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THE MATHEMATICAL OPTIMIZATION OF VIBRATION & SHOCK CONTROL SYSTEMS FOCUSING THE APPLICATION OF AIR SPRING DESIGNS RELATED TO AUTOMOBILE & AEROSPACE INDUSTRIES

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ABSTRACT: This is an Industry- Academia oriented presentation emphasizing the application of concepts of basic science & inter-disciplinary maths for the optimization of Industrial design. Effective vibration & shock control system designs are now important for plant machineries to transportation systems The effect of Vibration & Shock on Human body are minimized by the optimized design of isolation systems. Human body interactive Fuzzy Logic based hybrid designs are now visualized as a new concept for the cost & performance optimization of the large network of transportation systems from automobiles to long range deluxe buses.The brief history of Development of Steam Engines to Diesel- Electric Drives shows how the basic science concepts were transformed to Engineering Development. The transportation system design is an inter-disciplinary field amalgamating the Fundamentals of Physical & Mathematical Science principles with advance precession engineering skill leading to the development of large scale production of high speed drive systems, so called 'Engines' of different types. The Application of Hybrid Engines for Rail, Road & Marine ships will be briefed.Engine design & fabrication still remains a subject of precision, where micron level of accuracy is required. A brief history on the development of Automobile & Aerospace engines will reveal the development Hybrid concept in Power drives. The inter-disciplinary mathematical conceps used for the optimization of industrial designs will be focused..

Key Words- Vibration & Shock waves,Spring Mass Model, ODEs & PDEs, Air Springs, Isolation Efficiency Results.

1. INTRODUCTION

This is an Industry oriented presentation outlining the mathematical concepts used for the Design Optimization of Industrial Systems focussing the Vibration & Shock Isolators in a wide variety of Application.

We strat with a very common cyclic phrase saying 'Vibration is Life and Life is Vibration. In a literary sense the vibrations and Oscillatios are assciated with almost everything strating from Atoms and Molecules to Large Scale Structures and Super Scale clusters.like Galaxies. In a fuzzy sense the dimensional envelopes are stating from infinitesmalto infinitely large related to the expanding universe.Like Shakespeare's Rainbow on the sky all of specially the young students are fascinated by the word Ramanujan's ínfinity and Einstein's Relativity. The first slide titled as Vibrations in Expanding universe is just to inculcate a feeling of comparison of atomic dimension to the the magnitude of light year distances. The 'Not to Scale' word on the slide is emphasised" Due to the large data handling capability and storage capacity of a smallmobile,the visualisation of nano or micro-dimension of electronic micro-chips is fairly understandale even to a high school student..The MEMS (Micro Electro Mechanical System) and NEMS (Nano Electro Mechanical System) functioning and fabrication is an Engineering marvel.

When we work with such precesion, the ground disturbances of micro-seismic nature affects the accuracy of the patrs. Human body is not able to detect such feeble vibration. In vibration Engineering terminology this is knownas the perception level of human body.This is very similar to our lower threshold of our sound hearing level in industrial design of sound recording studio or Anechoic chamber design for automobile engine noise test centres.

2. THE RESPONSE ANALYSIS- OF VIBRATION & SHOCK - Numerical Calculations in precise domain. Precision Engineering fabrication – Engine Design, Turbo-machineries where the accuracy is in micron level. Examples-Piston Cylindermovement, ball bearing clearance, surface finish of lenses and mirrors for interferometers, memory chips and quantum dots.

2.1 The Human body interactive Designs for comfort & safety during road travel is focused. The input road spectrum is of statistical nature. Depending on road surfacethe maximum shock transmission is determined. In general village road, city road, highways are considered for the bus travel. Rough terrain criteria is used for army vehicles.The criteria for passenger comfort depends on the application environment.

2.2 For power plant machineries, Large size diesel generators ,pumps and compressors etc. the force transmission to the supporting structure is of prime consideration for the safety of the nearby buildings and structures. The stiffness of the supporting structure should be at least ten times higher than the system spring stiffness. The general criteria is Vibration isolation required ~ 90 % and for Test Laboratories it is of 98 % order.

The Fourier spectra (FFT) is used for determining the dominant exciting frequencies for the vibration analysis.

2.1 Input data required for calculation

For industrial plant machines the primary selection calculation for rotating machines requires the following input data.:-

1 The Total weight of the supported system on spring (Sprung mass)

2. Centre of gravity of the system .

3 Lowest operating speed of the system

4 The General assembly drawing of the system .

5 Location of the system - Ground floor / upper floor / roof top & Seismic zone number for earthquake protection.

6 Overall dimension of the equipment

3.1 Frequency spectrum-From Atomic & Molecular Spectroscopy to Machine Dynamics & Acoustics.

It is interesting to glance through the wide ranging frequencies involved in various types of vibrations. The atomic and molecular vibration frequencies are in optical and infrared frequency band in the frequency range of ~ 10^{12} to 10^{14} Hz and the forces involved are of electro-magnetic nature.. Acoustic vibrations in audible band is in the frequency range from 20 Hz. to 20 KHz order. The aerodynamic noise generated by a high speed jet aircraft is higher than 600 Hz. The frequencies of machine vibration are limited to 150 Hz or so. The effective frequencies involved in building vibration are considered from 1 to 80 Hz. The resonance frequencies related to human body organs are in the range from a few hertz to 30 Hz order. Infrasonic waves generated by earthquake is less than 20 Hz frequency . Micro-seismic vibrations generated by road traffic or rail movement near any laboratory building are considered in the lower range of 5 Hz or so. Vibration isolated tables with low natural frequency of less than 2 Hz. are used for the isolation of sensitive instruments in a micro- tech laboratory.[9 , 10] .The new negative stiffness (-K technology) a natural frequency of 0.5 Hz is achievable.

4. TYPES OF ISOLATORS FOR INDUSTRIAL APPLICATIONS

4.1 Elastomeric - Metal Bonded Isolators : -

For slowest operating speed = 1500 rpm, Deflection under actual load = 3 mm

Vertical isolation efficiency > 80% System natural frequency (f_n) = 9 Hz.

4.2 Springs and Viscous Dampers :

Spring Viscous dampers with high viscosity fluid are used to provide damping of 5 to 20% example Spring damper systems are suitable for machines generating high dynamic loading. Slowest Operating speed = 1500 rpm, Deflection at static loading = 10 mm. Vertical isolation efficiency > 95 %, System natural frequency = 5 Hz.

4.3 Air Springs :

Low frequency vibration isolated tables using air spring systems are used for such application. [7, 10] For slowest Operating speed = 500 rpm, Vertical isolation efficiency > 98%

System natural frequency = 1.8 Hz. The natural frequency of an air spring system can lowered by using additional air reservoirs attached to the air spring system. However the applications are limited to laboratories and ground testing of aerospace systems & components response studies for exciting forces of µg order.

4.4 Wire Rope and Cable Isolators – (Non linear system)

a. The all-metal & multidirectional configuration

b. Temperature from – 180 deg.C to + 300 deg.C.

c .The damping provided are high in the range of 15 to 20%

d. Applications in aerospace, naval ships and transportation

5. ODEs

Second order Differential equation (ODE) for the analysis of a dynamic system in single degree of freedom (SDOF) using a orthogonal set of co-ordinates x, y and z direction.

$M (d^2x / dt^2) + C (dx / dt) + Kx = F_0 \text{ Sin } \omega t$,

where M , C and K is the mass, damping and stiffness values e system,

C is the damping coefficient , K is the spring stiffness , F0 Sin wt represents the dynamic force.

Eigenfrequency of the spring mass system is calculated by using the

formula $f_n = \frac{1}{2\pi}\sqrt{K/M}$, K is the stiffness

5.1 PDE – Partial Differential Equations-

A general form of Second order Partial Differential Equation

in (x , y)domain

$A(x,y)\partial^2u/\partial x^2 + 2B(x,y)\partial^2u/\partial x.\partial y + C\,(x,y)\partial^2u/\partial y^2 = f\left(x, y, u, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}\right)$ where u is the unknown state variable and A, B, C are the coefficients of the equation.

The equation is Elliptic, Parabolic or Hyperbolic as per the following conditions :-

When $B^2 - 4AC < 0$ Elliptic , = 0 Parabolic, > 0 Hyperbolic

5. ISOLATION EFFICIENCY RESULTS

As an example the vibration isolation efficiency of a typical Fan – motor system with symmetric load distribution is shown here

Total Mass of the Fan Motor + Acc. = 1620 Kg.

No. of Spring isolators = 12 Nos.

Load per isolator = 135 Kg. each

Operating speed of fan-motor = 1500 RPM.

Open Spring selected 25/ 200 Type - Qty 12 Nos.

Stiffness of each spring = 78.4 N/mm each

Overall System stiffness = 941 N / mm

Static deflection (vertical) ~17 mm

Vertical Natural frequency = 3.8 Hz.

Ratio of Exciting freq./system nat. freq. = 6.5

Achievable Vibration isolation efficiency > 90 %

for speed @ 1500 RPM & above.

For Variable speed drive the slowest speed is considered for the vibration efficiency calculation.

6. THE RESPONSE CALCULATION –

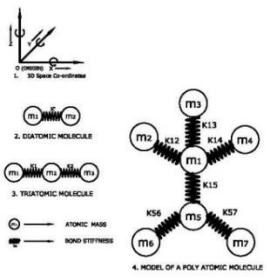
The response parameters are expressed in terms of transmitted acceleration, velocity and displacement amplitude depending on the application.The representative graph is plotted intime domain.for shock applications. Non linear isolation systems are used for shock attenuation.The tuned dampers are used to reduce the effecti of amplification build up near the resonance point.

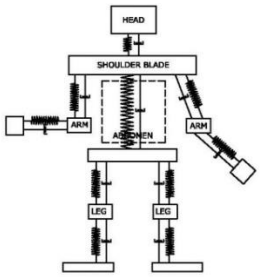
6.1 For heavy power plant machineries- spring-damper combinations are used for effective isolation. The optimization calculation for heavy machineries on RCC inertia block on elevated structure requires detailed modal analysis using FEA programs.

6.2 For Earthquake protection of Buildings&machines- base isolation techniques are used.For seismic shock the displacement parameter is of prime importance.The response is expressed in terms of floor drifts at different floors.The seismic shock is in the low frequency range of few Hertz only.

6.3 For Ships & Submarines- The Ships and submarine propulsion Engines and allied machineries are protected from piutch and roll condiotion during rough sea environment.Specifically the Naval Ship & Submarine machineries and equipments are subjected to high 'g shock during 'war environment.The shock isolators are used to bring down the transmitted shock to tolerant level for survival.The transmitted acceleration parameters are used for optimization.

Spring mass model (not to scale)





MODEL OF A POLYATOMIC MOLECULE **HUMAN BODY MODEL**

7.HUMAN INTERACTIVE DESIGN -For designing any suspension system for an automobile or any long journey buse we strat with an equivalent spring mass model of the system .Our human body is flexible by nature, consisting of joints, muscles and flexible organs like intestine, brain matter,lungs etc.which are having its characteristic resonance in the low frequency range. However it varies marginally from person to person. During a long journey some of the organs are excited repeatedly by the road vibration of statistical nature. Specially when the road is a hilly road or a rough road. Specially when the leaf spring fitted buses transmits the low frequencies and the passenger feels tired during the long journey. To a large extent the response varies on the location of passenger seat and also with the individual body structure. But when the leaf spring is replaced by Air spring of low frequency components are isolated and so the passenger feels comfortable with less faigue even after a long journey.

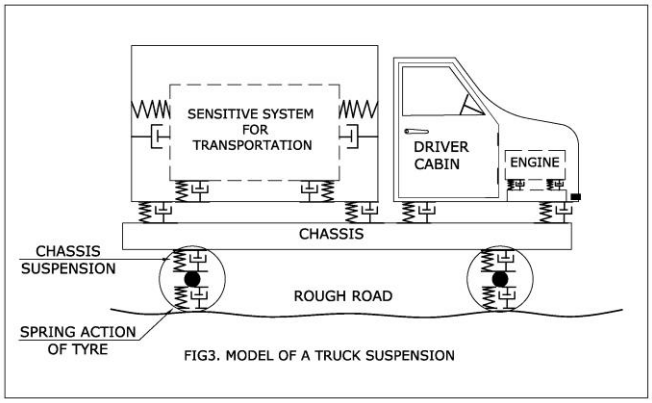
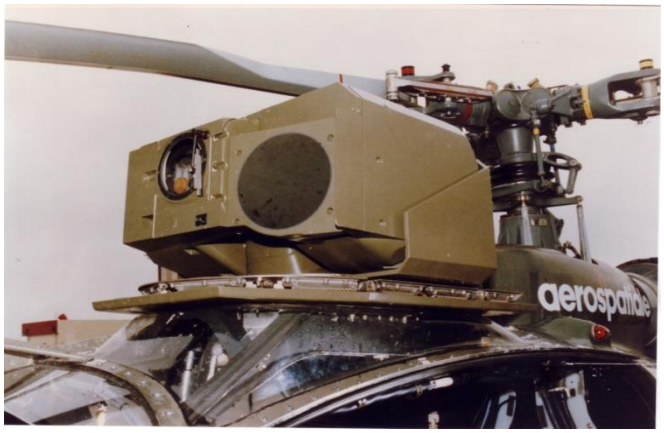


FIG3. MODEL OF A TRUCK SUSPENSION



INSTRUMENT MODULE BELOW THE HEAD ROTOR OF A HELICOPTER – WIRE ROPE ISOLATOR *(SOCITEC-)*

8 . APPLICATIONS RELATED TO AVIONIICS & AEROSPACE LABORATORIES.

The electronic & Optical modules used in multistage Space vehicles are isolated using specially fabricated silicone isolators.to reduce the shock transmission during the stage seperation. The aircraft modules are protected against the landing shock.It is interesting to note that the aircraft engines also needs protection during transportation by truck before fitting the engines in aircraft. Since the aero structures are flexible in nature the shock effect during landing is reduced to 2-3 g level whereas when it is transported by truck the shock level exposure is of 6-8 g order.. So to reduce the shock level wire rope isolators are used for safe transportation by road.

For jet engine test beds also iisolators are used below RCC concrete bed so that the vibration tranfer to the buildings and structures are effectively reduced during the ground testing of the aerojet engines.

9 . SHOCK ANALYSIS & NON LINEAR SYSTEMS -

For shock analysis Half sine pulse or triangular pulse with a short time duration is considederd.. The corresponding velocity is used as input to estimate the corresponding displacement and transmitted acceleration for the nominal fn of the Shock isolator. The damping is adjusted to damp the shock in 3 cycles for general application. Finally shock decays to a steady state vibration of low amplitude.

10 . APPLICATION IN MICRO-ELECTRONIC WORK SHOP & ADVANCE METROLOGY LABS -

The high precesion exprimental set ups in an advance metrology laboratory is affected by the ground disturbances of micro-seismic nature due to the traffic flow on a nearby road or by the train passing through near by railway track. In addition to this there is a continuous Structure Borne Noise (SBN) due to the infrasturual facility like air conditioning machines, compressors,lifts etc. running in the same laboratory building.

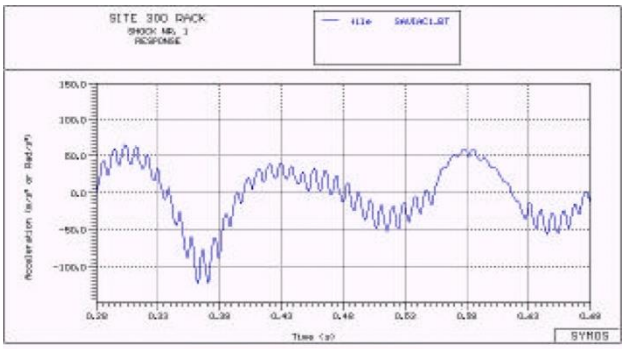
These vibrations affect the results in high resolution microscopy, Spectroscopy and interferometery.Such low frequency vibrations of micro-seismiic order are isolated by using the Air spring with a low natural frequency < 2Hz.For bigger area requirements in Aerospace or Automobile test labs bigger size bocks are supported on Air springs.

11. CONCLUSION;-

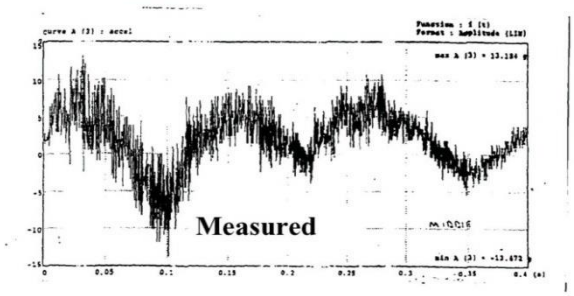
Due to the complex and statistical nature of vibration input the Vibration isolation efficiency results are not so precise like engine design and engine parts fabrication in micron level accuracy.

Instead for the system optimization the Fuzzy Logic and Generic logic concepts are used.

The results are validated by actual measurement after installation. The results are found to be well within the acceptable range of +2/-10% of the calculated results.



Calculated



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