Static lateral stiffness of wire rope isolators

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Abstract:

This paper presents an analytical model for the static lateral stiffness of Wire Rope Isolators (WRI). The wire rope isolator, which is a passive isolation device, has been widely adopted as a shock and vibration isolation for many types of equipment and lightweight structures. The major advantage of the WRI is its ability to provide isolation in all three planes and in any orientation. The WRI in the lateral roll mode, is required to possess the required lateral stiffness to support and isolate the equipment effectively. The static lateral stiffness of WRI depends mainly on the geometrical characteristics and wire rope properties. The model developed in this paper is validated experimentally using a series of monotonic loading tests. The flexural rigidity of the wire ropes, which is required in the model, was determined from the transverse bending test on several wire rope cables. It was observed that the lateral stiffness is significantly influenced by the wire rope diameter and height of the isolator. The proposed analytical model can be used for the evaluation of lateral stiffness and in the preliminary design of the WRI.

Keywords: Shock, Vibration, Wire rope isolator, lateral stiffness, Flexural rigidity.

1. Introduction

The protection of equipment and lightweight structures from vibrations due to earthquakes or due to the operation of heavy machinery is a major concern in industries and earthquake prone countries (Constantinou and Tcidjbakhsh, 1984; Su *et al.*, 1990; Balaji *et al.*, 2015a). The high levels of vibration may affect the functionality and can cause structural damages. Hence, vibration isolation is required to isolate valuable equipment and machinery from the undesirable vibrations. The Wire Rope Isolator (WRI), a type of passive isolator, is known to be effective in the isolation of vibrations and shocks and can be used to protect such equipment. WRI as an economical passive device has found many applications. The applications of the WRI includes vibration isolation of passage of fluid in the rocket engine (Tinker and Cutchins, 1992), in the seismic protection of equipment hosted in building structures (Demetriades *et al.*, 1993), and also in the isolation of pipes in nuclear (Loziuk, 1988) and petroleum industries.

The wire rope isolator is constructed from a stainless steel wire rope wounded in the form of a helix and held between two metal retainers as shown in Fig. 1. The individual wire strands of the wire rope are in frictional contact with each other and move relative to each other causing the dissipation of vibrational energy (Tinker and Cutchins, 1992). The wire rope has the ability to attenuate the vibration and it is able to absorb the impact energy efficiently (Weimin *et al*., 1997; Chungui *et al*., 2009). The main advantage of WRI is its ability to provide isolation in the three planes and in all directions, due to which, it can be mounted in any orientation (Fig. 2) to protect structures and equipment excited in any direction (Michael, 1989; Tinker and Cutchins, 1992). Such orientations induce tension/compression, shear, and roll load on the WRI as shown in Fig. 3.

WRI is a typical non-linear hysteretic damping device (Ni *et al*., 1999) and hence, it exhibits hysteresis behavior in restoring force–displacement relation. The restoring force has two components namely, elastic force and damping force (Gerges, 2008). The damping force is achieved from the wire rope through its inter-strand frictions and is hysteretic in nature. On the other hand, the elastic force is achieved from the spring design of the WRI and is non-hysteretic in nature. The stiffness is raised from both damping and elastic force. Earlier studies (Tinker and Cutchins, 1992; Demetriades *et al*., 1993) suggest that the stiffness characteristics of WRI depends on the diameter of the wire rope, width, height, length, number of turns and direction of load. The static loading behavior of the WRI indicates that for small displacements, the static stiffness curve can be assumed to be linear and becomes nonlinear for higher displacements (Demetriades *et al*., 1993, Ni *et al*., 1999a, Ni *et al*., 1999b; Balaji *et al*., 2015b). This indicates that, for small displacements, the static stiffness is majorly contributed from the elastic force and for higher displacements, and that the damping force plays a major role.

Among available literatures for the WRI, mostly have focused their work towards the cyclic loading behavior (Demetriades *et al*., 1993; Ni *et al*., 1999a; Ni *et al*., 1999b, Balaji *et al*., 2015b) and only very few researchers (Tinker and Cutchins, 1992; Ni *et al*., 1999a) have worked on the static stiffness. Ni *et al*. (1999a and 1999b) have conducted an experimental study on the static stiffness in each direction through shear, roll, and tension-compression loading to study the hardening and softening behavior of WRI. This study observed hardening under tension loading and softening under compression load. Further, it was demonstrated that the static stiffness curve under roll and shear load were similar and symmetric in both directions. Balaji *et al*. (2015c) have performed an experimental and analytical studies on the vertical stiffness of WRI. This study showed that the vertical stiffness of the WRI is highly influenced by the wire rope diameter.

Several experimental tests on the WRI (Demetriades *et al*., 1993, Paolacci and Giannini, 2008) have also confirmed that the WRI is characterized by a similar static vertical stiffness in both tension and compression loads under small displacements and similar static lateral stiffness in both shear and roll for all displacement amplitudes. The wide use of WRI in many vibration isolation applications suggests that it is essential to fully understand their characteristics (Tinker and Cutchins, 1992). The WRI's stiffness is an important characteristic in the design of vibration isolation systems, as it is required to provide the isolated equipment with a natural frequency lesser than the lowest excitation frequency to ensure a maximum of energy dissipation.

The WRIs are produced by different manufactures (Endine, 2014; AAC, 2014). These commercial isolators come along with catalogues explaining the selection procedure of WRI for different applications (Endine, 2014). These procedures are based on the static stiffness in all directions, which is determined from the monotonic loading tests. Despite the stiffness being one of the important parameters, literature lacks the research work on the static stiffness in the lateral direction due to limited understanding of the wire rope behavior. Hence, an analytical model is highly desirable for its usefulness in the selection and design of the WRI to achieve the required stiffness for different applications.

The objective of the present work is to develop an analytical model for the stiffness of the helical WRI in the lateral direction under roll load. The developed model is validated using a series of monotonic loading tests. The analytical model is developed based on Castigliano's second theorem and the strain energy principle. Finally, the analytical model is used in a parametric study to investigate the influence of wire rope diameter, width, height, and number of turns on the lateral roll stiffness of WRI.

2. Analytical Model

The analytical model for the WRI's stiffness in the lateral direction is obtained by establishing a relationship between the lateral displacement and the applied roll load. The attenuation of the input excitation is achieved by the WRI in the roll mode through the lateral displacement and through the friction between the individual wires. Hence, the strain energy and wire rope construction become the major factors in the design of the isolator. The relation between the strain energy and the displacement is provided by the Castigliano's second theorem (Budynas *et al.*, 2008). The following assumptions were made to simplify development of the analytical model:

1. The wire rope is considered as solid bar having uniform circular cross section;
2. The material of the wire rope is considered homogenous and isotropic;
3. The involvement of metal retainers in resisting the load is neglected;
4. The applied load is static;
5. The WRI is firmly clamped to the support.
6. The relation is developed for small displacement amplitudes within which force and displacement are linearly related.

2.1. Geometry of the WRI

The geometry of the WRI is simplified by considering a roll load carried by a single coil of wire rope. Fig. 4 shows the geometry of one coil of the WRI subjected to a roll load. Furthermore, a single wire rope coil is symmetric about the vertical axis, thus, one-half of the coil is considered in the model development (Fig. 5). The one-half coil, having a circular cross section of diameter D, can be divided into three regions namely AB, BC and CD (Fig. 5). The first (AB) and third (CD) regions comprise the top and bottom straight lines of length L, and the second region (BC) comprises the semicircle of radius R. The boundary limits for each region are taken as: Regions AB and CD: 0 to L and Region BC: 0 to π; where the length L is the half width of the metal retainer. The radius of curvature is determined as:

$$R = (H-T)/2 \qquad (1)$$

2.2. Analytical model of lateral stiffness

The displacement due to the lateral load can be calculated using Castigliano's second theorem. For the case of WRI, the cross section of the wire rope is small compared to the radius of curvature of its center line. The lateral load is acting in the roll load mode and the WRI is fixed to the base; the free body diagram is shown in Fig. 5. The simplified model is subjected to the reduced force *F*/2 and the indeterminate shear force (*Q*). The indeterminate bending moment at A can be shown to vanish by the principal of least work (Tse *et al.*, 2002). The strain energy (*U*) of the semicircular coil model is given by:

$$U = U_{AB} + U_{BC} + U_{CD} \tag{2}$$

where U_{AB} , U_{BC} , and U_{CD} are the strain energies of the first, second and third regions, respectively:

$$U_{AB} = \int_0^L \left(\frac{F}{2}\right)^2 \frac{1}{2EA} dx + \int_0^L \frac{1}{2EI} M_1^2 dx \tag{3}$$

$$U_{BC} = \int_0^\pi \frac{1}{2EI} M_2^2 R d\theta \tag{4}$$

$$U_{CD} = \int_0^L \frac{1}{2EI} M_3^2 dx \tag{5}$$

where M_1, M_2 , and M_3 are the moments in the regions AB, BC, and CD, respectively and are given by:

For region AB:

$$M_1 = Qx; \qquad 0 \le x \le L \tag{6}$$

For region BC:

$$M_2 = Q(R\sin\theta + L) - \frac{F}{2}(R - R\cos\theta); \qquad 0 \le \theta \le \pi \tag{7}$$

For region CD:

$$M_3 = Qx - \frac{F}{2}(2R); \qquad 0 \le x \le L \tag{8}$$

The indeterminate shear force Q shall be determined using Castigliano's theorem. It can be seen from Fig. 5 that due to the condition of symmetry the cross-section does not rotate during bending of the wire rope. Hence the displacement due to Q is zero, that is:

$$\frac{dU}{dQ} = 0 \tag{9}$$

Upon solving Eq. (9) for the indeterminate shear force, we obtain:

$$Q = \frac{3FL^2R + 3\pi FLR^2 + 6FR^3}{4L^3 + 6\pi L^2R + 24LR^2 + 3\pi R^3} \tag{10}$$

Thus, the total strain energy stored in the half coil wire rope is calculated to

be: $U = \frac{F^2}{8}\left(\frac{f(L,R)}{EI} + \frac{L}{EA}\right)$ (11a)

in which

$$f(L,R) = \frac{R^2\left(20L^4 - 48R^4 + 144L^2R^2 + 9\pi^2R^4 + 6\pi^2L^2R^2 + 48\pi LR^3 + 36\pi L^3R\right)}{2\left(4L^3 + 6\pi L^2R + 24LR^2 + 3\pi R^3\right)}$$

(11b)

Now, the deflection due to the lateral load, for the complete loop, can be obtained from the strain energy through Castigliano's theorem:

$$\delta = 2 \times \frac{dU}{dF} \tag{12}$$

From Eq. (11), the deflection of one full coil due to the applied load F is:

$$\delta = \frac{F}{2}\left(\frac{f(L,R)}{EI} + \frac{L}{EA}\right) \tag{13}$$

Eq. (13) represents the force-displacement relation of one full coil assuming small displacement amplitudes. Finally, the lateral stiffness, K_L, of the complete WRI, having N coils, is computed as:

$$K_L = N \times \frac{F}{\delta} = \frac{2\,N\,EI\,EA}{L\,EI + f(L,R)\,EA} \tag{14}$$

The product of the elastic modulus, E, and moment of inertia, I, in the analytical model of stiffness (Eq. (14)), signifies the resistance of the wire rope to bending and is referred to as the flexural rigidity (or bending stiffness). The axial stiffness, EA, which is the product of the elastic modulus and cross-sectional area of the wire rope, A, represents the axial resistance to deformations. The elastic modulus of the wire rope, in general, is load dependent (Zhu and Meguid, 2007). Furthermore, the wire rope has a lower moment of inertia compared to a solid bar (Prawoto and Mazlan, 2012). Evaluating the function $f(L,R)$ for practical pairs of L and R yields a value in the range of 10^5 to 10^6. Using this property, the sensitivity of the lateral stiffness of the WRI to EA is almost zeros ($\frac{\partial K_L}{\partial EA} = O(10^{-8})$). However, evaluating the sensitivity of the stiffness to EI yields a sensitivity in the order $O(10^{-5})$ for practical WRI constructs, hence, the WRI is much more sensitive to EI than to EA. Consequently, the WRI's lateral stiffness can be accurately expressed only as a function of EI and $f(L,R)$ by considering the wire rope cable as infinitely rigid in the axial direction without loss of accuracy:

$$K_L = \frac{2\,N\,EI}{f(L,R)} \tag{15}$$

A number of studies have attempted to develop analytical models for wire rope's behavior. For instance, Velinsky (1988; 1989; 2004) has carried out a detailed study on wire ropes with various configurations. The study was primarily focused on the design and the mechanics aspects of wire ropes having various configurations. Velinsky (1988) has developed a set of dimensionless parameters for the bending stiffness and for the bending to axial stiffness ratio to generalize the study. The sensitivity of these dimensionless parameters were also examined over various wire rope characteristics. Costello (1997) considered the wire rope bending stiffness as the sum of the bending stiffness of the individual strands without considering the interaction among wires. Based on this assumptions, Gerges (2008) has applied the following analytical model (Eq. 16-17) for strand's bending stiffness to a 6x19 WSC (Wire Strand Core) wire rope (see Fig. 6):

$$K_{rope} = K_{cs} + 6K_{gs} \tag{16}$$

where K_{rope}, K_{cs}, and K_{gs} are the bending stiffness of the wire rope, core strand, and the general strand, respectively. The bending stiffness of the center strand is given by:

$$K_{cs} = \frac{\pi E}{4}\left[R_{w1}^4 + \frac{6\sin(\phi_2)}{1+\frac{\upsilon}{2}\cos^2(\phi_2)} R_{w2}^4 + \frac{12\sin(\phi_3)}{1+\frac{\upsilon}{2}\cos^2(\phi_3)} R_{w3}^4 \right] \tag{17}$$

where R_{w1}, R_{w2}, and R_{w3} are the wire radii in the first, second, and third layer, respectively. ϕ_2 and ϕ_3 are the helix angles of the second and third layer. The bending stiffness of a general strand, which is in helix over helix, is given by:

$$K_{gs} = \frac{\pi E}{4}\left[R_{w1}^4 + \frac{6\sin(\phi_2)}{1+\frac{\upsilon}{2}\cos^2(\phi_2)} R_{w2}^4 + \frac{12\sin(\phi_3)}{1+\frac{\upsilon}{2}\cos^2(\phi_3)} R_{w3}^4 \right] \times \left[\frac{\sin(\phi^*)}{1+\frac{\upsilon}{2}\cos^2(\phi^*)} \right] \tag{18}$$

in which ϕ^* is the helix angle of the strand around the core in the wire rope. Eq. (16) can be used to estimate the bending stiffness of the wire rope. However, there is always a difficulty associated with measuring the wire radii accurately and in obtaining the lay angles accurately.

In general, the lay angle for strands range from 71° to 76° and 74° to 105° for wires (Gerges, 2008). Zhu and Meguid (2007) have investigated the flexural damping of the wire rope and as a part of their work; they obtained the bending stiffness of the wire rope through a transverse bending test. In this work, both analytical modeling and transverse bending test were used to evaluate the bending stiffness of the wire rope.

3. Experimental Work

The present study reports two experiments: (1) monotonic loading tests to validate the analytical model for the static lateral stiffness of WRI and (2) transverse bending tests to estimate the flexural stiffness of wire rope cables.

3.1. Monotonic loading tests

The static lateral stiffness of the WRI, which identifies the load carrying capacity in the lateral direction, is obtained from the response of the isolator to a unidirectional load in the lateral roll direction. The lateral stiffness of the WRI is determined from the slope of the force-displacement plot. Previous studies (Demetriades *et al*., 1993; Paolacci and Giannini, 2008) have suggested that the WRI exhibits linear behavior under small displacements and non-linear behavior under higher displacement magnitudes. In-house setup was developed to perform the lateral monotonic loading tests (Fig. 7). The applied load is transferred to the WRI through the pulley to make sure that the load is applied horizontally. The metal wire rope used for loading was connected firmly to the top metal retainer of the WRI while a steel cylinder is held inside the WRI to ensure the roll mode of loading as shown schematically in Fig. 7.

The displacement was measured using the digital dial indicator, which has a resolution of 0.01 mm, an accuracy of 0.02 mm, and a maximum range of 12.7 mm. The WRI was loaded at a slow rate of 0.1 Hz to minimize the inertia effects and to achieve the quasi-static condition. The load applied and the corresponding displacement were recorded after every load step. The loading was performed only up to 5 mm displacement. Table 1 summarizes the specifications of the WRI considered for the monotonic loading tests. The wire rope isolators used in the monotonic test were constructed from the 6×19 WSC stainless steel wire rope cable. The load-displacement plots are shown in Fig. 8. The obtained data points (displacement, load) were best fitted with a linear curve to obtain the slope, which represents the static lateral stiffness of the WRI.

3.2. Transverse bending tests

The material and the specifications of the wire rope cables influence the flexural rigidity of the wire rope (Costello and Butson, 1982). Zhu and Meguid (2007) have performed the transverse bending test for the 6×37 IWRC steel cable to obtain the bending stiffness and the present work follows a similar test procedure to estimate the bending stiffness, *EI*, for the 6×19 WSC stainless steel wire rope cables. ASTM A931-08 was also referred to for the geometric characterization and selection of wire rope test samples. The transverse bending test was performed on the wire ropes having diameters of 6.4 mm, 9.5 mm, 12.7 mm, and 15.9 mm. Fig. 9 shows a sketch of the cantilever test setup. The bending stiffness of the cantilever beam is determined using the end deflection due to the point load acting at the free end. Thus, the bending stiffness can be expressed as:

$$EI = \frac{L_O^3}{3}\left(\frac{W}{Y}\right) \tag{19}$$

where W is the load acting at the free end, L_o is the beam's length, and Y is the free end deflection. The point load was applied at the end of the 300 mm length wire rope to measure its end deflection (Fig. 9). The deflection was measured using the ABSOLUTE Digimatic

Indicator, which features an accuracy of 0.02 mm and a resolution of 0.01 mm. Three samples of wire ropes were tested and the average deflection for each load increment is calculated to plot the load-displacement curves shown in Fig. 10. The slope (*W/Y*) was obtained from the best fit linear curve.

The slope obtained from the transverse bending tests (Fig. 10) are substituted into Eq.(15) to estimate the bending stiffness of each wire rope cable. The analytical model of bending stiffness as given by Eq.(16) was also used to compare the results in order to confirm the transverse bending test, which is not a standardized procedure. Table 2 compares between Eq.(16) and transverse bending test results. The ratio of analytical to experimental bending stiffness is almost one, indicating that the test procedure is adequate and the analytical model provides good estimation of the bending stiffness. Hence, for a preliminary design, it is recommended to use Eq.(16).

4. Results and discussion

The analytical model represented by Eq.(15) is validated using the monotonic test results (shown in Fig. 8). The flexural rigidity required in the analytical model are obtained from the transverse bending test. The comparison between the analytical and experimental results is tabulated in Table 3. It can be observed that the analytical model results are in good agreement with the experimental results within 16 % error margin. The analytical model relates the lateral stiffness to the WRI geometric and mechanical properties. The analytical study is extended to assess the effects of wire rope diameter, width, height, and number of turns (coils) on the WRI's lateral stiffness. The developed analytical model may also be used to design the appropriate WRI to obtain a desired lateral stiffness or to evaluate the modification required in the geometric properties to target a specific increase or decrease in the stiffness.

4.1. Influence of wire rope diameter

The wire rope diameter plays a significant role in the behavior of the WRI. The measured effects of wire rope diameter on the lateral stiffness of WRI are not reported in the literature. Thus, the effect of the wire rope diameter on the lateral stiffness is investigated. Eq.(15) suggests that the lateral stiffness is highly dependent on the wire rope diameter and hence the wire rope diameter can be adjusted to control the stiffness and behavior of WRI. Fig. 11 shows the effect of wire rope diameter on the lateral stiffness for different number of turns for an isolator with R=35 mm and L=12.7 mm. Analyzing the plots reveals that the stiffness is a function of the wire rope diameter to the power of four. As a result for N=8, an increase in the diameter from 6.4 mm to 9.5 mm results in an increase of the stiffness by a factor of $\sim(9.5/6.4)^4 = 4.85$, which is equal to the stiffness ratio 38.09/7.75, and an increase in the diameter, say, from 9.5 mm to 15.9 mm induces an increase in the stiffness by a factor of $\sim(15.9/9.5)^4$. This significant increase in lateral stiffness is mainly due to the increase in the resistance of the wire rope to lateral deformation (i.e., flexural rigidity), which is due to the increased diameter, and hence inertia, of individual wires.

4.2. Influence of Width and Height

The geometry of the coil is fully defined by the width and height of the WRI, which in turn control the parameters L and R in Eq.(15). Therefore, any change in the width and height of the WRI affects the lateral stiffness. To assess this effect, we plotted the variation of lateral stiffness with the width and height in Fig. 12. It is observed that, in contrast to wire rope diameter, an increase in the width or height decreases the lateral stiffness. An evaluation of the sensitivities of the stiffness to the width and height demonstrated that the stiffness is twice more sensitive to the height than to the width.

Fig. 13 shows the effect of height-to-width ratio on the lateral stiffness. The lateral stiffness of the WRI decreases with increased height-to-width ratio, especially for bigger wire rope cable diameters. This increase in stiffness is attributed to the increased slenderness of the isolator ($H>W$) that makes the isolator softer in the lateral (roll) mode of loading. In addition, it is observed that the stiffness is more sensitive to the change in the wire rope diameter than to the width and height of the isolator, especially for slender isolators. Consequently, the current trend in the industry is to majorly maintain a height-to-width ratio between 0.75 and 0.85.

4.3. Influence of Number of turns

The increased number of turns provides the WRI with an increased load bearing capacity. With reference to Eq.(15), it is clear that the lateral stiffness is directly proportional to the number of turns. This key parameter can be used to control the lateral stiffness of WRI in case of space-restricted applications. In other words, when the space (in a direction perpendicular to the lateral direction) is limited, the desired lateral stiffness can be achieved by increasing or decreasing the number of turns. Although, the WRI can be constructed with any number of turns, it is generally manufactured with even number of turns (such as 2, 4, 6, or 8 turns) to provide an adequate stability of the equipment.

5. Conclusions

In this work, an analytical model for the lateral stiffness of wire rope isolators is presented. The developed model was validated with experimental data obtained from monotonic loading tests performed on a series of wire rope isolators. The significance of the developed model lies in providing the required understanding of the effect of geometrical and mechanical properties on the lateral stiffness of WRI. The developed analytical model can be used in the selection and design of WRI. In addition, this study has led to the following conclusions:

1. The lateral stiffness (in the roll mode) of the WRI is highly sensitive to the flexural rigidity (bending stiffness) of the wire rope cable. The axial stiffness of the wire rope cable has a negligible effect on the lateral stiffness of the WRI.

2. The lateral stiffness is significantly influenced by the wire rope diameter and height than the width.

3. The number of turns is directly proportional to the WRI's lateral stiffness.

4. An increase in wire rope diameter increases the lateral stiffness, however, an increase in either width or height results in the decrease in lateral stiffness.

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Captions for Figures

Captions for Tables