybrid vibration control performance of
PSPS and the driving voltage and current under active control are obtained, and the electrical parameter matching problem in the simplified PSPS is verified and analyzed by using the electromechanical coupling dynamic model of PSPS proposed in this paper.

The problem of electrical parameter matching not only exists in PSPS, but also in the research of vibration isolation control using piezoelectric materials. In this paper, the electrical parameter matching problem in PSPS is studied, which not only advances the engineering application of the helicopter gearbox strut, but also advances the vibration isolation scheme using piezoelectric materials towards the direction of engineering application.

**Data Availability**

No data were used to support this study.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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