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Attenuating vibration transmission from a Town Board Station (TBS) to the neighbor residential building using an optimum isolator: A case study

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A B S T R A C T

Town Board Stations (TBS) are usually located in residential areas. Pressure reduction through reducing valves in these stations generates considerable amounts of sound and vibrations. These mechanical waves have undesired effects on the equipment such as reducing the fatigue life of the gas transmission line. On the other hand, propagation of these wave in the residential area, causes discomfort for the neighbors of these stations. In this paper, vibrations generated in a TBS and transmitted to the residential building in the area are investigated through modeling and analysis. The aim is to study and propose a method for reducing vibration transmission from the TBS to residential buildings by using a numerical model. A vibration isolator is designed for this purpose with optimum parameters and considering the practical limitations of the problem. The performance of the isolator is verified with the help of the developed FE model. Results show the effectiveness of the designed vibration isolator for the operating range of the TBS.

1.Introduction

In a pressure reducing station, the gas flow through the pipes creates a considerable amount of sound (noise) as it passes through the reducing valves. The noise created in the valve propagates in the gas flow and results into vibrations of the pipes. Vibrations of the pipes are transmitted to their supports which are grounded and eventually, they are spread inside the ground. The path for transmission of vibration waves in the ground and the vibration amplitude and propagation speed depends on soil composition. Also, the vibration amplitude and propagation speed depend on soil

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composition. In case these vibration waves reach a neighbor building, they will be sensed by the residents as low frequency noise (rattle) waves making them feel uncomfortable.

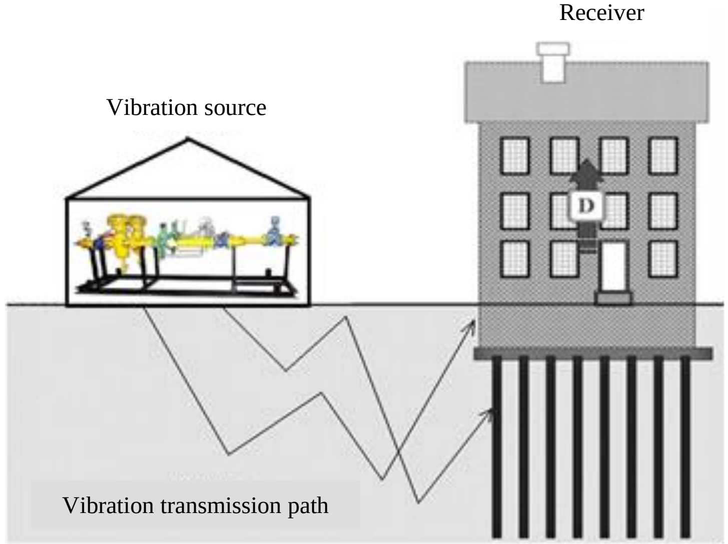

Fig 1: The process of vibration generation and transmission

The vibrations transmitted to a building may also be sensed as low frequency noise inside the building. Vibration transmission from a Town Board Station (TBS) to the neighbor buildings is a complicated problem which involves several parameters. As shown in Fig. 1, the process may be divided into three sections: The vibration source, the path for vibration transmission and the receiver. The vibration amplitude is generally reduced as transmitted from the source to the receiver for several reasons. The important factor affecting the vibration attenuation when transmitted from source to receiver is the damping of materials present in the transmission path. However, it is also possible that the vibrations get amplified throughout this path mainly due to the resonance of some equipment in the transmission path. To reduce the vibrations transmitted to the receiver (neighbor building) to an acceptable level, either the source or the transmission path should be modified. The acceptable vibration levels based on standard codes are discussed in [1].

The problem of noise and vibration in pressure reducing valves has been considered by many researchers in the past. The main approach used by researchers is to control noise and vibration in the source, i.e. the pressure reducing valve. For example, Amini and Owen [2] proposed a new design for valve plug and seat to reduce the mechanical vibration of the valve. Yu and Yu [3] studied the jetting noise at the nuzzle of a pressure reducing valve by using numerical and experimental results and proposed to reduce the jetting noise by optimizing the main channel structure of the valve body.

As it was stated earlier in this section, the generated vibration in a TBS can be transmitted to neighbor areas through ground which is usually known as ground-borne vibration. Ground-borne vibration is a serious concern for neighbors of a transit system route or maintenance facility which causes buildings to shake and rumbling sounds to be heard. Several numerical methods may be used to investigate the problem of vibration transmission in ground. These methods involve the Finite Difference Method (FDM), the Finite Element Method (FEM) and the Boundary Element Method (BEM) [4]. Usually, for problems which have limited boundaries, the FEM or FDM methods are employed. The BEM is more used for problems which have unlimited boundaries. There are many papers addressing the use of numerical simulations to study the effects of vibration generated by moving vehicles- i.e. high-speed trains, underground busses- on the neighbor residential area. The study of vibration transmission through the ground can be performed by 2D or 3D numerical models. The accuracy of 2D and 3D models are compared by Andersen and Jones [5] for the problem of vibration transmission from underground railway tunnels to the ground surface. Unterberger *et.al.* [6] used the FDM to model the vibrations caused by the Vienna metro line. In their analysis, only the metro tunnel and the surrounding ground were considered in modeling. To simulate vibrations caused by the train, they employed a harmonic force. A study on the problem of vibration transmission from a train to the human body is presented by Lai *et.al.* [7]. In this study, the effect of damping is considered through the vibration transmission route. Frequency Response Functions (FRF) which were measured both between the ground and building foundation as well as between the foundation and several floors are employed in this investigation. A 2D FE model is used by Schillemans [8] to simulate vibrations at the intersection of train tunnels. Three-dimensional finite element modeling coupled with infinite elements are used by Rahman and Orr [9] to investigate the ground vibrations at the surface caused by construction of the Dublin Port Tunnel.

To the best knowledge of the authors, the investigation of vibration generated in TBS has been limited to the control of vibration at the source and there are seldom published articles addressing the transmission of vibration from station to the neighbor buildings. Therefore, in this article, modeling and analysis of vibration transmission from a TBS to the neighbor residential building are presented. The analysis is performed using a FE model including the pipes and the equipment installed on them, the support structure of the pipes in the TBS, the skeleton frame of a 4-storey residential building, the foundation of the TBS and building, and part of the soil surrounding the building and the TBS. Results of vibration analysis on this model are used to propose solutions for attenuating vibration transmission from the TBS to the neighbor residential building. The main objective of this paper is to design a vibration isolator for the support structure of the pipes and to study the effects of this vibration isolator on the vibration transmitted to a neighbor building. It is worth noting that the results presented in this paper are from a numerical model which is based on a real problem. This means that all dimensions are real and it is tried in FE modelling to construct a correct FE model by selecting appropriate elements. There are two types of models used in FE analysis; correct models and accurate models. Correct models are obtained by proper modelling and meshing the geometry of a structure. If a model is correct, its accuracy can be increased by tuning its parameters using experimental data and an accurate model is then obtained. Although accurate models can exactly predict the response of the structures, the correct models can be used to study the overall behavior of the structure and the effect of different parameters on the structural response. Therefore the results obtained from a correct model is valuable and useful. In the following section, a correct model is constructed for the structure considered in this paper.

2. Finite Element modeling

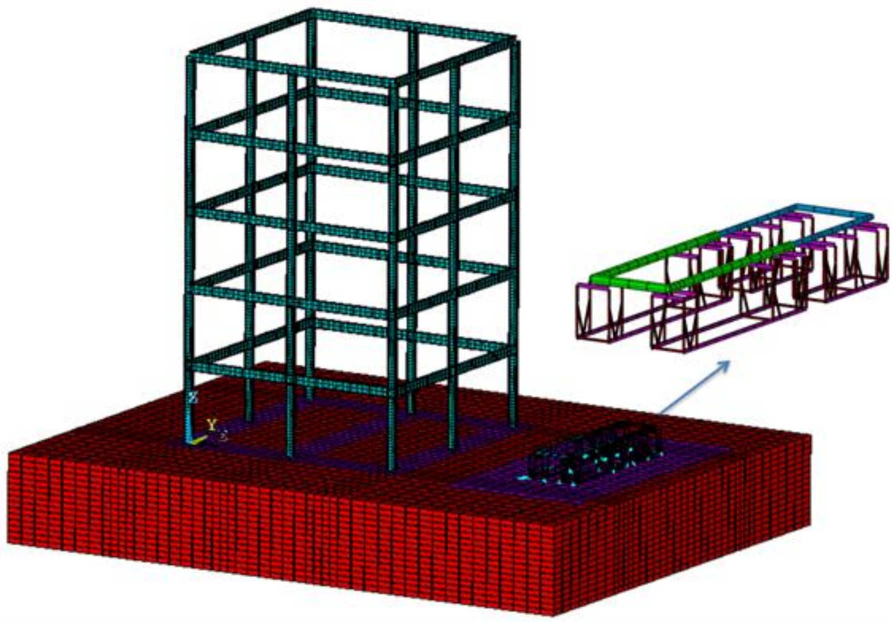

Fig 2: FE model for the TBS, the neighbor residential building and the surrounding soil

Investigation of vibration transmission from the TBS to the neighbor residential building is performed using a FE model constructed in this section. All parts located on the path from the TBS to the building should be considered in such model. In general, the vibration transmission path is described as follows; Vibrations are generated in the pipes of the TBS due to the jetting noise in pressure reducing valves. The vibrations generated in the pipes are transmitted to the concrete foundation of the TBS through the support metal structure of the pipes. The residential building is close to the TBS. Therefore, vibrations are transmitted through the surrounding soil from the TBS foundation to the foundation of the building. Finally, the skeleton frame of the building transmits vibrations from the foundation to all floors.

Modeling the TBS is described first. The TBS is composed of three main sections; (i) pipes and the equipment installed on the pipes, (ii) the support structure for pipes and (iii) the concrete foundation of the TBS. The equipment installed on the pipes include valves and filters. The ANSYS software is used in this study for modeling. The pipes and their support structure are considered made of steel. The properties of the steel used in modeling are shown in Table 1. The element *Beam188* is used for modeling the pipes and their support structure. The equipment installed on the pipes are modeled as concentrated masses using the element *Mass21*. The foundation of TBS is assumed to be made of concrete. This foundation is modeled using the *Solid45* element. There is a considerable amount of damping in a concrete structure which has effects on the dynamic behavior. Although damping in real concrete structures is generally non-proportional, the so-called Rayleigh damping model is commonly used to incorporate damping in structures when assessing their seismic response. In this model, damping is assumed as a linear combination of stiffness and mass matrices of the structure, i.e. $[C] = \alpha[K] + \beta[M]$. It should be noted that the stiffness matrix and mass matrix coefficients in Rayleigh damping model are case dependent. Therefore, they can be estimated uniquely for different structures by employing experimental data. Many efforts have been paid in the past to estimate these coefficients as well as to investigate the effects of a stiffness-proportional or mass-proportional Rayleigh damping model on the dynamic response of structures. Ito and Uomoto [10] used the impact acoustic and surface vibration of a concrete block and estimated the coefficients of the Rayleigh damping model. Cruz and Miranda [11] employed the acceleration signals recorded during different earthquakes to evaluate the Rayleigh damping model. Since in this paper, a numerical case study is considered, there are no real values available for Rayleigh damping model coefficients. Therefore, in the FE model for concrete structure, typical stiffness-proportional damping is assumed by considering $\alpha = 0.001$ and $\beta = 0$. The joint between the pipes and support structure is assumed to be rigid in the model. The joint between the support structure and ground is once assumed rigid and once flexible in the modeling strategy. By rigid joint it means that the corresponding nodes are rigidly connected to each other (i.e. they are merged). As will be described, using the flexible joint is the solution for attenuating vibration transmission in this work. In modeling the flexible joint, it is assumed that vibration isolators are used between the support structure and the ground. Vibration isolators are used to attenuate the transmission of oscillatory forces to the ground and thus, to reduce the vibrations sensed in residential buildings. Optimum parameters of such isolator to minimize transmission of vibratory forces to the ground will be designed in the following sections. For modeling such isolator (or flexible support), the element *Combin14* is used in this work.

Next, the details for modeling the residential building is described. It is assumed that a 4-storey residential building is close to the TBS. In the metallic skeleton frame of the building, the vertical members (columns) and horizontal members are assumed to be $W\ 24 \times 335$ and $W\ 30 \times 99$ steel beams respectively. The elements *Beam188* and *Solid45* are used respectively for modeling the skeleton frame (steel) of the building and its foundation (concrete). The frame is assumed to be made of steel and the foundation is assumed to be made of concrete. Finally, the soil surrounding the TBS and the neighbor residential building is considered for modeling. In order to take into account the effect of the ground in vibration transmission from the TBS to the neighbor residential building, a volume of the soil with dimensions $24m \times 19m \times 3m$ is modeled. The element *Solid185* is used for this purpose. The soil properties for this modeling effort are addressed in Table 1. In this work, linear dynamic behavior and Rayleigh damping model is assumed for the soil. Referring to the explanations presented earlier about the damping of concrete and given the damping effect for soil is greater than concrete, a stiffness-proportional Rayleigh damping model is considered for soil which assumes $\alpha = 0.01$ and $\beta = 0$. The final FE model is shown in Fig. 2. After application of the boundary conditions, the model is used for analysis. It should be noted that usually in FE modeling of an infinite media, such as soil, the boundary condition at the truncated boundaries should be non-reflecting which can effectively absorb the incident stress waves and can represent almost accurately an infinite space [12]. The non-reflecting boundary conditions are categorized into local type and global type. In the local type, a combination of spring and viscous damping elements are used at the boundaries to absorb the mechanical energy [13]. In this paper, a relatively high value for the soil damping ratio is used in FE modeling and it is assumed that due to high damping, the waves are relatively damped when they reach the boundaries. Keeping this assumption in mind, the degrees of freedom which are perpendicular to the ground surface are fixed for the underground nodes in the model.

Table 1: Material properties used in construction of the Finite Element model

Material	Young modulus (GPa)	Density (kg/m^3)	Poisson's ratio
Steel	210	7800	0.28
Concrete	27.7	2400	0.15
Soil	0.957	2082	0.25

3. Vibration isolator: Optimal design and performance evaluation

It was addressed earlier that two main methods may be employed to attenuate vibration transmission from the TBS to the neighbor residential building. The first method is to remove the vibration source or to attenuate vibration transmission from the station to the ground. The other method is to modify or reinforce the transmission route of vibrations such that vibrations are less transmitted from the ground to the building. In the current study, the first method is employed. A vibration isolator is designed for the TBS for this purpose. Sound and vibration is unavoidably produced in a TBS due to pressure reduction in reduction valves. Thereupon, to control vibrations one can attenuate vibration transmission from the station to the ground using isolators. In this section, an optimum vibration isolator is designed for the TBS with the help of an

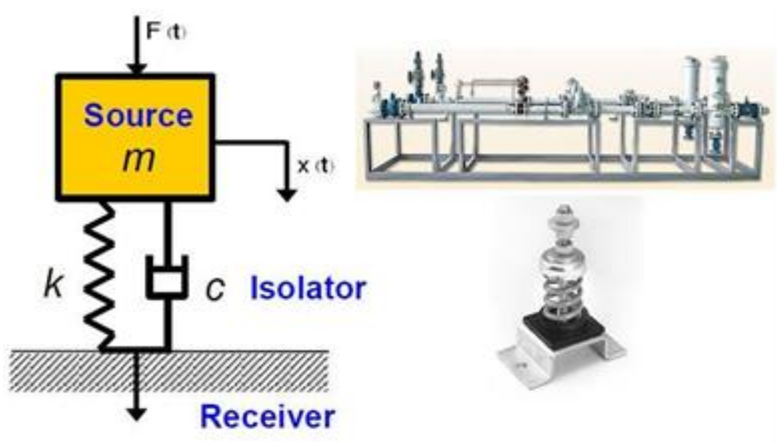

Fig 3: The SDOF model for TBS

equivalent SDOF model and its performance - in real conditions - is investigated using the FE model of the TBS station only, i.e. pipes, equipment and supporting structure, as will be described later in this section. The equivalent SDOF model for the station is shown in Fig. 3 in which the pipes, equipment and supporting structure are considered as a lumped mas and the isolator is considered as a spring and viscous damping.

It is assumed in Fig. 3 that a dynamic force $F(t) = F_e e^{j\omega t}$ is applied on the mass m. This force resembles the dynamic excitation causing vibrations of the pipes in a station. From the classical vibration theory, one may obtain the ratio of transmitted force to the ground - F_t - over the excitation force on mass m - F_e- as follows [14]. The transmitted force is the sum of the forces generated in spring and damper elements when the equivalent model in Fig. 3 vibrates. The spring and damping forces can be obtained by assuming a harmonic response as $x(t) = Xe^{j\omega t}$ and substituting it in the governing equation of the structure. Because of the simplicity, calculation of these forces are omitted in this paper.

$$F_r = \left|\frac{F_t}{F_e}\right| = \sqrt{\frac{k^2 + (c\omega)^2}{(k - m\omega^2)^2 + (c\omega)^2}} = \sqrt{\frac{1 + (2\zeta r)^2}{[1 - (r)^2]^2 + (2\zeta r)^2}} \tag{1}$$

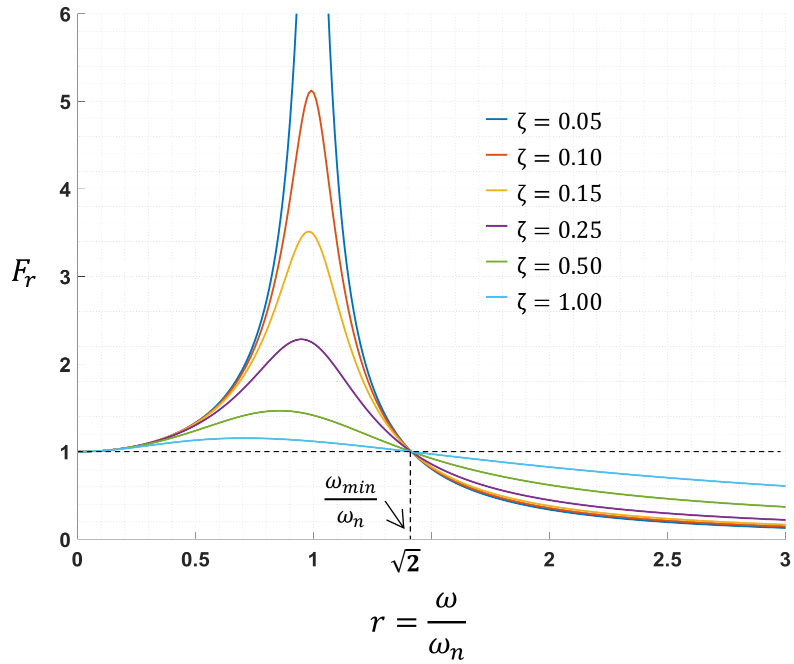

Fig 4: Transmitted force ratio versus the ratio of excitation frequency

In Eq. (1), ζ is the system's damping ratio and $r = \omega/\omega_n$ is the ratio of excitation frequency over the system's natural frequency. Using Eq. (1), it is shown that if $\omega_n \le \omega/\sqrt{2}$, the amplitude of the force transmitted to the ground is less than the excitation force amplitude applied on mass m. This is independent of the damping coefficient c of the system as shown in Fig. 4. This shows that in the frequency range that is usually called the optimum design region of the isolator, i.e. $\omega \ge \sqrt{2}\omega_n$, the stiffness coefficient plays a more important role in the isolator response than its damping coefficient. Therefore in order to optimally design the isolator, one should first decide about the minimum frequency, i.e. ω_{min}, over which vibrations should be attenuated. Then, an isolator is selected such that its stiffness coefficient satisfies $\omega_n \le \omega_{min}/\sqrt{2}$. In other words, in case the objective is to attenuate the transmitted vibrations for excitation frequencies greater than $\omega > \omega_{min}$, the maximum stiffness coefficient for the isolator is obtained from $k_{max} = m\,\omega_{min}^2/2$. It is worth noting that if n isolators are used, the stiffness of each isolator will be $k' = \frac{k_{max}}{n}$. However, there are limitations for the stiffness coefficient of isolators such as their static deflection after installation. For example, the static deflection should not exceed the initial length of the isolator. Therefore, when stiffness coefficient is determined for the isolator, its static deflection should also be taken into account. Considering that n isolators is used, the static deflection of one isolator is obtained as $d = \frac{m'g}{k'} = \frac{2g}{\omega_{min}^2}$ where $m' = \frac{m}{n}$ is the amount of mass supported by one isolator. Having k_{max} and d as functions of ω_{min}, an algorithm can be drawn for optimum design of isolators as:

1- Having known m and deciding about ω_{min}, k_{max} is calculated
2- Having known n, k' is calculated and a suitable isolator is selected
3- d is calculated and it is compared with the allowable deflection of the selected isolator, i.e. d_{all}
4- If $d < d_{all}$ the selected isolator is acceptable. Otherwise a new isolator should be selected
5- If it is not possible to select an isolator, a greater ω_{min} is selected.

The above algorithm is followed for the TBS considered in this paper and an optimum isolator is designed. The mass of pipes, equipment and support structure for the TBS is estimated as $m = 3498\,kg$. Assuming $\omega_{min} = 5\,Hz$, the maximum stiffness coefficient for the isolator, which is also its optimum value, is $k_{max} = 1726199\ N/m$. Given such stiffness coefficient for the isolator, its static deflection is calculated as $20\,mm$ which is acceptable. The diagram of maximum stiffness coefficient k_{max} and static defletion d of the isolator versus ω_{min} is shown in Fig. 5.

To evaluate the performance of the designed isolator, the FE model of the TBS described in earlier sections is employed. This model included the pipes, the installed equipment and the support foundation only and does not include concrete, soil and the building. The joint between the pipes and the support structure is assumed rigid in this model. The joint between the support structure and the ground is once considered rigid - for the case without vibration isolator – and once considered flexible for the case with vibration isolator. Therefore, in the FE model, the joint between the support structure and the ground is once assumed rigid and once equipped with a flexible element resembling the vibration isolator which was designed in the current section. It is assumed that $n = 20$ isolators are used between support structure and ground. In both cases, the force transmitted to the ground caused by applying an external force at a determined position in

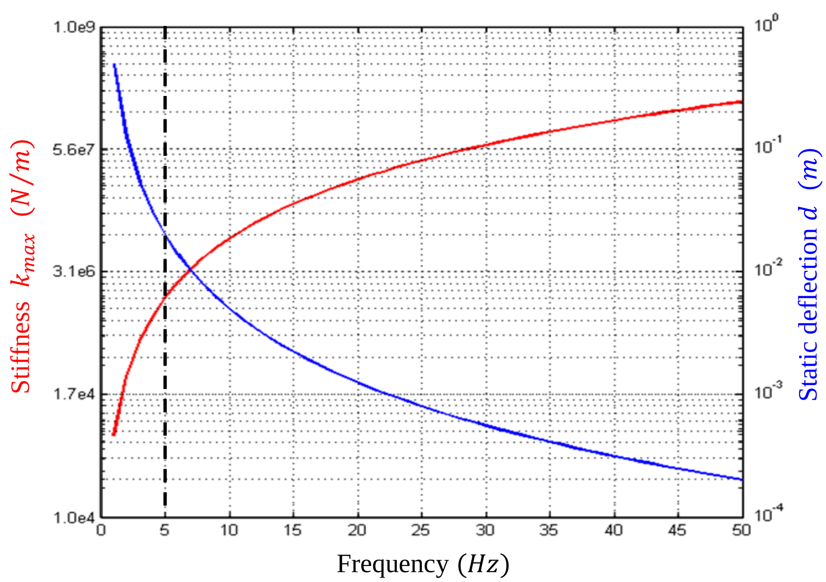

Fig 5: Maximum stiffness k_{max} and static deflection d versus ω_{min}

the TBS with different frequencies is calculated to be compared. As discussed earlier, if the ratio of transmitted force to the ground over the applied force on the pipes is smaller than one, that means the vibration isolator is performing well. The transmitted force for the two cases of with and without vibration isolator (flexible and rigid joints respectively) are shown in Fig. 6. As shown in this figure, using the vibration isolator has well attenuated the transmitted force from the TBS to the ground. This shows the significance and effectiveness of the vibration isolator. When the transmitted force to the ground is reduced, vibrations of the neighbor buildings are reduced as well. Thereupon, in order to reduce vibration transmission, using vibration isolators are found effective. It is worth mentioning that based on the results shown in Fig. 6, the isolator has not performed effectively for frequencies below 60 Hz while its performance at high frequencies is found effective. In the following section, vibration transmission to the neighbor building is investigated.

It is worth mentioning that since in obtaining the results presented in Fig. 6, the FE model of the TBS is used, the frequency values corresponding to the peak points in Fig. 6 are the natural frequencies of TBS.

4. Vibration transmission to the neighbor residential building

To have an estimate about the dynamic characteristic of the models with and without isolator, firstly, the natural frequencies and mode shapes of the FE model are extracted through modal analysis. Some of these modes and natural frequencies for the two cases of with and without vibration isolator are shown in Fig. 7. To study the amount of vibration transmission from the TBS to the neighbor residential building, a harmonic force, as shown in Fig. 8, is applied on the pipes and vibration responses at different floor levels of the building are investigated. In Fig. 8, the harmonic force F is applied on the pipes and responses are estimated at points A, B, C and D at different floor levels of the building. The amplitude of force F is considered to be one Newton. Vibration displacement is measured at different floor levels using the equation $Amplitude = \sqrt{x^2 + y^2 + z^2}$. In this equation, x, y and z are vibration displacements at different floor levels along the Cartesian coordinates respectively. In Fig. 9, the amplitude of vibration responses

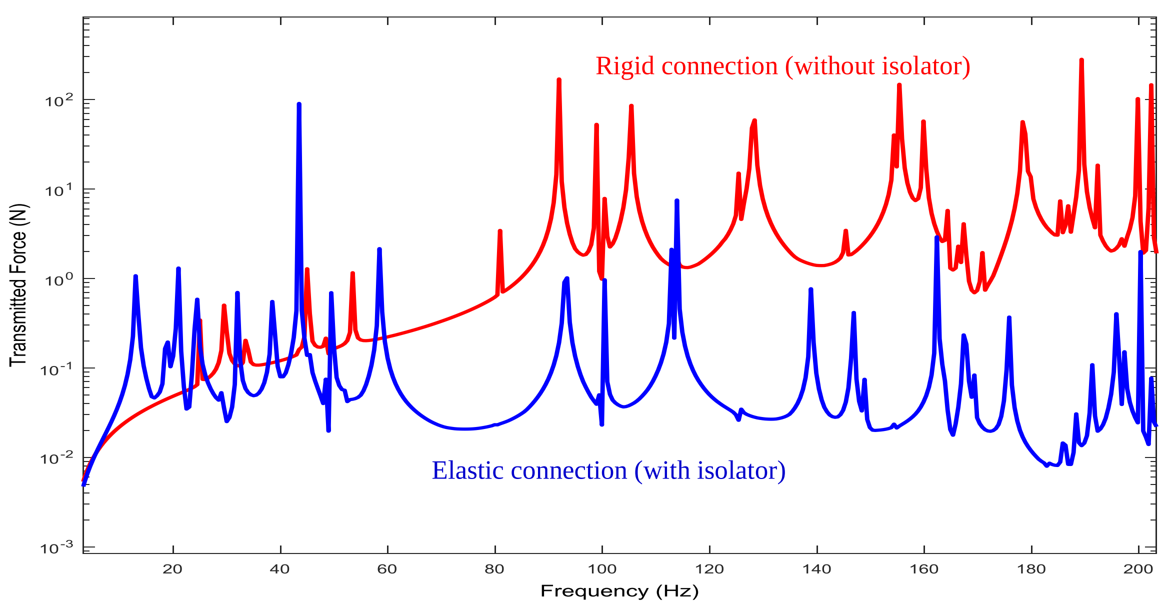

Fig 6: The transmitted force to the ground for flexible (blue) and rigid (red) joints between the support structure and the ground

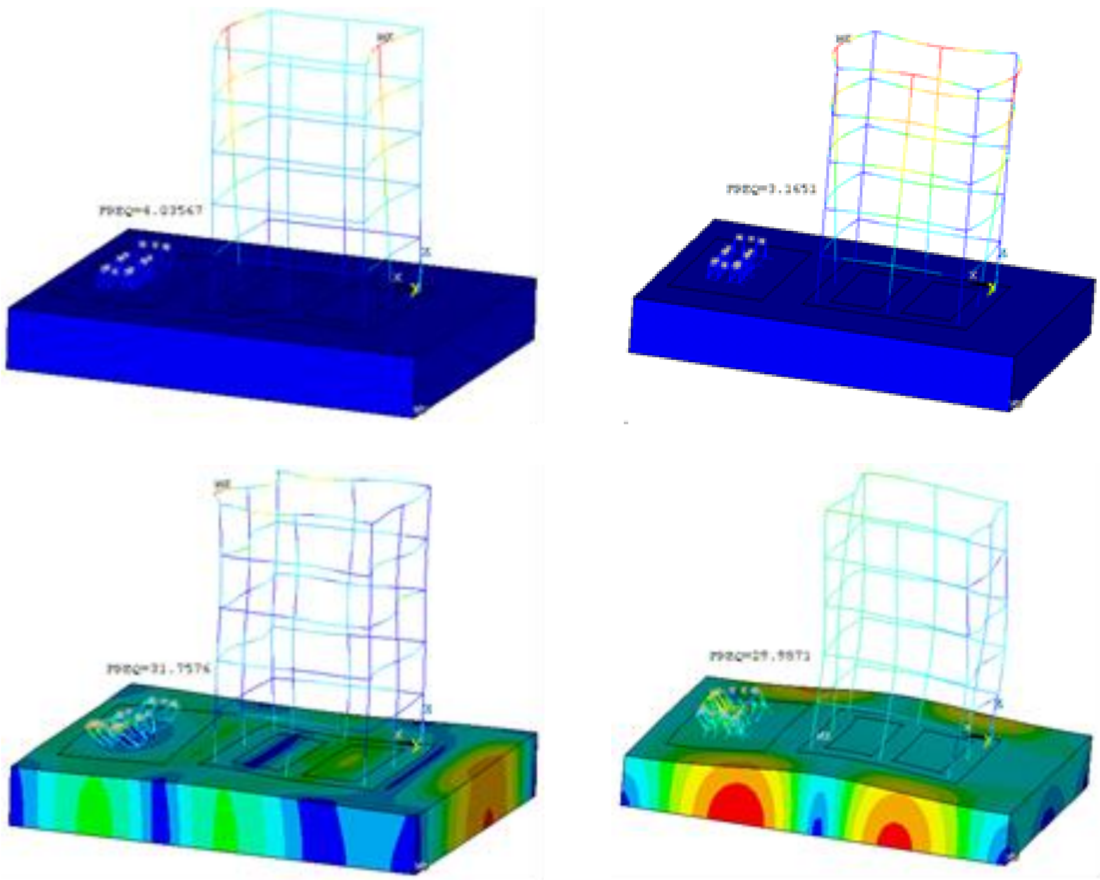

Fig 7: Comparison of mode shapes for different FE models: Flexible joint (right) and rigid joint (left)

versus excitation frequencies at different floor levels are presented. As it is evident from these results, using a vibration isolator has well attenuated vibration transmission at excitation frequencies above 60 *Hz*. Given the generated vibrations at a TBS is generally at high frequencies, it is concluded that the design of the vibration isolator is effective in attenuating vibration transmission from the TBS to the neighbor residential building.

5. Conclusion

In this paper, modeling and analysis of vibration transmission from a TBS to the neighbor residential building was presented as a case study before field implementation. For this purpose, a FE model was established in the ANSYS software which is composed of the TBS, the surrounding soil and the neighbor residential building. A vibration isolator was then designed for the TBS with the objective as to reduce vibration transmission to the neighbor building. Performance of the isolator was then investigated using the established FE model for the problem. Results of analysis indicated that the designed vibration isolator performs well at excitation frequencies above 60 Hz which is the typical range for operation of a TBS.

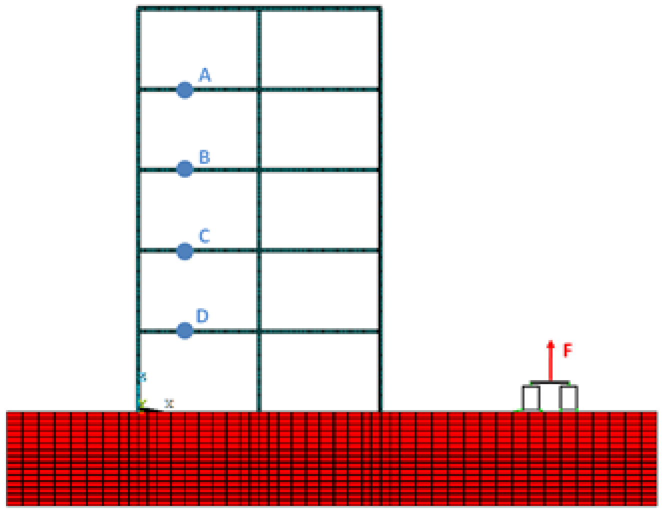

Fig 8: Schematics for application of excitation force and response measurement at different floor levels

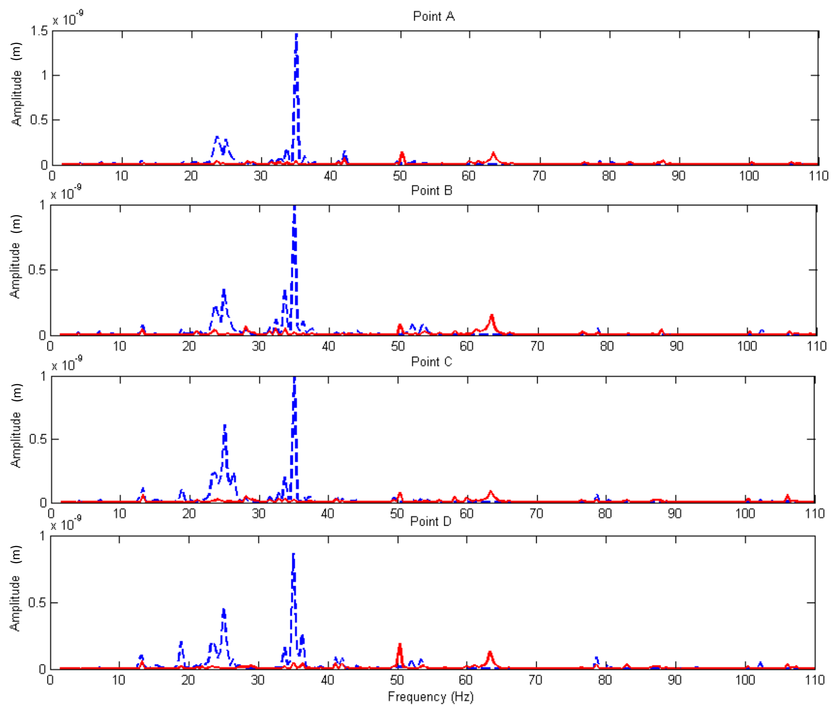

Fig 9: Amplitude of vibration responses at different floor levels: Flexible joint (dotted blue line ---) and Rigid joint (solid red line —)

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