Sensitivity Analysis of Design Parameters on Fluidlastic Isolators Performance

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Abstract. Control of vibration in helicopters has always been a complex and challenging task. The fluidlastic isolators become more and more widely used because the fluids are non-toxic, non-corrosive, nonflammable, and compatible with most elastomers and adhesives. In the field of the fluidlastic isolators design, the selection of design parameters is very important to obtain efficient vibration-suppressed. Aiming at getting sensitivity of property of fluidlastic isolator to design parameters, a dynamic equation is set up based on the theory of dynamics. The orthogonal experimental method is used to analyze the parametric sensitivity of the design parameters on the property of fluidlastic isolator. Two control indexes for design are taken as the experimental indexes, and five parameters influencing the property of the isolator are taken as the experimental factors. Arranged for the tests based on the orthogonal experiment table, 2 indexes 6 factors orthogonal experiment is carried out. Range analysis is adopted to study the sensitivity. The results show that for the combustion efficiency of dynamic stiffness of fluidlastic isolator, the order of significance levels in turn decreases with η, K_1, c , L, ρ and K_2 respectively. For the combustion efficiency of dynamic stiffness of fluidlastic isolator, the order of significance levels in turn decreases with η, K_1, c, K_2, ρ and L respectively.

1. Introduction

Helicopter vibration is a critical aspect of helicopter design and a major reason for extended lead time during the aircraft development phase. Control of vibration in helicopters has always been a complex and challenging task. Increasing demands for expanding the flight envelop of helicopters, such as nap of earth flying, high speed, high maneuvers, coupled with the need to improve system reliability and reduce maintenance costs has resulted in more stringent vibration specifications.

Various methods have been applied to vibration control in the engineering field [1-5]. Traditionally, passive isolators and dampers are used to attenuate mechanical vibrations. The traditional approach to passive vibration isolation is to install relatively soft springs or elastomeric isolators to provide a primary low natural frequency [6-9]. These isolators would also incorporate sufficient damping to control resonant response. Soft systems with primary natural frequencies well below the N/rev exciting frequency are required to achieve isolation. Such systems result in large relative motion between the pylon and the airframe due to static loads. Natural frequencies low enough to isolate N/rev vibration would have static (1G) deflections up to 0.50 inches. Since flight

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controls and power transmission drive shafts cross this interface it is advantageous to keep the relative motion as small as practical. An effective method for isolating the N/rev vibration that did not allow large relative motions between the pylon and airframe was needed.

There are many design parameters such as the density of fluid, area coefficient (R_1), and rubber performance that can affect the property of fluidlastic isolator [10-12]. Each of these parameters is important considerations in the design of a fluidlastic isolator and affects property of fluidlastic isolator to a greater or lesser degree. A key ingredient in developing reliable and efficient procedures for design optimization of fluidlastic isolator is sensitivity analysis.

The paper discusses the sensitivity of property of fluidlastic isolator to design parameters such as the density of fluid, rubber performance. These parameters are important consideration in the design of a fluidlastic isolator and affects performance to a greater or lesser degree. The dynamic equation is set up based on the theory of dynamics. The dynamic analysis is carried out. The effects of design parameters on property of fluidlastic are studied by orthogonal experimental method.

2. Mathematical model

Figure 1 and Figure 2 show the cross-section and the mechanical model of Fluidlastic Isolator.

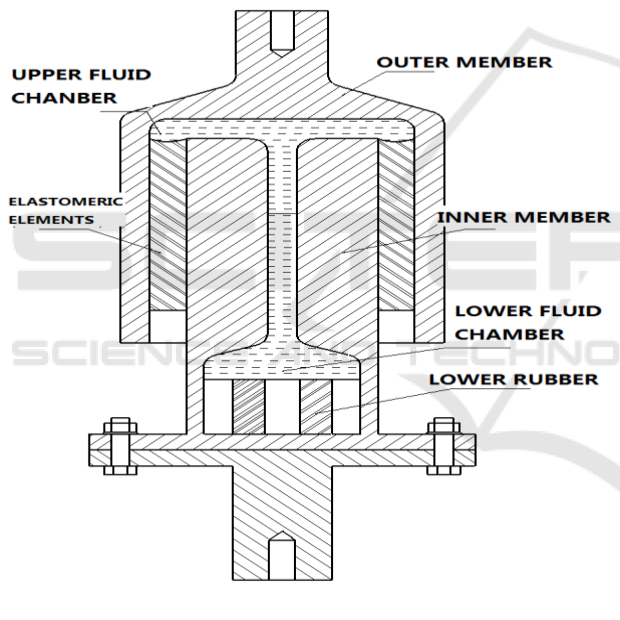

Figure 1. Cross-section of Isolator.

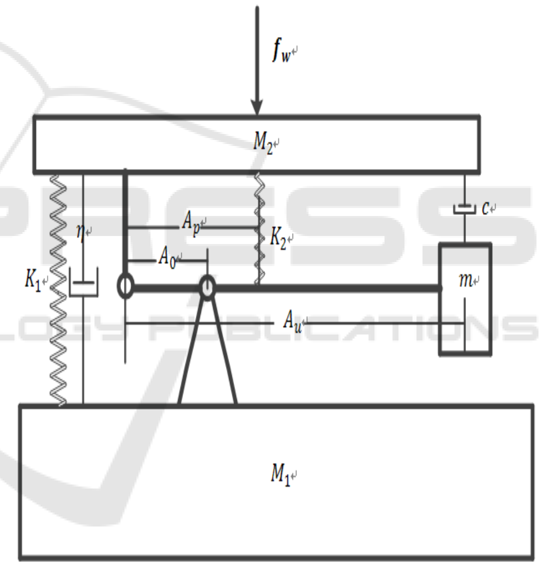

Figure 2. Mechanical model of Isolator.

According to the Figure 1 and Figure 2, the equations of motions (EOM) for the fluidlastic tuned isolator can be expressed as:

$$M_1\ddot{x}_1 = -K_1(1+i\eta)(x_1 - x_2) - f - [m(\ddot{x}_0 + \ddot{x}_2) + c\dot{x}_0] - K_2 x_d \quad (1)$$

$$M_2\ddot{x}_2 = K_1(1+i\eta)(x_1 - x_2) + f + K_2 x_d + c\dot{x}_0 + f_w \quad (2)$$

$$[m(\ddot{x}_0 + \ddot{x}_2) + c\dot{x}_0](A_u - A_0) + K_2 x_d (A_p - A_0) = fA_0 \quad (3)$$

Where, c is the Viscosity coefficient of liquid, η is Loss coefficient of rubber, f is the load that the M_2 imposed on the lever mechanism. The A_p , R_1 and R_2 is defined as:

$$A_p = A_u A_0 / A_d \tag{4}$$

$$R_1 = \frac{A_u}{A_0} = \frac{x_0}{x_1 - x_2} \tag{5}$$

$$R_2 = \frac{A_d}{A_0} = \frac{x_0}{x_d} \tag{6}$$

When the vibration load is a harmonic excitation, the load and displacement can be written as follows:

$$\left.\begin{aligned} f_w &= Fe^{j\omega t} \\ x_1 &= X_1 e^{j\omega t} \\ x_2 &= X_2 e^{j\omega t} \end{aligned}\right\} \tag{7}$$

The Transmissibility of vibration can be written as (8):

$$T = \left|\frac{X_1}{X_2}\right| = \left|\frac{\omega^2 m(R_1-1)R_1R_2^2 - K_2R_1^2 - jc\omega R_1^2R_2^2 - K_1(1+i\eta)R_2^2}{\omega^2 mR_1^2R_2^2 - K_2R_1^2 - jc\omega R_1^2R_2^2 + \omega^2 M_1R_2^2 - K_1(1+i\eta)R_2^2}\right| \tag{8}$$

When X_1, Δ_1, c, η are all equal to zero, the frequency of undamped isolation system can be obtained:

$$\omega_{iso} = \left(\frac{K_1R_2^2 + K_2R_1^2}{(R_1-1)R_1R_2^2 m}\right)^{\frac{1}{2}} \tag{9}$$

The amplitude of vibration can be written as:

$$X = \frac{R_1R_2^2F}{\left[K_1(1+i\eta)R_2^2 + K_2R_1^2\right] - m(R_1-1)^2R_2^2\omega^2 + jcR_1^2R_2^2\omega} \tag{10}$$

From the equation (7), the dynamic stiffness of isolation system can be obtained:

$$K_D = \frac{F}{X} = \frac{\left[K_1(1+i\eta)R_2^2 + K_2R_1^2\right] - m(R_1-1)^2R_2^2\omega^2 + jcR_1^2R_2^2\omega}{R_2^2} \tag{11}$$

According to the static equation, the static stiffness of isolation system can be also obtained:

$$K = K_1 + K_2\frac{R_1^2}{R_2^2} \tag{12}$$

3. Parameter sensitivity analysis

Table 1 gives the design parameters of fluidlastic including the density of fluid, viscosity coefficient of fluid, tuning port lengh, stiffness of rubber, loss coefficient of fluid, stiffness of (K_2). The boundary values of K_1, K_2, ρ, L, c and η are set at 5e6 to 1.5e7, 1e4 to 8e4, 1e3 to 5e3, 0.1 to 0.3, 0.05 to 5 and 0.05 to 5.

Table 1. Design parameters of fluidlastic.

level	K1	K2	ρ	L	c	η
1	5e6	1e4	1e3	0.1	0.05	0.05
2	8e6	3e4	1.5e3	0.12	0.1	0.1
3	1e7	4e4	1.8e3	0.2	0.5	0.5

The sensitivity analysis of design parameters on property of fluidlastic are studied through orthogonal experimental method. Five relevant factors including the density of fluid, viscosity coefficient of fluid, tuning port length, stiffness of rubber, loss coefficient of fluid, stiffness of (K_2) are studied. The orthogonal table $L_{25}(5^6)$ is designed and show in Table 2 based on five investigation factors and five corresponding levels.

Table 2. Design of orthogonal table $L_{25}(5^6)$ and analysis results.

No	K_1	K_2	ρ	L	c	η	T	K_D/23.87
1	5e6	1e4	1e3	0.1	0.05	0.05	0.122	90.106
2	5e6	3e4	1.5e3	0.12	0.1	0.1	0.050	62.935
3	5e6	4 e4	1.8e3	0.2	0.5	0.5	0.143	138.419
4	5e6	5 e4	3 e3	0.25	1	1	0.342	253.485
5	5e6	8 e4	5 e3	0.3	5	5	0.532	474.724
6	8e6	1e4	1.5e3	0.2	1	5	0.205	743.486
7	8e6	3e4	1.8e3	0.25	5	0.05	0.199	146.667
8	8e6	4 e4	3 e3	0.3	0.05	0.1	0.316	156.815
9	8e6	5 e4	5 e3	0.1	0.1	0.5	0.173	969.695
10	8e6	8 e4	1e3	0.12	0.5	1	0.462	2504.493
11	1e7	1e4	1.8e3	0.3	0.1	1	0.345	3161.499
12	1e7	3e4	3 e3	0.1	0.5	5	0.279	1857.246
13	1e7	4 e4	5 e3	0.12	1	0.05	0.123	103.191
14	1e7	5 e4	1e3	0.2	5	0.1	0.392	596.747
15	1e7	8 e4	1.5e3	0.25	0.05	0.5	0.218	2251.392
16	1.2e7	1e4	3 e3	0.12	5	0.5	0.473	2930.703
17	1.2e7	3e4	5 e3	0.2	0.05	1	0.413	5674.165
18	1.2e7	4 e4	1e3	0.25	0.1	5	0.442	3353.537
19	1.2e7	5 e4	1.5e3	0.3	0.5	0.05	0.100	399.778
20	1.2e7	8 e4	1.8e3	0.1	1	0.1	0.478	944.904
21	1.5e7	1e4	5e3	0.25	0.5	0.1	0.335	551.430
22	1.5e7	3e4	1e3	0.3	1	0.5	0.613	5074.972
23	1.5e7	4 e4	1.5e3	0.1	5	1	0.949	10439.771
24	1.5e7	5 e4	1.8e3	0.12	0.05	5	0.743	5570.818
25	1.5e7	8 e4	3 e3	0.2	0.1	0.05	0.083	606.392

The range analysis is applied to clarify the sensitivity of design parameters on the property of fluidlastic isolator including dynamic stiffness and transmissibility of vibration. First, the average value of each experimental index of factors at five levels is calculated. Next, the range of each factor of at five levels is also calculated. The influence coefficient of these six factors can be confirmed by comparison with the value of range. The bigger the range is, the more the influence will be.

4. Results and discussion

A civil helicopter is chosen for this study. The N/rev frequency of this helicopter is close to 25Hz.

High loads and very small motions of high stiffness isolators are even more challenging. Effectiveness of a tuned isolator in a system can be estimated by measuring the dynamic stiffness

(K_D) over the frequency range of interest. The K_D value at the tuned (N/rev) frequency is a good indicator of the effectiveness of the isolator in the system.

Fluidlastic isolators must also be designed to handle a specific range of input motions. The dynamic stiffness versus frequency curve is shown in Figure 3. The dynamic stiffness varied with the frequency. The dynamic stiffness varies from nominally 1.03E7 N/m statically (f = 0 Hz) to approximately 1.91E6 N/m at 25 Hz. Effective dynamic stiffness at 25Hz is less than 20% of the static stiffness. So, the "rigid" isolator can still provide effective performance. However, the static stiffness is relatively high. It is advantageous to keep the relative motion between the pylon and airframe as small as practical.

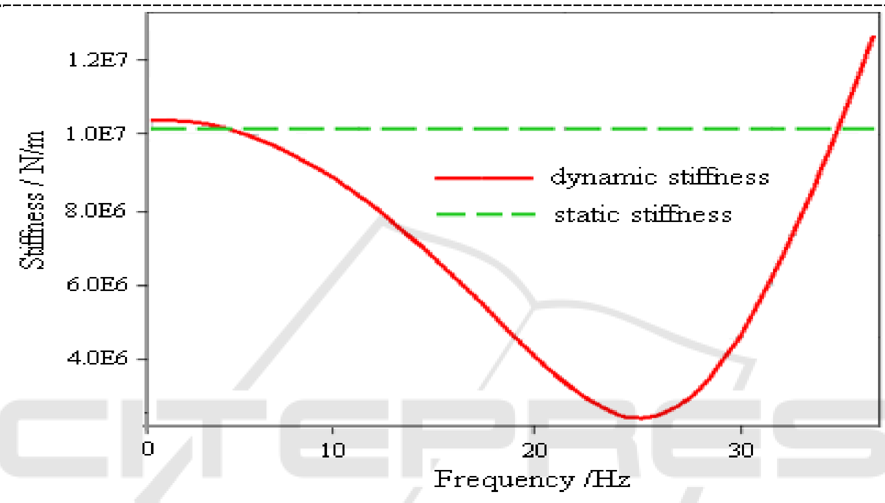

Figure 3. Fluid isolator stiffness versus frequency.

The range analysis is applied to clarify the sensitivity of design parameters on the property of fluidlastic isolator including dynamic stiffness and transmissibility of vibration.
According to Table 2, it is showed that the design parameters have obvious influence on the performance of isolator. The value of dynamic stiffness and transmissibility of vibration varies widely at different assembly of design parameters. The result of transmissibility is in the range 0.05 to 0.949. Dynamic analysis has shown that fluidlastic isolator can reduce the vibration effectively. The integration of these parameters is very important when selecting parameters for fluidlastic isolators design.

The range analysis of sensitivity of design parameters on dynamic stiffness is shown in Table 3. Table 3 summarizes the range analysis of the effect of different factor on the dynamic stiffness. According to the results of constricting the R values of different factors, the significant sequence of all the investigated influencing factors of design parameters was in turn. For the combustion efficiency of dynamic stiffness of fluidlastic isolator, the order of significance levels in turn decreases with η, K_1, c, L, ρ and K_2 respectively.

Table 3. Range analysis of influencing factors for T.

level	K1	K2	ρ	L	c	η
1	0.093	0.093	0.100	0.110	0.106	0.036
2	0.082	0.090	0.089	0.093	0.062	0.092
3	0.077	0.119	0.096	0.076	0.079	0.088
4	0.106	0.094	0.114	0.120	0.119	0.184
5	0.149	0.111	0.125	0.130	0.165	0.129
R	0.104	0.055	0.057	0.085	0.144	0.203
Sensitivity:	$\eta > K_1 > c > L > \rho > K_2$					

The range analysis of sensitivity of design parameters on transmissibility of vibration is shown in Table 4. Table 4 summarizes the range analysis of the effect of different factor on the transmissibility of vibration. According to the results of constricting the R values of different factors, the significance sequence of all the investigated influencing factors of design parameters was in turn. For the combustion efficiency of dynamic stiffness of fluidlastic isolator, the order of significance levels in turn decreases on η, K_1, c, K_2, ρ and L respectively.

Table 4. Range analysis of influencing factors for K_D.

level	K1	K2	ρ	L	C	η
1	204	1495	2324	2860	2749	269
2	904	2563	2779	2234	1631	463
3	1594	2838	1992	1552	1090	2273
4	2661	1558	1161	1311	1424	4407
5	4449	1356	1555	1854	2918	2400
R	6369	2954	2418	2340	3484	6386
Sensitivity:	$\eta > K_1 > c > K_2 > \rho > L$					

Referring to the Table 2, Table 3 and Table 4, it should be noted that the property of fluidlastic isolators can be affected by design parameters obviously. But the property of rubber (loss coefficient of rubber and stiffness of rubber) is, by far, the most significant design driver.

However, six parameters are analyzed only in this paper. The intercoupling among different parameters has not been considered. In order to obtain more accurate results, more parameters such as tuning port length, area coefficient should be considered in the next study. The interrelationship among these parameters will be also analyzed.

5. Conclusions

The dynamic equation is set up based on the theory of dynamics. The orthogonal experimental method is used to analyze the parametric sensitivity of the design parameters on the property of fluidlastic isolator. Findings are listed below:

(1) The fluidlastic isolator can reduce the vibration effectively. The integration of these parameters is very important when selecting parameter for fluidlastic isolators design.

(2) The property of fluidlastic isolators can be affected by design parameters obviously. But the property of rubber (loss coefficient of rubber and stiffness of rubber is, by far, the most significant design driver.

(3) The order of significance levels in turn decreases with η, K_1, c, L, ρ and K_2 respectively. For the combustion efficiency of dynamic stiffness of fluidlastic isolator, the order of significance levels in turn decreases with η, K_1, c, K_2, ρ and L respectively.

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