Nonlinear Transient Vibration Analysis of Mounting Superstructure for Road Generated Shock Load Response

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Abstract - Vibration during road transportation may cause damage to the vibration sensitive article being transported. Hence, there is a need for design & development of mounting superstructure with special vibration isolation fixtures. These isolators mainly act as chocking points for the vibration energy. The fragility limit of the article can sustain is ±1g in vertical direction. This paper deals with the nonlinear transient vibration analysis of the superstructure using wire rope isolators under axial loading. The main contribution of the paper is to investigate and discuss the shock load response of the designed mounting superstructure when subjected to road generated shock pulses.

Key Words: Mounting superstructure, vibration energy, fragility limit, nonlinear transient analysis, wire rope isolators, axial loading, shock response

1. INTRODUCTION

Vibration isolation is the procedure by which the undesirable effects of vibration are reduced. Basically, it involves the insertion of a resilient member or isolator in between the vibrating mass and source of vibration so that reduction in dynamic response of the system is achieved under specific conditions of vibration excitation. Many factors such as maximum moving dimension (MMD) of vehicle, overall weight of the cargo, dynamic/shock load, natural frequency govern the selection of vibration isolators and design of superstructure. In this case, authors have used wire rope vibration isolators for the purpose of vibration isolation; here the metallic wire functions as both resilient member as well as energy dissipater. The main principle by which wire rope systems are designed and by which they work is that of inherent interfacial damping or sliding friction. As adjacent wires move relative to each other, friction causes part of kinetic energy of the wires to be converted into heat, thereby dissipating vibration energy. Such isolators exhibit nonlinear stiffness in different directions such as compression, roll and shear. Although they are widely used, the knowledge regarding their dynamic response under shock loading is very limited. In this case, the sensitive article is to be protected against the harmonic motion of its base for which the displacement transmissibility, T_d is given by,

$$T_d = \frac{X}{Y} = \left\{\frac{1+(2\varepsilon r)^2}{(1-r^2)^2+(2\varepsilon r)^2}\right\}^{1/2}$$

where X: amplitude of mass, Y: amplitude of base, ϵ: damping factor, r: ratio of exciting frequency and natural frequency. Analytical intractability and limitations in computational resources make it difficult to systematically study the non-linearity phenomenon in large. For the most part, detailed studies of non-linear vibrations are conducted using small systems (with perhaps just one or two degree of freedom). A good qualitative understanding of the phenomenon observed for the small system is invaluable when the same phenomenon is subsequently encountered in larger systems. The utility of precise numerical solutions remains high wherever appropriate, however, in nonlinear dynamics, it is difficult to extract the qualitative essence from simulations alone. There is a difference between linear and nonlinear system. This difference is based on the settling time, maximum overshoot and steady state error. Maximum value for settling time for the displacements and accelerations has been observed due to nonlinear behavior of basic components. Hence, it is necessary to include non-linearity in dynamic response analysis [1].

The superposition principle, which is very useful in linear analysis does not hold true in case of non-linear analysis. Since, mass damper and spring are the basic components of vibrating system, non-linearity in the governing differential equation may be introduced through any of these components. In many cases linear analysis is not sufficient to find out the exact behavior of the physical system. The main reason for modeling physical system non-linearly is the total unexpected behavior if the nonlinear system which cannot be predicted by the linear method.

1.1 Transient Vibrations

When an external excitation is applied to a system, a transient motion occur which is temporary and time dependent. The transient vibration is important when excitation is sudden and unexpected or continuous. In this case, a sudden excitation is given to the base of the structure to find out the response at centre of gravity (CG) for shock loading condition. Because of this shock loading, transient vibrations are generated in the system. A shock causes significant increase in displacement, velocity, acceleration or stress in mechanical system. A shock may be described as pulse shock, velocity shock or a shock response spectrum. The pulse shocks are introduced by suddenly applied forces or shock response spectrum. The sudden forces or displacements can be in the form of square, half-sine, triangular or similar shapes. A velocity shock is caused by sudden changes in the velocity. The shock response spectrum describes the way in which system responds to a specific shock. Many military specifications such as MIL STD-810 and Joint Services Specification 55555 define different types of shock pulses and detailed methods for testing with these pulses. Here, the JSS 55555, Test No. 24 is followed for specifying the shock loading condition of the mounting superstructure, when subjected to truck transportation. For shock isolation, the maximum peak response or the transmissibility must be less than unity [2].

2. LOAD CASES CONSIDERED FOR ANALYSIS

For sensitive equipment the response might cause damage through exceeding the allowable levels of stress or strain resulting from the transmitted displacement, velocity or acceleration. Alternatively, the equipment might be positioned in a finite space and a large relative displacement could cause the equipment to impact another structure. A preloaded isolator experiences a much better shock isolation compared with the linear model, however, when the equivalent damping of the system is small, i.e. low or no preload, the system approaches the linear mass spring model [3].

a) Vertical loading: It comes under inertial loading which is attributable to the inertia {mass matrix} of a body, such as gravitational acceleration, angular velocity and angular acceleration.

b) Road generated impact/ shock loading: These sudden shocks can affect the structural integrity and performance of electronic and electrical equipment of the payload when they are subjected to such non-repetitive mechanical shocks. The transport environment may be divided into two phases, truck transportation over highways and mission/field transportation. This paper deals with only the truck transportation over highways.

2.1 Description of Superstructure Assembly

The Mounting superstructure consists of base frame bolted to the vehicle platform. The mounting frame is connected to base frame through wire rope isolators and saddle supports are welded to the mounting frame. The sensitive article will rest on top of the saddle supports. The material of system is considered as structural steel for the purpose of analysis.

Table -1: Material properties

Material	Structural Steel
Young’s Modulus	200 GPa
Poisson’s Ratio	0.3
Density	7850 Kg/m^3
Yield Strength	250 MPa
Ultimate Tensile Strength	460 MPa

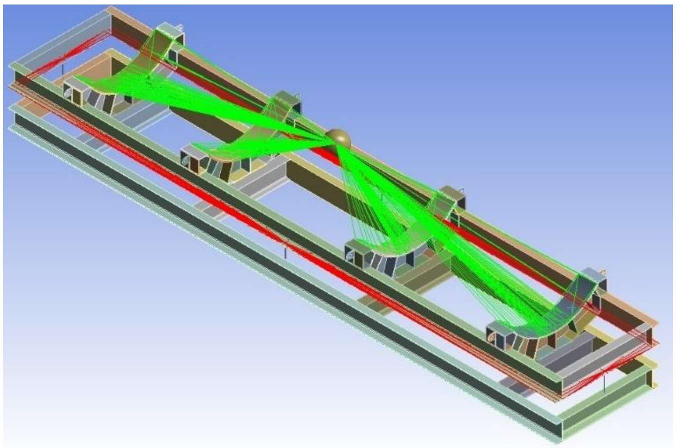

Fig -1: Mounting superstructure assembly

3. SELECTION OF WIRE ROPE ISOLATORS

A common type of isolator used for vibration and shock isolation are the wire rope springs. These isolators are regarded as highly effective for extreme conditions found in military, naval and aerospace applications. These isolators are made up using a series of steel strands twisted around a core strand, and the resulting wire rope is arranged in a leaf or helical fashion. Without mass loading, these isolators behave closely to the linear mass spring system. In such case, isolators exhibit high natural frequency with relatively low damping. From the vibration isolation theory, a low natural frequency system means better isolation. However, when the isolators are loaded the natural frequency decreases which allows for better isolation range. The damping characteristic in wire rope isolator is high as long as the spring is loaded due to the relative motion in the wire strands creating friction and thus dissipating energy [4]. In this case, as the payload is about 6000Kg and number of isolators is limited to 8, authors have selected WR-28-200-08 model from manufacturer's catalogue based on static load distribution method and number of isolators is defined based on space constraint and uniform distribution of load.

Table -2: WR28-200-08 Isolator Characteristics [6]

Max Static Load	12.28 kN
Max Deflection	50.8 mm
Vibration Stiffness, K_V	2362 kN/m
Vibration Damping, C_V	534 kN.s/m
Shock Stiffness, K_S	1010 kN/m

There are minimum and maximum threshold values for the static load that can be supported by the wire rope isolators and this characteristic affects directly the equivalent damping ratio in the system [5]. The non-linear characteristics of wire rope isolators are given in the form of load vs. deflection curve.

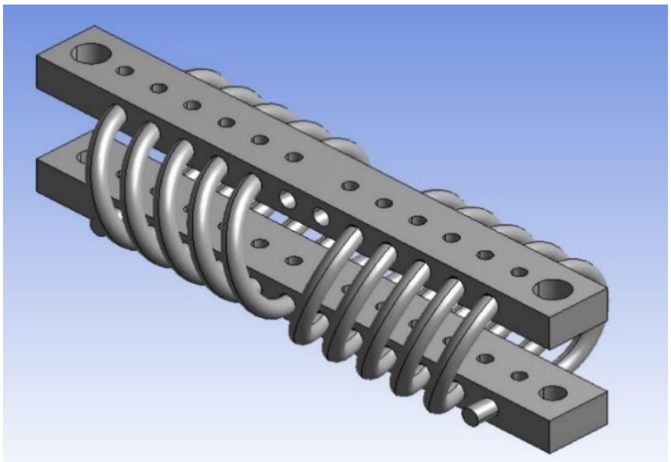

Fig -2: Wire rope isolator model

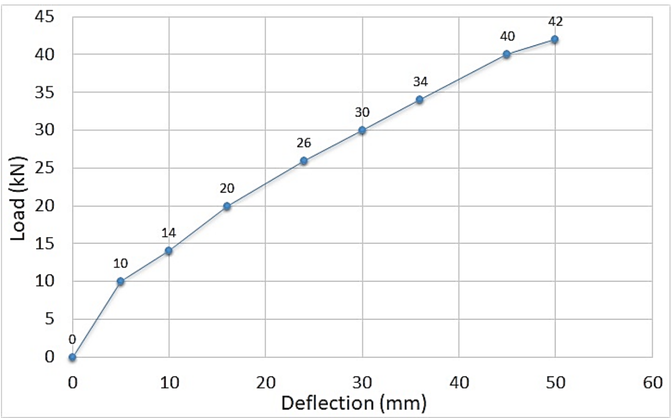

Chart -1: Load vs deflection graph for WR28-200-08 [6]

3.1 Finite Element Modeling

Nonlinear analysis methods are required whenever geometric, material or contact nonlinearities exist in the structure. Finite element programs can solve the nonlinear problems in number of ways. In all cases, the algorithms have to iterate to achieve equilibrium for such problems. Obtaining final convergence and equilibrium when running these iterative problems can be very challenging.

When dealing with non-linearity, the fine the mesh, the larger the stiffness matrix. Therefore, the solution might lead to divergence due to derived unbalanced forces induced in the system during analysis. In case of nonlinear effects, fine meshes are not always better than coarse meshes, where solution depends on equation stability.
In this case, Ansys Mechanical is used for nonlinear transient dynamic analysis. Authors have used patch conforming tetrahedron mesh method. Mesh controls are kept coarse to avoid expensive computations and solution convergence. Wire rope isolator nonlinear characteristics such as damping and load-deflection curve are applied in the analysis settings.

3.2 Nonlinear Transient Analysis

This paper mainly deals with the non-linear vibration isolation up to fragility limit of sensitive article at its center of gravity (CG) when it is subjected to transportation shock or impact loading on highways. The basic equation of motion solved by a transient dynamic analysis is:

$$(M)\{\ddot{u}\} + (C)\{\mathring{u}\} + (K)\{u\}\{F(t)\}$$

Where (M)= mass matrix, (C)= damping matrix, (K)= stiffness matrix, {ü}= nodal acceleration vector, {ů}= nodal velocity vector, {u}= nodal displacement vector, {F(t)} = load vector. Authors have opted for Full Method transient analysis to capture all types of non-linearity in the system. Full method avoids mass matrix approximation and all nodal displacements are also numerically integrated at the specified time steps. In this case, the load is applied as per JSS 55555, Test No. 24 which specifies the basic pulse for shock loading [7]. The duration of nominal pulse & peak acceleration of nominal pulse specified for the basic design of equipment installed only in trucks or semitrailers by JSS 55555 is,

$$A_o = 200\ m/s^2,\ D = 18\ ms$$

Half sine acceleration input is given by,

$$V = (2g/\pi) \times A_o \times D \ \ldots\ldots\ldots\ldots\ (1)$$

The peak acceleration is converted into half sine pulse saw tooth curve [8] to excite base with abrupt velocity change. Structure response for given shock loading should be observed for minimum 43.2 ms as per JSS Test Method.

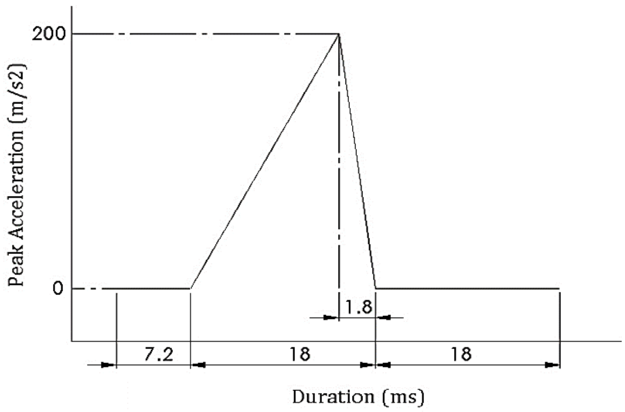

Fig -3: Half sine saw tooth pulse [7]

The same shock pulse is applied on the base frame of the structure. A nonlinear analysis requires multiple sub-steps within each load step so that the program can apply the specified loads gradually and obtain an accurate solution. Authors have used Combin39 element to produce nonlinear force-deflection relation in isolators. Isolators on each section of frame are considered to be acting in parallel for ease of computation. All load steps are provided with a damping ratio of 15% as per WR28-200-08 characteristic. The first load step is defined for a period of 0.0072 second from the initial zero without any load. The load steps are defined as per the basic pulse for shock loading and are described in following table:

Table -3: Transient analysis load steps

Load Step	End of Each Time Step (s)	Step Size (s)	Base Frame	
			Shock Input (m/s)	Constraints
1	0.0072	0.001	0	All DOF
2	0.0234	0.001	2.292	UX, UZ
3	0.0252	0.0018	0	UX, UZ
4	0.0432	0.01	0	All DOF
5	1	0.01	0	All DOF

3. FEA RESULTS AND DISCUSSION

The acceleration values were given as half sine shock load to the base and vibration response time history, deformation time history at CG of article was calculated during shock loading. The peak response and maximum deformation at mounting frame, saddles and base frame was also observed. The results are shown below:

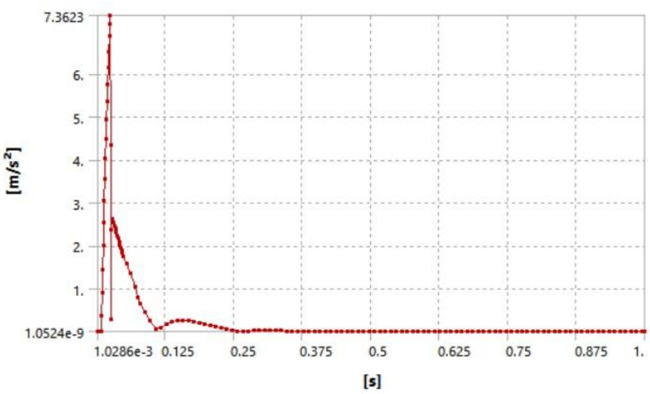

Fig -4: Vibration response time history at CG of article

The vibration response time history at CG of article shows that peak response of 0.75g was generated at the time of shock loading i.e. at load step 2, 23.4 ms. At the end of impact loading, few degrees of vibration response appeared at the CG. The vibrations were damped progressively because of nonlinear damping ratio of wire rope isolators. Authors selected duration of 1 second for observation of vibration response to capture any fluctuations in later stages. The vibration response observed is less than the fragility limit of sensitive article.

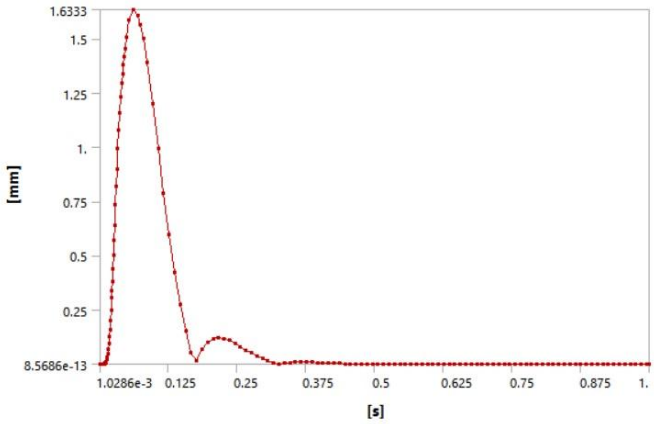

Fig -5: Deformation time history at CG of article

The maximum deformation of 1.6333 mm was observed at CG of article which is within acceptable limit. The vibration response and deformation can further be reduced by increasing number of isolators, their damping ratio or stiffness characteristics.

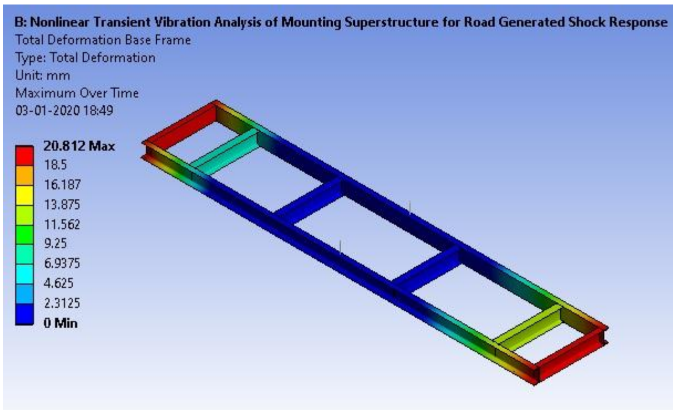

Fig -6: Total deformation of base frame

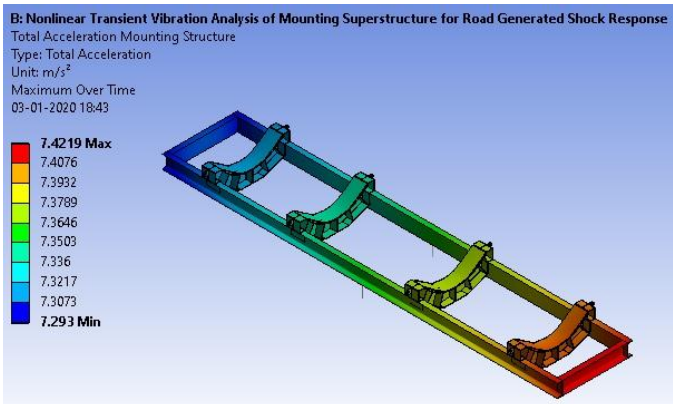

Fig -7: Total acceleration of mounting frame and saddles

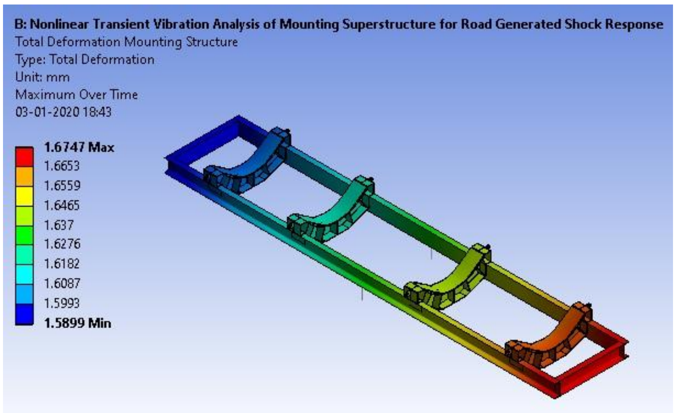

Fig -8: Total deformation of mounting frame and saddles

As the base frame is bolted to vehicle platform, it experienced maximum deformation of 20.8 mm. The deformation can be reduced by increasing thickness of channels or adding ribs between flanges. Furthermore, rubber packing or polyurethane can be used between base frame and vehicle platform to provide some damping. The structural rigidity and stiffness of mounting frame and saddles can also be improved for achieving more isolation in the system. Furthermore, payload and space constraint should be taken into consideration while improving the present design.

Table -4: Result Summary

Half sine Shock Pulse for Base Excitation	2.292 m/s
Max acceleration at CG of article	7.3623 m/s^2 = 0.75g
Max displacement at CG of article	1.63 mm
Max displacement of base	20.81 mm
Max static deflection at CG of article	27.80 mm

4. CONCLUSIONS

The results from transient analysis shows that the mounting superstructure with selected wire rope isolator model is capable of isolating the vibration sensitive payload from the road bound shocks within the required limits. This shows that selected wire rope isolators are safe from transient point of view. Authors have used coarse mesh for stabilization of nonlinear equation and limitations in computational resources. Hence, future studies can be carried out on the for optimization of present design to more efficient one by using the method of topology optimization.

An extensive study on the vibration response during road generated random vibration for highway road conditions needs to be studied as a future scope of work. Study on the dominating modes of vibration and the effect of natural frequency of the system on the sensitive components of the payload is an important prospect for future work. Another important scope for future work is carrying out such analysis by studying the actual road profile of transportation route and applying shock load accordingly.

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BIOGRAPHIES

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