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PERFORMANCE STUDY OF WIRE ROPE ISOLATORS FOR VIBRATION ISOLATION EQUIPMENT AND STRUCTURES

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ABSTRACT

The wire rope isolator (WRI) can effectively provide vibration isolation of equipment and structures. The main advantage of WRI is the effective isolation in all three planes and in all directions. The WRI provides the damping of the external disturbance through its friction between the wire strands. The present work is the study on the performance of WRI in the isolation of equipment supported on structures. This study is performed in four different cases namely, Fixed Structure and Fixed Equipment, Isolated Structure and Fixed Equipment, Fixed Structure and Isolated Equipment, Isolated Structure and Isolated Equipment. The present work compares the performance of WRI in all the four cases. The study also extended on the parametric study for the effects of frequency of external excitation, weight of the equipment and excitation direction. It is found that the WRI were effective in providing the isolation for the frequency studied and increased weight of the equipment enhances the performance of WRI. The present study can be used to identify the different ways to provide the isolation of the equipment supported on the structures through WRI.

Keywords: wire rope isolators, vibrations; isolation, vibration control, excitation, damping.

INTRODUCTION

Vibration is one of the important factors to consider during the design process and its detrimental effect on the equipment and structures is of major concern. In many cases, the vibrations are unavoidable, but it will be within tolerable limits. In other cases where the vibration becomes intolerable, the isolation system is applied to cut off the path of the vibration to enhance the safety of the receiver [1, 2]. A general isolation system has two main components namely, Stiffness (K) and Damping (C) [3]. Firstly, the stiffness of the isolation system provides the restoring force and also influences the natural frequency of the isolated system. The lower value of transmissibility can be achieved by decreasing the stiffness which results in shifting the natural frequency of the system to a lower value [4]. Secondly, the damping component of isolator enables the energy dissipation of the external excitation to suppress it. The amount of damping required is subjective and varies with respect to applications.

In general, the isolation system can be used in two different cases as shown in Figure-1. Case 1: The isolation system can be used to reduce the force transmission from the equipment of mass M, to support structures as in the case of heavy machineries. The disturbances from the rotating machineries are in general, harmonic in nature and depend on the RPM of the machinery. The disturbing frequency of the machine is readily identified as the lowest RPM [5]. Case 2: The isolation is also used to isolate the sensitive equipment whose precision is affected by the disturbing surroundings. The basic principle of vibration control remains same for both the cases [6]. Different types of passive isolation devices are used and they can broadly categories as linear and non-linear isolators. Earlier developed passive isolation systems are linear in nature and hence possess the inability to provide isolation in the frequency range lower than its natural frequency and this disadvantage can be overcome by using the nonlinear isolators. Recently Wire Rope Isolators (WRI), a type of passive isolator which exhibits non-linear behaviour in both stiffness and damping, has become the subject of intensive studies.

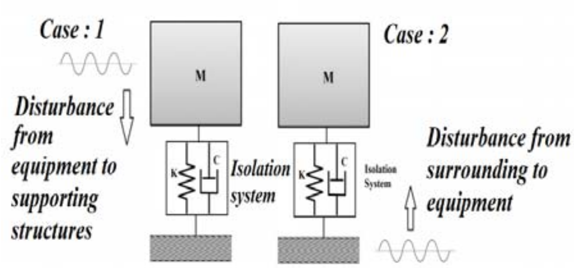

Figure-1. Applications of isolation system.

WIRE ROPE ISOLATORS

Wire Rope Isolators (WRI), a type of passive isolators, known to be effective in isolating the vibration and shocks, can be used to protect the system [7, 8]. WRI is made up of wire rope held between a metal retainer either in a form of helical or arch and called helical WRI (Figure-2(a)) or polycal WRI (Figure-2(b)) respectively. The individual wire strands of the wire rope are in frictional contact and move relative to each other and hence friction causes the dissipation of vibrational energy [9-11]. The wire rope has the ability in attenuating the

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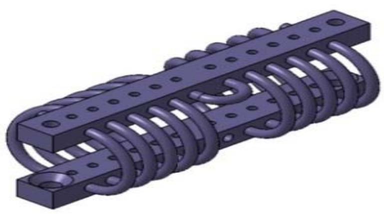
vibration and able to absorb the impact energy efficiently [12, 13].



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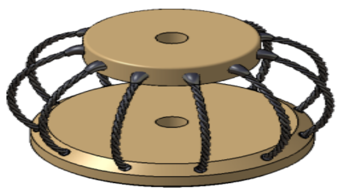

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Figure-2. (a) Helical wire rope isolator (b) Polycal wire rope isolator.

WRI has been extensively applied for shock and vibration isolation in military and industrial applications [14]. The primary advantage of WRI is their ability to provide isolation in three planes and in all the directions due to which it can be mounted in any orientation (Figure-3) to protect structures and equipment excited in any directions [7,8]. Such orientation induces tension/ compression, shear and roll load on the WRI as shown in Figure-4.

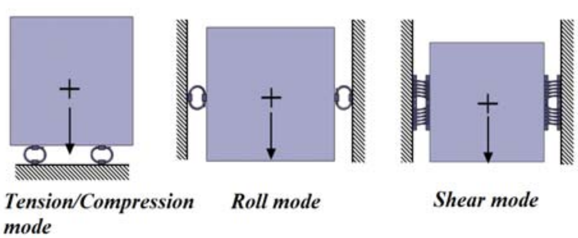


Figure-3. Orientations of WRI used in applications.

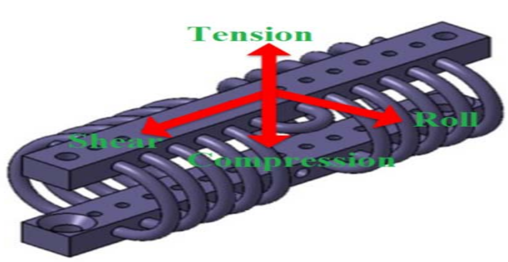


Figure-4. Loading of the WRI.

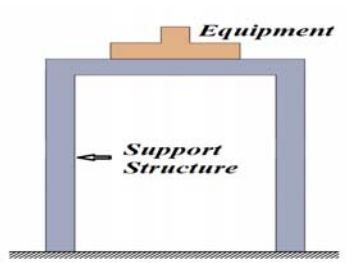
The field of WRI is relatively new, hence only few research works are available and among the available research work, mostly are dedicated towards the cyclic loading behaviour. The major contribution on the behaviour of WRI is presented. Tinker and Cutchins [7, 8] performed the experimental study for the damping phenomenon and suggested that the energy dissipation occurs through the friction between the individual wire strands. Demetriades *et al*. [11] performed a study on the hysteresis behaviour and experimentally tested the isolation capabilities of WRI. The study shows that the WRI exhibits hysteresis curve under cyclic loading and the hysteresis curve is symmetric for shear and roll load and asymmetric for tension/compression loading. They have developed a mathematical model for hysterical behaviour using Bouc-Wen model. Furthermore, the study also found that WRI provides 10% and 20-30% damping for large and small deformations respectively.

Balaji *et al*. [2] performed the experimental study on the hysteresis behaviour of WRI under cyclic loading in vertical and horizontal direction and suggested that the wire rope diameter primarily influence the hysteresis behaviour. The behaviour of WRI under monotonic [7, 8] and cyclic loading [11] is presented in the literatures. However, only few literatures [11, 15] are available on the performance of WRI. The literatures also lack the comparison study between different arrangements of WRI for the isolation of the equipment and together with the supporting structure. Hence, the objective of the present work is to study the performance of the WRI under base excitation between different arrangements of WRI with the equipment and support structure. The present study also extended for the effects of frequency and excitation directions. The performance of WRI is identified based on the acceleration reduction achieved on the isolated equipment and structure.

PERFORMANCE STUDY

The equipment isolation is the focus of our study. The study on the performance of WRI under different arrangements to obtain the effective isolation of sensitive equipment is performed. The systems such as disk drives, sensitive mobile electronics, electronic cabinets, small pumps and motors comes in the category of equipment supported on the structure. Under the situation when operated near heavy rotary machineries, the harmonic disturbance can affect the functionality of these devices. Hence, it is essential to provide an isolation system to minimize the disturbance. As WRI can provide isolation in all plane and effective against both shock and vibrations [8, 11] hence, it can be considered as a better solution to isolation problems.

The performance of WRI in isolating the equipment from the vibrational environment is studied in four cases, Case 1 : Fixed Structure and Fixed Equipment (FSFE), Case 2 : Isolated Structure and Fixed Equipment (ISFE) , Case 3 : Fixed Structure and Isolated Equipment (FSIE). Case 4: Isolated Structure and Isolated Equipment (ISIE). Figure-5 shows all cases under consideration. The performance study is performed by comparing the acceleration response of the equipment and structure under harmonic base excitations. The equipment is mounted on the top of the support structure. Upon base excitation, the top of the structure experiences slightly amplified vibrations than the base. The comparison is made between the acceleration response at the top level of the structure and the equipment.



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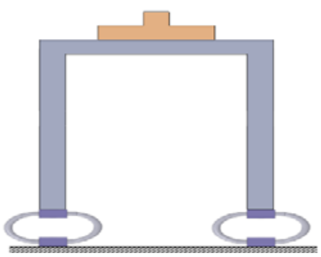

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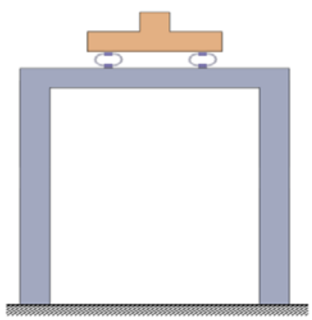

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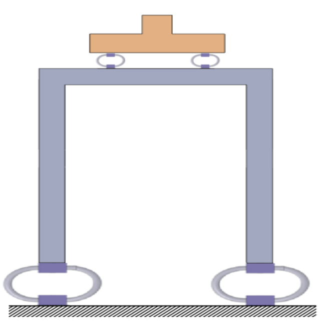

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Figure-5. Different arrangements of WRI isolation system under consideration (a) FSFE (b) ISFE (c) FSIE (d) ISIE.

The frequency of the excitation plays a major role in the performance of the WRI and hence the present study also extended on frequency effects. The selection procedure [16, 17] of the WRI isolation system suggests that the natural frequency of the isolated system required being less than the disturbing frequency for better isolation. Based on this fact, the natural frequency of the isolated equipment is calculated as 0.56 Hz and the system is excited with the different frequencies more than the 0.56 Hz. The study compares the different arrangements of structure-equipment isolation using the acceleration response of the equipment and structure, subjected harmonic base excitation in harmonic shaking table.

EXPERIMENTAL SET UP

The experimental work was performed using the harmonic shaking table available in structural lab, UTM, Malaysia. The structure used has the overall dimension of 900 mm x 900 mm x 1200 mm made up of steel. The acceleration data was recorded using 4 accelerometers (Acc No.1, Acc No.2, Acc No.3, Acc No.4) each placed at the different location on the structure as shown in the Figure-6. The Acc No.1, Acc. No2 Acc No.3 were used for the equipment, top level of the structure and shaking table, respectively and Acc No.4 were used for the noise. The sensitivity of the accelerometers used was 101.8 $mV/m/s^2$, 101.4 $mV/m/s^2$, 102.9 $mV/m/s^2$, 102.3 $mV/m/s^2$ respectively.

The specifications of the isolator [18] used for the equipment and structure is shown in the Table-1. Figure-6 shows the fixed structure configuration. The bolts were used to fix the base of the structure with the shaking table and C-clamp was used to consolidate the fixing condition. For the cases of structure isolation, each leg of the structure was fixed over the WRI through bolts. The isolation of the equipment was achieved by two isolators were used. Each case was individually test in the shaking table under harmonic base excitation.

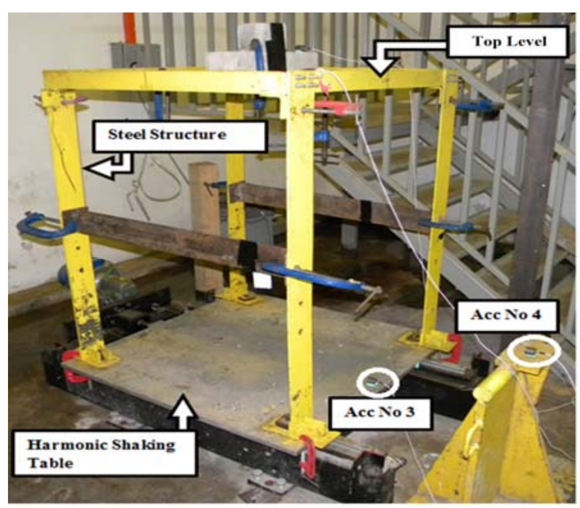

Figure-6. Shaking table test arrangements (a) Test setup for case 1.

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Table-1. Specifications of the WRI.

Isolation	Wire rope diameter (mm)	Width (mm)	Height (mm)	Length (mm)	Vertical stiffness (N/mm)
Equip.	3.2	38	30	128	77
Struct.	9.5	105	90	216	504.5

RESULTS AND DISCUSSIONS

This section contains the details on the input excitation and also provides the comparison and discussion on each case test result. The harmonic shake table used in the present work, provides the base excitation at input frequency at the constant displacement amplitude of 40 mm and hence the input displacement and acceleration sine wave can be written as

$$D = D_o \sin(2\pi f t) \quad (1)$$

$$A = -D_o (2\pi f)^2 \sin(2\pi f t) \quad (2)$$

where D_o is the displacement amplitude (40 mm), f is the excitation frequency and t is the time period. The controller of the shaking table is provided only with the frequency control which facilitates the input desired frequency. Since the harmonic shaking table is based on frequency controlled at constant displacement amplitude, the peak acceleration is frequency dependent and can be obtained from Equation. (2). The four cases under consideration were compared for the performance study of WRI.

Figure-7 shows peak acceleration comparison of the fixed structure and fixed equipment. This arrangement does not have any isolation device. This arrangement was tested to observe the increase in the acceleration at the equipment under base excitation. The top levels of the structures often experience the amplified accelerations relative to the lower level [19] . It can be observed that the acceleration in equipment is increased 2 times than the base excitation. In the present work, the support structure was made slender to increase the acceleration at the top level in order to study the effectiveness of WRI in reducing the acceleration. However, this increase in the acceleration can significantly reduce by proper design of the support structure. Figure-8 shows the acceleration-time plot for different cases at 1.25 Hz. The acceleration response of the equipment has other components which may be due to the non-linearity of the WRI.

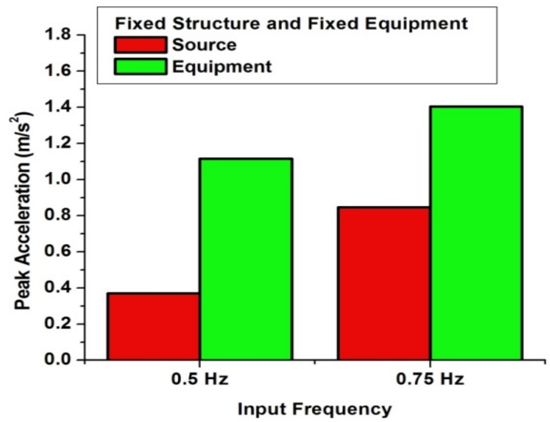
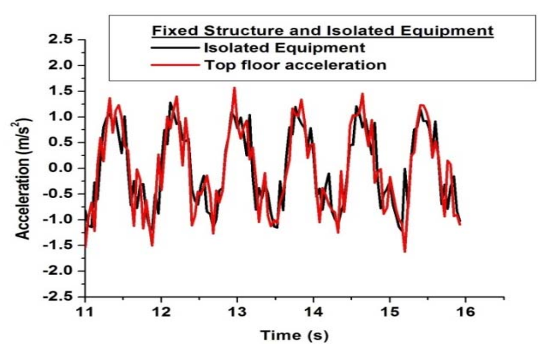


Figure-7. Comparison of peak acceleration between equipment and top level for fixed structure and fixed equipment.

The energy dissipation in the WRI is provided by the frictional contact between the individual wire strands. The different arrangements has their difference in the amount of acceleration received at the equipment level. The fixed structure amplifies the acceleration on the top level of the structure and the amount of amplification depends on the vertical height of the top level from the fixed end with ground. Hence, the WRI has to dissipate this extra amplified acceleration due to the vertical height and together with source acceleration.



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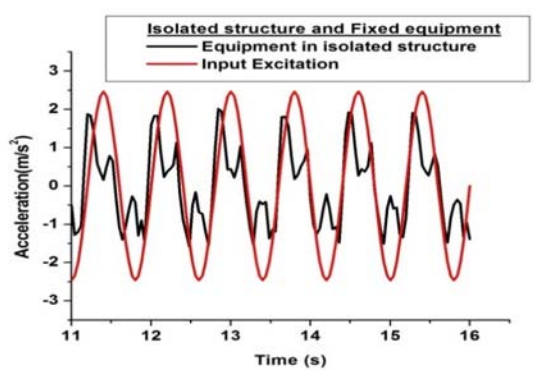

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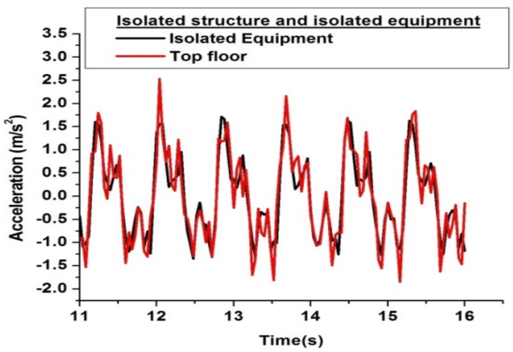

(c)

Figure-8. Acceleration-time plot for different case (a) FSIE (b) ISFE (c) ISIE.

The case of ISFE arrangements will have the reduced acceleration at the leg of the structure but still the acceleration can be amplified by the supporting structure and reach the fixed equipment. When compared between the cases of ISFE and FSIE, the acceleration of about 1.96 m/s^2 and 2.3 m/s^2 was observed on the top level of the structure for the FSIE and ISFE respectively. It can be understood that, when the equipment is available at the increased height of the structure and may encounter amplified vibrations, which can significantly affect the system performance. This case also demands the proper design of the support structure, as the improper design could develop undesirable amplification of the acceleration and worsen the equipment performance. This case also requires increased maintenance of the support structure and on the fittings between the beam and columns as any amplification after the isolation system is undesirable.

The case of FSIE focuses on the equipment required to isolate. This case has a relative advantage than the ISFE that, the design of the support structure can be relaxed and can be compensated with the WRI having better specification for the equipment, to deal with the amplified acceleration at the top level. Moreover, the further amplification of acceleration by any known or unknown factor of the structure can be reduced at the WRI available at the equipment support. This case can be more reliable with relative advantages and required less maintenance of the support structure.

In order to compare the various cases, the peak acceleration ratio between the equipment and the top level of the structure is taken and however, in the case of ISFE, the ratio is taken to source. Figure-9 shows the peak acceleration ratio comparison between the cases. The ISIE case has shown the relatively less acceleration ratio. The case of ISIE, where the isolation of both structure and equipment is performed, can be relatively effective however; it makes the system over design. The peak acceleration ratio (Figure-9) comparison supports the ISIE case but this over design may not be economical. This case is not neglected, but can be used in the situation where the support structure is encountered with the dynamics forces along its height in addition to the base excitation.

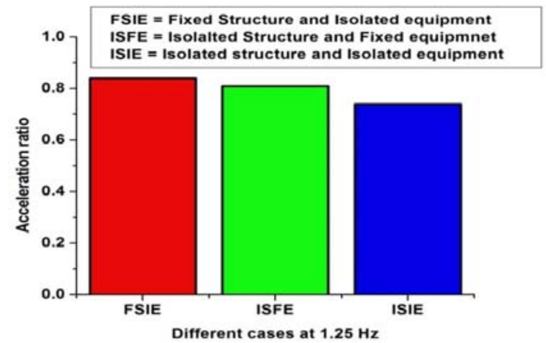

Figure-9. Peak acceleration ratio comparison between different cases.

Although all the case such as FSIE, ISFE and ISIE represents the different approaches for the isolation of the equipment, the FSIE would be more economical for the application and possess relative advantages with the ISFE case. Moreover, it is much easier to isolate the required equipment than the entire structure and hence, it is suggested that the isolation of equipment with the fixed structure can provide the required isolation

PARAMETRIC STUDY

The present work is also extended to study the effects of frequency and mass of the equipment on the performance of WRI. All the cases under consideration was involved in the frequency study. The results of the each study are discussed in this section.

FREQUENCY STUDY

Figure-10 shows the peak acceleration for all the cases under consideration. The isolator performance is significantly influenced by the forcing frequency. The isolators provide effective isolation for the forcing frequency higher than the natural frequency of the isolated system. The isolated equipment has the natural frequency of about 0.56 Hz hence for the frequency range 0.5 Hz amplification was observed in the FSIE case, as shown in the Figure-10 (a). However the damping of the WRI, provided by the friction between wire strands, limits the amplification of the acceleration. The isolation with the softening characteristics provides better isolation at frequency higher than the natural frequency of the isolated system. The WRI possess the softening characteristic in lateral direction and hence was found to exhibit better performance in the higher frequency range as shown in the Figure-10. It can also observed that the ISIE case, provides better isolation in all frequency range however, the required isolation can be achieved with much simpler FSIE case.

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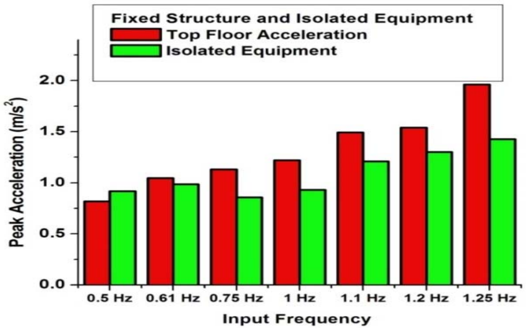

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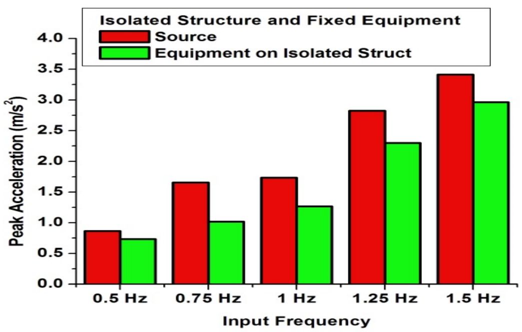

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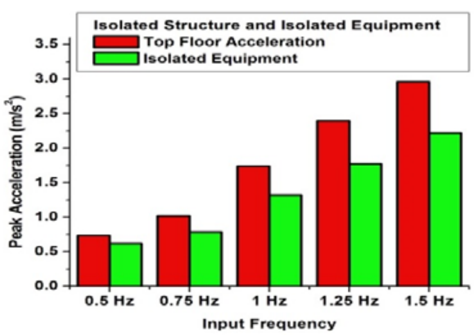

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Figure-10. Comparison of peak acceleration for different cases (a) FSIE (b) ISFE (c) ISIE.

WEIGHT OF THE EQUIPMENT

The study on the effect of weight of the equipment was performed by conducting the experiments with two weights 11 kg and 13 kg. The increased weight implies the decrease in the natural frequency of the isolation system and hence it expected to achieve better isolation for increased weight. The vibration control at frequency range higher than the natural frequency of the isolation system is generally achieved by increasing the inertia. Figure-11 shows the acceleration ratio between the equipment and top level of the structure for different frequency. It is observed that the increased weight produces positive effect in reducing the acceleration ratio further. This is due to the decrease in the contact points between the wire strands under compression load and attributed as the softening characteristics of WRI.

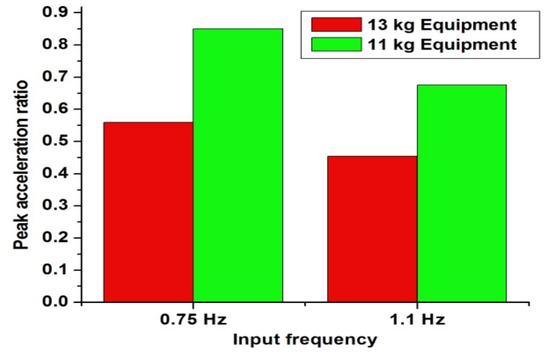

Figure-11. Peak acceleration ratio comparison for different excitation direction.

EFFECT OF LOADING DIRECTION

The major advantage of WRI is that, it can provide effective isolation in all planes. This property of the WRI is studied by exciting the WRI in its shear and roll direction (Figure-4). The peak acceleration ratio at 1 Hz is shown in the Figure-12. It can be observed, that the WRI were able to provide effective isolation in different directions. This behavior mainly due to the inherent ability of the wire rope to dissipate the energy through the friction between the wire strands. The multi directional effectiveness of the WRI is attributed due to the helical twisting of wire strands.

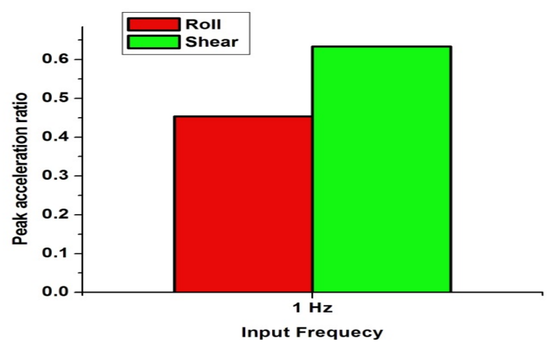

Figure-12. Peak acceleration ratio comparison for different weight for the equipment.

CONCLUSIONS

The isolation of equipment and structures can be effectively provided by the WRI. The WRI provides the damping of the external disturbance through its friction between the wire strands which also makes it effective in all three planes and directions. The present work was the study on the performance of the WRI. The following conclusions have been made from the present study.

- WRI was found effective for all cases under consideration.
- In the present study, the peak acceleration ratio of 0.84, 0.74 and 0.81 for FSIE, ISIE and ISFE respectively, was obtained.
- FSIE case can be provide effective isolation of the equipment with economic advantages.

- WRI were found to provide better isolation for higher frequencies far from the natural frequency of the isolation system.
- Increased weight of the equipment resulted in the better isolation attributed due to the softening of the WRI
- The WRI was found effective for both shear and roll

ACKNOWLEDGEMENTS

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