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Wire rope isolators for vibration isolation of equipment and structures – A review

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Abstract. Vibrations and shocks are studied using various techniques and analyzed to predict their detrimental effect on the equipment and structures. In cases, where the effects of vibration become unacceptable, it may cause structural damage and affect the operation of the equipment. Hence, adding a discrete system to isolate the vibration from source becomes necessary. The Wire Rope Isolator (WRI) can be used to effectively isolate the system from disturbing vibrations. The WRI is a type of passive isolator that exhibits nonlinear behavior. It consists of stranded wire rope held between two metal retainer bars and the metal wire rope is made up of individual wire strands that are in frictional contact with each other, hence, it is a kind of friction–type isolator. This paper compiles the research work on wire rope isolators. This paper presents the research work under two categories, namely monotonic and cyclic loading behaviors of WRI. The review also discusses the different terminologies associated with vibration isolation system and highlights the comparison between various isolation systems.

1. Introduction

Vibrations and shocks are studied using various techniques and analyzed to predict their detrimental effect on the equipment and structures. In many cases, the vibrations are unavoidable, but it will be within tolerable limits. In other cases where the vibration becomes intolerable, it is required to analyse the system for the effects of vibrations and improve the mechanical properties or in a place where are system design restricted in improving mechanical properties, it is then required to add an isolation system to counter the vibrations [1]. The application of vibration isolation system requires an understanding of the vibration control components, namely, source, path and receiver of the vibration [2].

The source of the vibration can be either natural or man-made. The natural sources include earthquake, wind, ocean waves, etc. and man-made sources include vibrations due to the operation of heavy machineries, construction works, roads and railways, etc. The path is the medium through which the vibration is transmitted, such as building components, pipe ducts, etc. The receiver refers to the building or equipment which receives the vibration from the source. The vibration control is employed based on the level of vibrations that a receiver can withstand without undergoing structural damage or affecting the functionality. The cases in which the level of vibrations is unacceptable, the isolation system is generally applied to cut off the path of the vibration to enhance the safety of the receiver.

In order to understand the isolation system, first it is required to understand the terms, namely, transmissibility and natural frequency. Transmissibility is a ratio of the vibrational force being measured in a system to the vibrational force entering a system (Figure 1). The transmissibility is a direct measure of the amount of vibrations transmitted by the isolation system, for example, if an isolation system has the transmissibility of 0.8 then it indicates that 80% of the vibration forces have been transmitted through the isolation system. The isolation efficiency provides the direct measurement of efficiency of isolation system and it is given by,

$$\text{Isolation efficiency} = 1 - \text{Transmissibility} \quad (1)$$

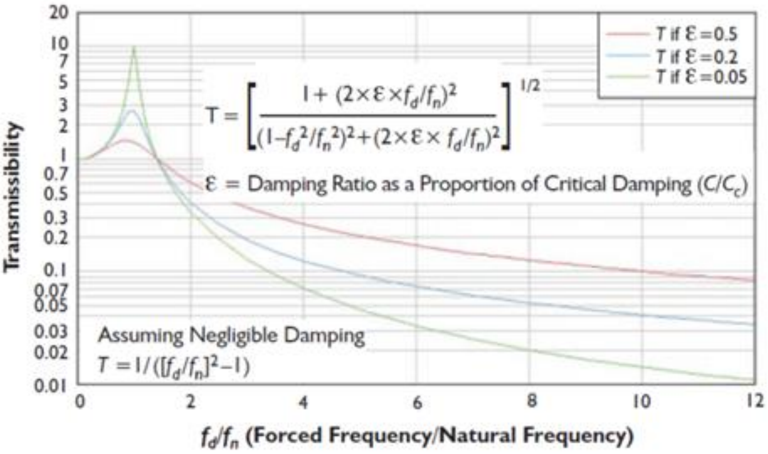


Figure 1. Transmissibility curve with respect to frequency ratio [2]

Natural frequency is the frequency at which the system will vibrate in the absence of any driving force or damping. Theoretically, when there is no external force is applied against the system vibration, then the system vibrates forever as per Newton's first law. However, in the real world, there exist the force in different forms which act against the vibration and bring the system to rest and such phenomenon is called as damping. It is absolutely required to prevent the system vibrate at its natural frequency, as this results in the larger magnitude of displacement and further to failure of components or structures in a phenomenon called resonance.

The concept of isolation and damping are often misunderstood, however, both are different from each other. It is required to understand the exact difference between them in order to proceed further. Damping refers to the absorption of vibrational energy which has entered the system and dissipating it by converting the kinetic energy of vibration into a different form of energy. On the other hand, isolation refers to the prevention of vibrations from entering a system. The transmissibility curve shown in figure 2 depicts the region of isolation and damping. Damping is primarily used to prevent the system from vibrating in a larger amplitude at its natural frequency, however; the isolation refers to the region, which are having lower values of transmissibility [1-3]. However, both isolation and damping are used in conjunction to achieve the desirable performance [2].

A general isolation system has two main components, namely, stiffness and damping. Firstly, the stiffness of the isolation system controls the static deflection required for different levels of isolation. The lower value of transmissibility can be achieved by increasing the static deflection. The amount of transmissibility required for an application differs in each case and depends mainly on the criticalness of the application. In general, the transmissibility of about 3% for critical applications and 5 % for sensitive applications and 10% for non-sensitive are applied [2]. The values indicated are only for reference and the exact amount of transmissibility required has to be calculated for the required applications.

Secondly, the damping component of isolator enables the energy dissipation of the external excitation to suppress it. There are three types of damping: viscous, coulomb, and structural/solid damping. Viscous damping is dependent on the velocity of the movement. Coulomb damping is dependent on surface friction and the pressure between surfaces. Structural damping, also known as hysteresis, is internal friction within the material; all materials exhibit some amount of hysteresis. The amount of damping required is subjective and varies with respect to applications. Most of the structures have less than 5% inherent structural damping. According to the previous study [3], the general guidelines for amount of damping can be taken as 20-25 % of damping for standard automobile suspension, 30% damping is typical for a heavy duty suspension and 40% damping is typically used for high performance suspense and damping levels above 40% proves very uncomfortable to human and tends to loose structural joints.

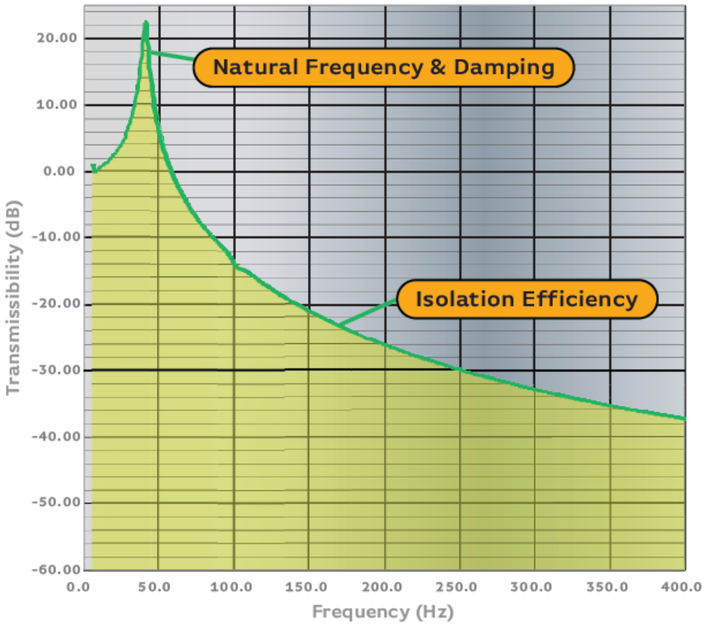


Figure 2. Transmissibility curve with region of damping and isolation [1]

2. Types of isolation system

The isolation system is categorized into three types, namely, Passive system, Active system and Semi-Active system. The active vibration isolation system generally can achieve high performance in suppressing the structural vibrations [4-6]. Semi-active vibrations isolations, also called as adaptive–passive system, contains along with the spring and the dampers, a feedback circuit which consists of a sensor, controller, and an actuator (such as Magneto-rheological (MR) or shape memory alloys). Feedback circuit monitors real time vibration excitation using sensors and controls the actuators to dissipate the energy and achieves relatively better isolation than passive isolation methods [5, 7]. However, a fully active isolation system (figure 3) isolates the vibration directly using actuator systems without having additional passive dampers [8-10].

Many researchers have studied the performance of various control methods for damping using MR fluids [11-19] and stated that the damping property of the MR fluid actuators can be controlled by varying the viscosity of the MR fluid using a magnetic field. However, active systems are very design intensive and require sensors and processors to provide real time data to the isolator. In addition, it requires a large amount of power to operate. These necessary features of active isolation systems make it the most expensive isolation design. As a consequence of the expense and the large power requirement, active isolation systems are very uncommon in major industries, except in critical applications that require high level isolation such as sensitive testing equipment [20].

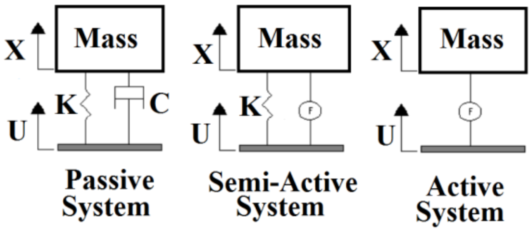


Figure 3. Types of isolation system [9]

Passive vibration isolation, on the other hand, refers to vibration isolation or mitigation of vibrations using passive techniques such as rubber pads or mechanical springs. In its simplest form, it is represented as a combination of a spring having stiffness (K) and a damper having damping coefficient (C), as shown in the figure 3. The spring provides the elasticity to the structure and energy dissipation is provided by the damper. Presently, passive energy dissipation devices are the most widely used vibration protection systems in industries and buildings because of its simple design and low cost [20]. These systems encompass a range of materials and devices for enhancing the damping, stiffness and strength, and can be used both for natural hazard mitigation and for rehabilitation of aging or deficient structures. Contrary to semi-active systems, passive energy dissipation systems do not need an external supply of power in order to operate. Moreover, since energy dissipation devices are not an integral part of the supporting structure, they can easily be replaced for maintenance without compromising the structural integrity [21].

The conventionally designed passive vibration Isolators exhibit linear behavior in both elastic stiffness and damping, which restricts the energy dissipation capability [22]. The design of conventional passive isolators needs a trade-off with stiffness and damping. The low transmissibility over a wide range of frequency can be obtained by reducing the elastic stiffness of the isolator as small as possible, however, such case will lead to large static and quasi-static displacements which are likely to be detrimental to the equipment supported [2].

On the other hand, damping of the isolator needs to be increased to reduce the transmissibility at the resonance which may cause deterioration to the transmissibility over the high frequency range. Moreover, the linear passive isolators are useful only if the excitation frequencies are well above the natural frequency of isolators and thus they are limited to cases which has moderate environmental disturbance. However, under cases such as shock, random ground motions or impact loads the spectrum contains low frequencies which are dangerous to the structures or equipment. Hence the limitations of linear can be overcome by developing a passive vibration isolator which exhibits non-linear behavior [22].

Several authors have developed different types of nonlinear vibration isolators and have investigated the unique dynamic behaviors [23-25]. A comprehensive survey of recent developments of nonlinear vibration isolators has been performed by Ibrahim [22], in which many cited studies [26-31] reveal that the introduction of nonlinear damping and stiffness are of great benefit in vibration isolation. Recently Wire Rope Isolators (WRI), a type of passive isolator which exhibits non-linear behavior in both elastic stiffness and damping, has become the subject of intensive studies [32, 33].

3. Wire rope isolators

Wire rope isolators consist of wire rope strands held between two metal retainer bars in the form of helix shape (Figure 4 (a)) or polycal shape (Figure 4 (b)). As the name implies, wire rope isolators use metal wire rope made up of individual wire strands that are in frictional contact with each other. WRI can provide flexibility in all directions and possess inherent damping characteristic derived from rubbing and sliding friction between the intertwined cables. It is therefore a kind of friction-type damper which adopts stranded wire rope as the elastic component and utilities friction damping (Coulomb damping) between the individual wire strands. This friction dominant property causes the viscous damping in WRI to be relatively insignificant [34, 35].

The advantages of WRI include wide temperature range operations between -100ºC to +250ºC [36] and less susceptible to the detrimental effects of environmental conditions like extreme temperature, salt, fog, grease, radiation, dust and low manufacturing cost [37]. The polycal type of WRI is primarily used for micro mechanical and electronic applications [37]. For heavy machinery applications the helical WRI is used [38].

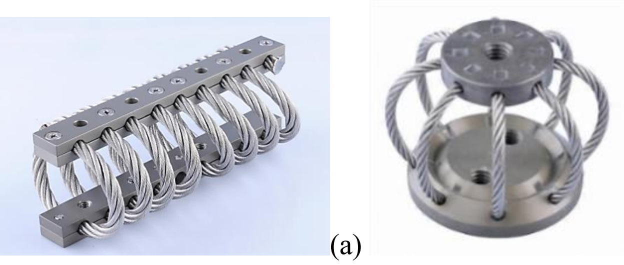

(a) (b)

Figure 4. (a) Helical Isolator [36] (b) Polycal Isolator [36]

4. Characteristics of WRI

The geometric characteristic of the WRI is shown in figure 5. As WRI is a type of passive isolator, it can also be represented in a simplified form as a spring-damper element with static elastic stiffness (K) and damping coefficient (C) (Figure 6(a)) [39]. The static elastic stiffness can be determined from the load-displacement curve under monotonic loading and the damping coefficient can be determined using the hysteresis curve obtained from cyclic loading. Monotonic loading refers to loading in one direction and cyclic loading refers to a set of loading-unloading sequence. There are three loading modes (Figure 6) in which WRI can be used- tension/compression load (along Z), shear load (along X) and roll load (along Y) [32, 39].

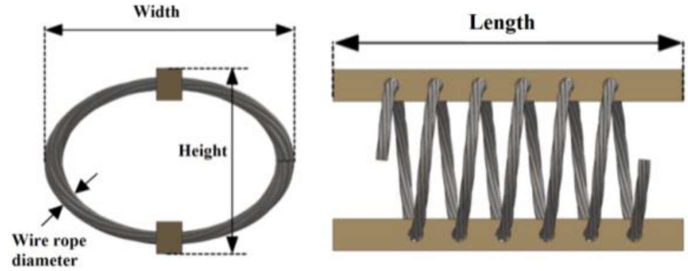


Figure 5. Geometric characteristics of the WRI

5. Selection of WRI

ITT Inc [38] develops a series of vibration and shock insulators of all types and sizes, including WRI and has provided the possible orientations of WRI that can be used in practical applications as shown in figure 7. The orientation of the WRI depends mainly on the supporting structure to fix the WRI. In the majority of the cases, the tension/compression loading mode is preferred. However based on the availability of the supporting structures, the WRI can also be used in the shear and the roll mode. ITT Inc [38] provides the procedure for selection of WRI required for applications. The procedure mainly relies on the calculation of static elastic stiffness (K) of the WRI. Upon estimating the K, based on the weight of the equipment to be supported and disturbing frequency, it is then required to identify a suitable WRI model from the catalogue.

The catalogue contains the values of the static elastic stiffness values of all WRI provided by ITT Inc., which have been experimentally determined under monotonic loading. The static elastic stiffness in all different loading modes are available in the catalogue. The WRI, which possess static elastic stiffness in the loading mode as required for the application will be selected. The selection procedure of WRI is fully based on the monotonic loading response and it should be noted that the behavior under cyclic loading is not considered during the selection process due to a lack of information for this loading type. The research work on the behavior of WRI under monotonic loading and cyclic loading is presented in the next section.

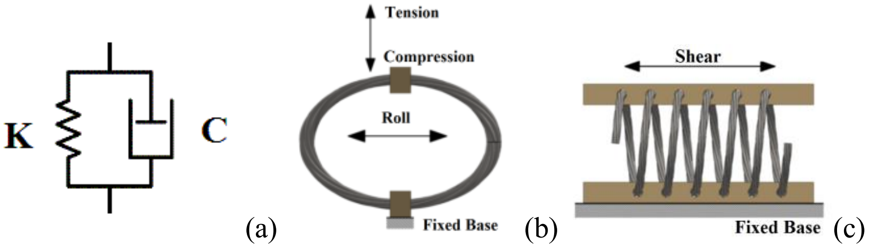


Figure 6. (a) Spring-Damper element (b) Tension/compression and roll, (c) Shear

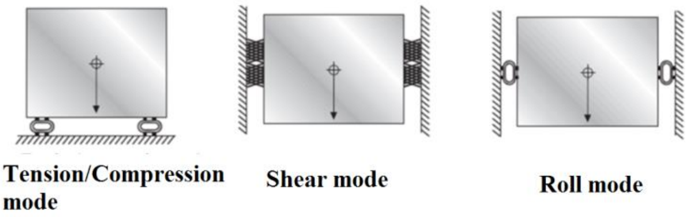


Figure 7. Possible orientations of WRI as suggested by ITT Inc [38]

6. Behavior under monotonic loading

The study of WRI behavior under monotonic loading provides the knowledge on the static elastic stiffness. ITT Inc [38] and Devflex Co [36] develops a variety of WRI in different sizes and stiffness values which facilitates the easy selection of WRI for a particular application. The selection procedure relies mainly on the static elastic stiffness of the WRI and presently the experimental methods are used for its determination. Tinker et al [34, 35] preformed a monotonic shear loading on WRI for the static stiffness (Figure 8). However, a comprehensive study on the static elastic stiffness of WRI is not available in the literatures. All available literatures on WRI were on the cyclic loading behavior. Though the selection procedure relies mainly on static stiffness, presently experimental methods are used to estimate the stiffness. However, an analytical model for the static elastic stiffness will avoid the time consuming experimental work.

Knowledge of the behavior of WRI's post elastic limits enables the prediction of the WRI's capability to sustain further loadings. However, no analytical research on the static elastic stiffness and the post elastic behavior of WRI is available. An accurate analytical model, including all the influencing parameters will greatly assist the appropriate selection and the design of WRI.

7. Behavior under cyclic loading

The study of WRI behavior under cyclic loading can provide the knowledge on isolation capabilities. WRI exhibits hysteresis behavior under cyclic loading due to energy dissipation through coulomb damping. The literature shows only limited research on the hysteresis behavior of WRI using experimental methods [32-35, 39]. A study has been conducted by Demetriades et al. [39] on the hysteresis behavior of the WRI using a cyclic loading test. They show that WRI exhibits symmetrical hysteresis curve for roll and shear loadings as shown in figure 9(a) and asymmetrical hysteresis curve (Figure 9(b)) for tension/compression loading. They also reported that WRI provides a 10% damping for large deformation and about 20% to 30% for small deformation. Tinker and Cutchin [35] studied the damping phenomenon, the stiffness and the hysteresis behavior and reported that the damping in WRI arises from the friction between the individual wire strands.

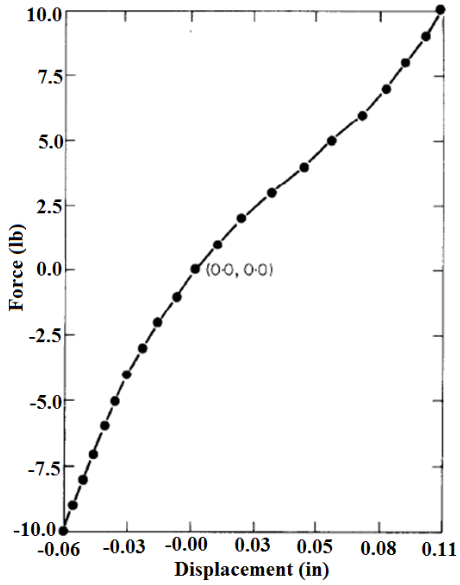
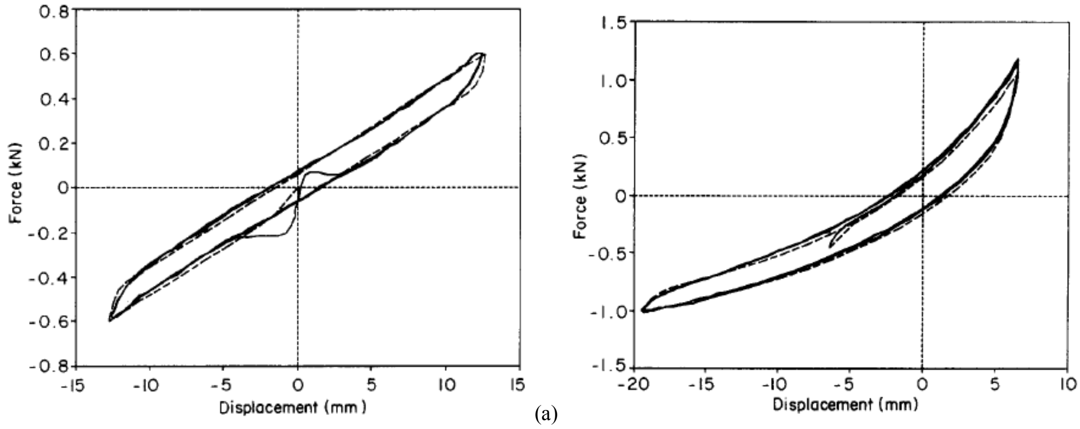


Figure 8. Experimental stiffness curve of WRI under shear load [35]

Schwanen [40] reported that the asymmetric hysteresis curve during tension/compression is due to hardening and softening of the wire rope spring and found that the wire rope spring undergoes softening in compression and hardening in tension. The softening is due to the decrease in the contact points between the wire strands under compression load. The hardening in the tension is due to the increase in the contact points under tension load, which results in increased friction between the wire strands. Massa et al. [33] introduced a ball bearing in the polycal WRI to increase its vertical stiffness. Ball bearing provides additional stiffness in the vertical direction to support the normal load of the equipment and hence increases the load carrying capacity. Paolacci and Giannini [32] conducted a study on the effectiveness of steel cable dampers for the seismic protection of electrical equipment. They developed a numerical model for electrical equipment supported by WRI and subjected it to the seismic load of the 1980 Irpinia earthquake (Italy). The study shows the effectiveness and potential of WRI as a base isolation system



(a) (b)

Figure 9. Hysteresis behaviour (a) under shear loading (b) under tension/compression loading [39]

7.1. Bouc-Wen Model

The hysteresis behaviour of the WRI depends on their geometrical properties including wire rope diameter, length and width and the number of turns and loading directions [39]. The area under the hysteresis curves is the energy dissipated by the WRI during the cyclic loading test [34, 35]. A well-developed mathematical model of hysteresis behavior would facilitate the prediction of energy dissipation capabilities and avoids the time-consuming experimental work. The generalized Bouc-Wen (BW) model is commonly used to model the symmetric hysteretic behavior. Many researchers have used the BW model to perform mathematical modelling for the hysteresis system in their area of research work such as magetorhelogical dampers [13, 42, 43] and piezo electric actuators [41]. The generalized Bouc-Wen model of the hysteresis curve is given by

$$Q(x, \dot{x}, t) = g(x, \dot{x}) + h(x) \tag{2}$$

where Q is the restoring force , g the non-hysteretic component (Equation 3), an algebraic function of the instantaneous displacement x and the velocity $\dot{x}$ and h the hysteretic component (Equation 4), a function of the time history of x [42].

$$g = c\dot{x} + \alpha k x \tag{3}$$

$$h = (1 - \alpha)kz \tag{4}$$

where k is the pre-yielding stiffness and α the ratio of post-yielding to pre-yielding stiffness. z is described by the non-linear differential equations of Equation.5,

$$\dot{z} = \left(\frac{1}{\eta}\right)\left[A\dot{x} - \upsilon\left(\beta|\dot{x}||z|^{n-1}z - \vartheta|\dot{x}||z|^{n}\right)\right] \tag{5}$$

In Eq.5 the model parameters A, υ, β, ϑ, η and n govern the amplitude, the shape of the hysteresis loop, and the smoothness of transition from the elastic to the inelastic region. Different choices of model parameters control the shape of the hysteresis curve. When using the Bouc-Wen model for a practical application, it is necessary to perform the identification of the model parameters using system identification techniques. Many researchers have used techniques like the least square method [43], Kalman filter method [44], genetic algorithm based identification [45] to identify the system parameters, so that the output of the model matches as accurate as possible with the experimental data. The symmetrical hysteresis behavior of WRI under shear and roll loading can be modelled using the BW model. However, under tension/compression loading it exhibits asymmetrical behavior and the BW model has to be modified suitably for accurate prediction of this asymmetric behavior.

8. Conclusion

The conventional passive isolators exhibits linear behavior and it needs an improvement to enhance the safety of the isolated system. WRI is a non-linear passive isolator and can provide a better isolation than the conventional passive isolators. The major advantage of WRI is that, it can provide isolation in all three planes and in all orientations. The behavior of WRI can be studied under monotonic and cyclic loading to understand its stiffness and damping behavior. WRI is a newly developed isolation system relatively, when compared with the linear vibration devices hence literature has only few research work. This survey presented the major research work carried on WRI. This paper also highlighted the area for the future scope of work in the field of wire rope Isolators.

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