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A Comparison of Vibration Isolation Characteristics of Various Forms of Passive Vibration Isolator

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Key Words : Vibration (진동), Vibration Isolation (진동 절연), Transmissibility (전달율).

ABSTRACT

Transmission of unwanted vibration to sensitive systems can cause various problems including performance degradation and system malfunction. The most common approach to limit the transmission of harmful vibration disturbances to the sensitive system is adapting passive vibration isolator. The classical passive vibration isolator comprising a viscous damper and spring element in parallel, however, exhibits conflicting performance characteristics in that low amplification at the resonance, which is desirable, can only be achieved at the sacrifice of vibration isolation performance in high frequency region, which is undesirable. In this paper, vibration isolation characteristics of various passive isolator schemes in literature to circumvent this conflict are introduced and compared.

정밀 시스템에 전달되는 진동은 시스템의 성능 저하 및 오작동을 초래할 수 있기 때문에 저감되어야 한다. 진동을 저감시키는 가장 일반적인 방법은 진동이 전달되는 경로에 수동 진동 절연 장치를 도입함으로 전달되는 진동을 절연시키는 방법이다. 탄성소자와 점성 감쇠기로 구성된 일반적인 수동 진동 절연 장치는 공진에서의 전달율을 낮추기 위해서 고주파수 대역에서 진동 절연 성능을 희생해야 하는 단점을 지니고 있다. 본 논문에서는 공진에서 낮은 전달율과 고주파수 대역에서 높은 진동 절연 성능을 동시에 가진 수동 진동 절연 장치들의 특성을 비교 분석하였다.

1. Introduction

Transmission of vibration disturbance to precision machineries or payloads may result in serious performance degradation or system malfunction. Although various methods exist to limit the transmission of unwanted vibration, use of vibration isolator is often the preferred solution. In simplest form, vibration isolation can be achieved passively by inserting a resilient member (usually energy dissipating member is also included) into the vibration transmission path. One major drawback of using a conventional isolator composed of a resilient member and viscous damper is that amplification at the resonance can be lowered only at the expense of degraded isolation performance at high frequencies(1). Although active/semi-active vibration isolation method can be adapted to circumvent this trade-off(2-3), passive method is still preferable in many cases due to its simplicity and reliability.

Variations from the conventional passive vibration isolator to achieve low amplification at the resonance while maintaining high roll-off rate at high frequencies utilizing only the passive components have been studied(1,4-8). In this paper, vibration isolation characteristics of passive isolators that have been designed to simultaneously achieve high damping at the resonance and high isolation roll-off rate are

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compared in terms of their absolute transmissibility.

2. Isolation Characteristics of Passive Vibration Isolators

The performance of a vibration isolator can be evaluated through absolute transmissibility which is defined as the ratio of the magnitude of transmitted vibration to harmonic excitation[1]. Because the transmissibility of motion (motion transmission from base) is equivalent to that of the force (force transmitted to fixed foundation), only motion transmissibility is used to analyze isolation characteristics of various passive isolators.

2.1 Conventional Isolator

A conventional passive vibration isolator is composed of a resilient member and viscous damper as shown in Fig. 1. The equation of motion for the system shown in Fig. 1 is given in equation 1 and the absolute motion transmissibility is derived as equation 2 where c is the viscous damping coefficient, k is the stiffness, ζ is critical damping ratio ($\zeta = 1/\sqrt{4mk}$), ω_n is the natural frequency ($\omega_n = \sqrt{k/m}$), and ω is the excitation frequency.

$$m_p \ddot{x}_p + c\dot{x}_p + kx_p = c\dot{x}_b + kx_b \qquad (1)$$

$$\left|\frac{X_p}{X_b}\right| = \left|\frac{i2\zeta\omega_n\omega + \omega_n^2}{-\omega^2 + i2\zeta\omega_n\omega + \omega_n^2}\right| \qquad (2)$$

Transmissibility of the conventional isolator for various k and ζ values is shown in Figs. 2 and 3, respectively. Change of stiffness affects the natural frequency of the isolated system and, thus, the isolated frequency range which starts at $\omega = \sqrt{2}\omega_n$, but the roll-off rate after the resonance is unaffected. The lower limit of the stiffness is usually determined by the maximum allowable static deflection. While stiffness only has effect on the natural frequency of the system, damping has effect on the amplitude at the resonance and isolation roll-off rate. Increase of critical damping ratio reduces amplification at the resonance but the roll-off rate is also decreased. From equation 2, one can see that with no damping, the roll-off rate is -40 dB/decade ($1/\omega^2$) while with damping, the roll-off rate is decreased to -20 dB/decade ($1/\omega$). Thus, in conventional passive vibration isolator there is always a tradeoff between low overshoot and high roll-off rate. In order to achieve both low amplification and high roll-off rate, alternate schemes must be adapted.

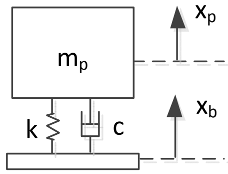

Fig. 1 Conventional vibration isolator

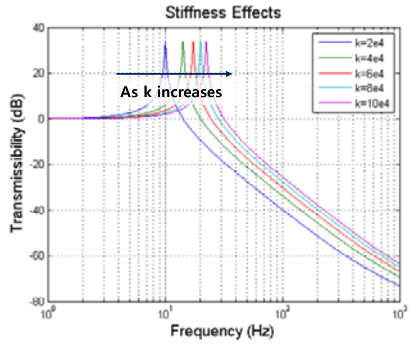

Fig. 2 Effect of stiffness on the transmissibility

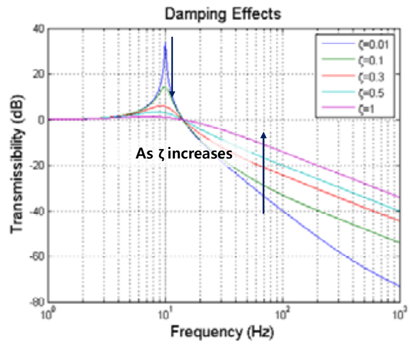

Fig. 3 Effect of damping on the transmissibility

2.2 Skyhook Damper

The skyhook damper[9] is an ideal passive vibration isolator that can achieve low amplification at resonance without aggravating isolation performance at high frequency region. In the skyhook damper, viscous dashpot is attached to the inertial reference frame (hence the name skyhook) as shown in Fig. 4 so that the damping force is proportional to the absolute velocity of the payload ($\dot{x}_p$).

The equation of motion of skyhook damper and its transmissibility are given in equations 3 and 4, respectively. Due to the absence of the term containing ω at the numerator of the transmissibility, the roll-off rate is -40 dB/decade regardless of the damping value.

$$m_p \ddot{x}_p + c\dot{x}_p + kx_p = kx_b \qquad (3)$$

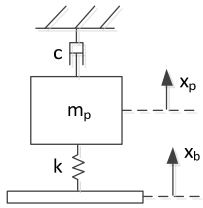

Fig. 4 Skyhook damper

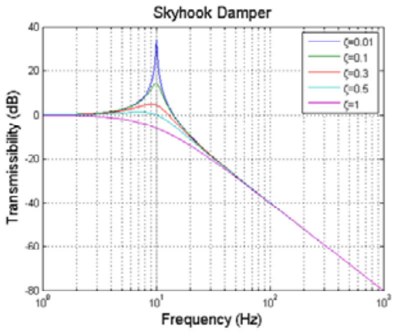

Fig. 5 Transmissibility of skyhook damper

$$\left|\frac{X_p}{X_b}\right| = \left|\frac{\omega_n^2}{-\omega^2 + i2\zeta\omega_n\omega + \omega_n^2}\right| \tag{4}$$

The transmissibility of the skyhook damper is shown in Fig. 5. As expected, the roll-off rate remains the same regardless of the damping value unlike the conventional isolator. In addition, whereas the isolation frequency is always fixed at $\omega = \sqrt{2}\omega_n$ in the conventional isolator, isolation effects can be achieve at the lower frequencies by using high damping in the skyhook damper.

Although skyhook damper shows desirable isolation characteristics using just passive components, physical realization of skyhook damper, specifically the connection of viscous damper to inertial reference frame, is not practical in most situations. Either active or semi-active control method is used to realize skyhook damper in practice.

2.3 Isolator with internal damping

Various damping mechanisms other than viscous damping exist including frictional and structural damping. Damping mechanism of a particular interest is that of viscoelastic materials which are one of the most commonly used damping materials. Viscoelastic materials are materials that exhibit the behavior of both an elastic solid and a viscous fluid. For such materials, complex stiffness is adapted to represent deformation that is in phase with stress (elastic) and that lags the stress by 90 degrees (viscous)[4].

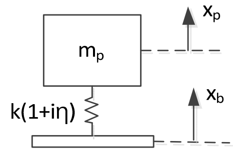

Fig. 6 Isolator with internal damping

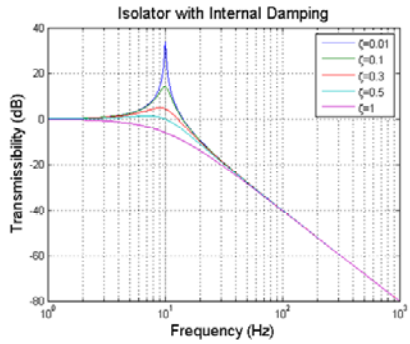

Fig. 7 Transmissibility of isolator with internal damping

Fig. 6 shows isolator with internal (hysteresis) damping represented using the complex stiffness k(1+iη) where η is the loss factor (η=2ζ). The equation of motion and transmissibility of isolator with internal damping are given in equations 5 and 6, respectively.

$$m_p\ddot{x}_p + k(1+i\eta)x_p = k(1+i\eta)x_b \tag{5}$$

$$\left|\frac{X_p}{X_b}\right| = \left|\frac{\omega_n^2(1+i\eta)}{-\omega^2 + \omega_n^2(1+i\eta)}\right| \tag{6}$$

Because the damping term is dependent on the displacement rather than the velocity of the mass, the roll-off rate is unaffected by the damping value. The transmissibility of isolator with internal damping is shown in Fig. 7. As can be seen, increase in damping value results in reduction of amplification at the resonance without deteriorating high frequency isolation performance. In real application, however, complex stiffness is frequency dependent and the isolation at high frequency is not as effective as predicted. In addition, the elastic modulus and loss factor of viscoelastic materials are heavily dependent on the temperature and to a less degree on frequency and pre-stress so designing isolator using viscoelastic material is not as simple as it may look. However, the improvement in high frequency isolation performance is still significant and the application of viscoelastic materials is the most frequently adapted method in vibration isolation.

2.4 Virtual Skyhook Isolator

The concept of virtual skyhook isolator that has the performance of a skyhook damper without the need of an inertial reference was introduced by Griffin et al [5]. The configuration of the virtual skyhook isolator is show in Fig. 8. Tuned secondary spring-mass-damper system is attached to the payload mass in a similar fashion to vibration absorber. The difference between virtual skyhook isolator and other tuned mass dampers is that the former focuses on the attenuation of high frequency isolation characteristics whereas the latter is generally used to reduce vibration at the resonance. In order to achieve high roll-off rate with low amplification at the resonance, damping of viscous dashpot that connects the base and payload mass must be small, and the natural frequency of secondary system must be tuned at the proximity of the natural frequency of the primary system. The equation of motion and the transmissibility are given in equations 7 and 8, respectively.

$$\begin{aligned} m_p\ddot{x}_p + (c_1+c_2)\dot{x}_p + (k_1+k_2)x_p &= c_1\dot{x}_b + k_1x_b + c_2\dot{x}_2 + k_2x_2 \\ m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 &= c_1\dot{x}_p + k_1x_p \end{aligned} \tag{7}$$

$$\left|\frac{X_p}{X_b}\right| = \left|\frac{-ic_1m_2\omega^3-(m_2k_1+c_1c_2)\omega^2+i(c_2k_1+c_1k_2)\omega+k_1k_2}{m_pm_2\omega^4-i\{c_1m_2+c_2(m_p+m_2)\}\omega^3-\{c_1c_2+k_1m_2+k_2(m_p+m_2)\}\omega^2+i(c_2k_1+c_1k_2)\omega+k_1k_2}\right| \tag{8}$$

The transmissibility of a virtual skyhook isolator is shown in Fig. 9. The value of parameters used in simulation is: m_1= 5kg, m_2 = 0.05m_1, k_1=20,000 N/m, k_2 = 908 N/m, ζ_1=0.0001 and ζ_2 is varied. Simulation results show that by tuning the parameters low amplification at resonance is achieved with -40dB/ decade roll-off rate. In order to apply virtual skyhook isolator, additional components are necessary and it can be applied in cases where the attachment of secondary system to the primary system is possible. Reference 5 claims that good performance can be achieved with relatively small secondary mass (about 5% of the primary mass).

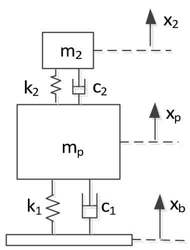

Fig. 8 Virtual skyhook isolator

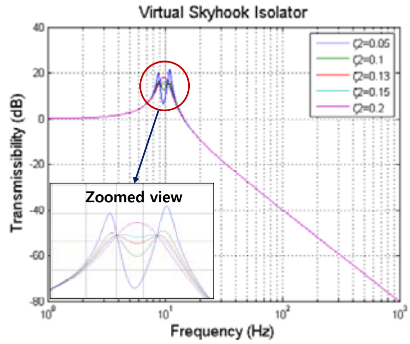

Fig. 9 Transmissibility of virtual skyhook isolator

2.5 Relaxation Isolator

Relaxation isolator, also known as a Zener model, has an additional spring component in series with viscous damper of a conventional isolator as shown in Fig. 10. Tuning of the stiffness of the additional spring element with other isolator parameters can result in passive vibration isolator with low amplification at resonance while maintaining high roll-off rate at high frequency region. The equation of motion of the relaxation isolator and its transmissibility are given in equations 9 and 10, respectively.

$$\begin{aligned} m_p\ddot{x}_p + c\dot{x}_p + kx_p &= c\dot{x}_0 + kx_b \\ c(\dot{x}_0 - \dot{x}_p) &= Nk(x_b - x_0) \end{aligned} \tag{9}$$

$$\left|\frac{X_p}{X_b}\right| = \left|\frac{ick(N+1)\omega + Nk^2}{-imc\omega^3 - Nkm\omega^2 + ick(N+1)\omega + Nk^2}\right| \tag{10}$$

The effect of damping on the transmissibility is shown in Fig. 11 when N=5. For the limiting case of c=0 and c=∞, the relaxation isolator behaves the same as undamped conventional isolator with natural frequency of $\omega_0 = \sqrt{k/m_p}$ and $\omega_\infty = \sqrt{k(1+N)/m_p}$, respectively. For damping values in between the two extremities, resonance occurs in between ω_0 and ω_∞. For all damping values, the transmissibility passes the point (N+2)/N at the frequency of $\omega = \omega_0\sqrt{2(N+1)/(N+2)}$ [6]. The optimum damping value that yields lowest amplification at this frequency is $\varsigma_{opt} = N\sqrt{(N+2)}/(N+1)$ [6] where $\varsigma_{opt} = c_{opt}/\sqrt{4m_pk}$.

Transmissibility at various values of N with optimum damping is shown in Fig. 12. At low values of N, resonance peak is clearly observed even with the optimum damping value. The peak is reduced as N is increased, but the frequency where isolation effect initiates is deterred with the increased N. For large values of N, the roll-off rate is slowly increased from -20 to -40 dB/decade as the frequency increases. Fig. 13 shows variation of maximum transmissibility and normalized isolation frequency ($\omega_{norm} = \omega / \sqrt{2}\omega_0$) as N is varied. Fig.13 can be used to select the desired value of secondary stiffness by considering amplification at resonance and frequency where isolation effect takes place. Physical realization of relaxation isolator is not difficult to achieve, and relaxation vibration isolators for space application have been successfully fabricated using bellows[7] and shunted circuit with electromagnetic transducer[8].

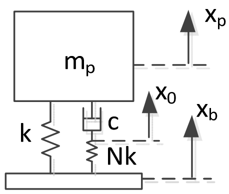

Fig. 10 Relaxation isolator

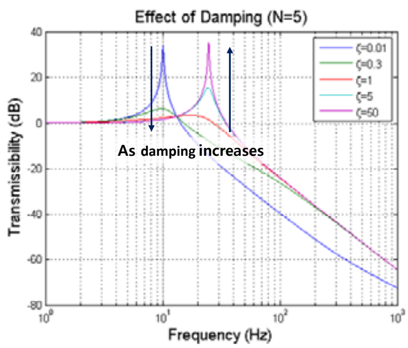

Fig. 11 Transmissibility of relaxation isolator as damping changes

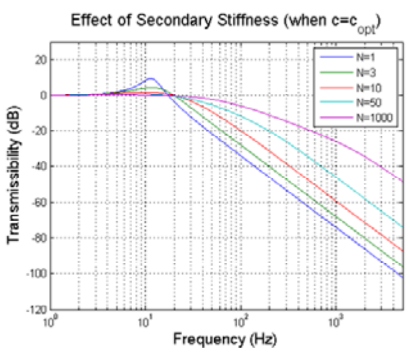

Fig. 12 Transmissibility of relaxation isolator as secondary stiffness changes

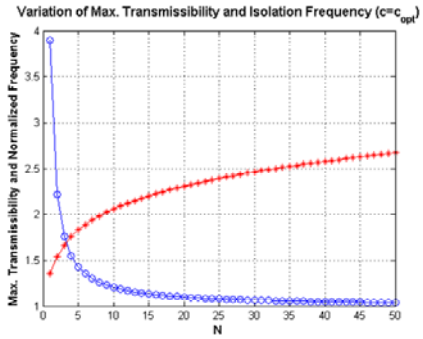

Fig. 13 Variation of maximum transmissibility and normalized isolation frequency according to N

2.6 Comparison of various passive vibration isolator characteristics

In this section passive vibration isolators that have been introduced in the previous sections are compared. Fig. 14 shows transmissibility of the isolators with the critical damping ratio of 0.65 (except for virtual skyhook isolator) and when m_p is 5 kg and k is 20,000 N/m. Aside from the conventional isolator, all vibration isolators exhibit -40dB/decade roll-off rate while maintaining low amplification at the resonance. Best isolation performance is given by skyhook damper. Virtual skyhook damper shows worst performance at resonance. Although the roll-off rate is the same, vibration isolation effect take place at higher frequencies for relaxation isolator and isolator using internal damping compared to skyhook damper and virtual skyhook isolator. Comparison of various isolators is summarized in Table 1.

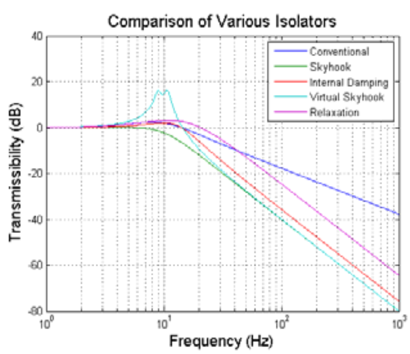

Fig. 14 Comparison of transmissibility of various forms of passive isolators

Table 1 Comparison of various forms of passive isolators

Isolator Type	Transmissibility	Comments
Skyhook Damper	$\left\lvert \frac{X_p}{X_b} \right\rvert = \left\lvert \frac{\omega_n^2}{-\omega^2 + i2\zeta\omega_n\omega + \omega_n^2} \right\rvert$	Ideal isolator which can reduce vibration at resonance without any sacrifice of attenuation performance at high frequency region. Physical realization is not possible with only passive means.
Isolator with internal damping	$\left\lvert \frac{X_p}{X_b} \right\rvert = \left\lvert \frac{\omega_n^2(1+i\eta)}{-\omega^2 + \omega_n^2(1+i\eta)} \right\rvert$	Low amplification at resonance is possible while maintaining high roll-off rate. Physical properties of viscoelastic material are highly dependent on external factors such as temperature and are hard to characterize. Most widely used material for vibration isolation.
Virtual Skyhook Isolator	$\left\lvert \frac{X_p}{X_b} \right\rvert = \left\lvert \frac{-ic_1m_2\omega^3 - (m_2k_1 + c_1c_2)\omega^2 + i(c_2k_1 + c_1k_2)\omega + k_1k_2}{m_pm_2\omega^4 - i\{c_1m_2 + c_2(m_p+m_2)\}\omega^3 - \{c_1c_2 + k_1m_2 + k_2(m_p+m_2)\}\omega^2 + i(c_2k_1 + c_1k_2)\omega + k_1k_2} \right\rvert$	High frequency isolation performance can be maintained with moderate amplification at the resonance. Addition of secondary system may limit practical implementation.
Relaxation Isolator	$\left\lvert \frac{X_p}{X_b} \right\rvert = \left\lvert \frac{ick(N+1)\omega + Nk^2}{-imc\omega^3 - Nkm\omega^2 + ick(N+1)\omega + Nk^2} \right\rvert$	Low amplification at resonance and high roll-off rate can be achieved simultaneously. For a given static deflection, isolation effects take place at higher frequency compared with other methods.

3. Conclusion

In this paper, vibration isolation characteristics of various passive isolators have been discussed and compared. The tradeoff between low amplification at the resonance and isolation performance at high frequency which exist in conventional isolator can be avoided using only the passive components by adapting different schemes including skyhook damper, virtual skyhook isolator, isolator with internal damping and relaxation isolator.

후 기

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