Effect of Different Test Fixture Variables on The After-Treatment System Dynamics: A Review

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Abstract- *This paper covers the basic idea of using the test fixtures for vibration analysis and the effect of different design variables on the dynamics of After-treatment system. This paper additionally helps in identifying the fixture design variables which may affect the After-treatment system and may cause damage. In real environment these random vibrations are transferred on to the brackets, used to mount the After-treatment system. Hence, the system dynamics varies for testing with actual bracket and testing with fixture. This review helps in understanding the system dynamics of vibration test fixtures and mounting bracket.*

Keywords- After-treatment system, Modal Analysis, Random vibration analysis, Vibration, Vibration test fixtures.

I. INTRODUCTION

The automobile has come to symbolize the essence of a modern industrial society. The very important aspect of Automobile industries is to perform vibration testing on components to get the best possible solution for our problem. But in actual practice, it is not possible to get best solution. The possible reasons for not getting best results may be a lot of uncertainties and vague assumptions made in analysis process.

Vibration Test Fixtures are the indispensable part in the manufacturing industry. The vibration testing poses a challenge to design good vibration test fixture. The off-highway and on-highway heavy duty vehicles are subjected to large number of forces like vibrations which are highly random in nature. These vibrations are the most important mode of failure in After-treatment system. After-treatment system is the emission control device which helps to reduce the environmental pollution causing due to automobile emission. To qualify or verify the acceptability of After-treatment system for certain environment, vibration testing is done. As After-treatment system cannot be placed directly on the shock testing machine (Shaker table), thus the vibration test fixture acts as interface between the system and the machine. Shaker table is used to generate an input spectrum such as forces or accelerations that mimics real working conditions as much as possible.

The purpose of test fixtures is to couple mechanical energy from a shaker table into a test specimen.

In real environment these random vibrations are transferred on to the brackets, used to mount the After-treatment system. The uncertainties in mechanical properties, tolerances in fabrication and assembly processes of Fixture and Bracket may cause differences in their results. Hence, the system dynamics varies for testing with actual bracket and testing with fixture.

II. AFTER-TREATMENT SYSTEM

Diesel exhaust After-treatment systems are required for meeting both EPA 2010 and final Tier 4 emission regulations. A system that treats post-combustion exhaust gases prior to tailpipe emission. It differs from emission reduction techniques in the combustion process and allows for greater power from the engine without worrying about emissions increasing.

The Cummins solution for meeting emissions regulations consists of a highly capable base engine with cooled-EGR, along with the Cummins After-treatment System a proprietary package that combines a Diesel Particulate Filter (DPF) with SCR technology to remove over 90% of particulate matter (PM). Cummins engines and after-treatment system are an integrated solution. Designing and building the system in-house allows Cummins to calibrate the engine and After-treatment system for optimum fuel economy, performance and near-zero emissions [1].

The After-treatment System on our vehicle is made up of three systems:

1) Fuel dosing
2) Diesel Particulate Filter (DPF) System (DOC/DPF)
3) Selective Catalytic Reduction (SCR) System

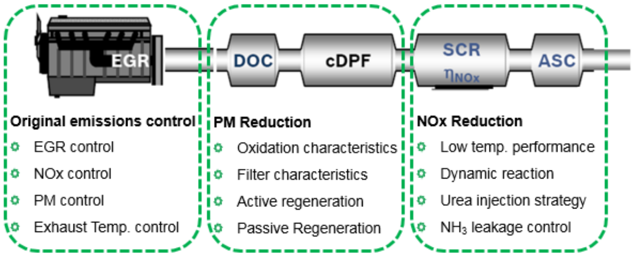

Figure 2.1 After-treatment System Layout

1) *Fuel Dosing*

HC was delivered to the DOC through an airless exhaust fuel doser. A tip coking resistant design was selected. No air purging or tip cleaning service was necessary. Late post injections were used for engines less than 130 kW.

The exhaust fuel doser was mounted next to the engine turbocharger to maximize fuel evaporation and mixing. For engines with two-stage turbochargers, a fuel doser was placed between the two turbines. The second stage turbine served as an active mixer.

Uniform HC distributions maximized DOC catalytic efficiencies and exhaust temperature homogeneities for DPF regenerations. Perfect HC mixing avoided hot spots on the DOC and reduced its degradation rate [1].

2) *Diesel Oxidation Catalysts*

The diesel oxidation catalyst (DOC) owes its name to its ability to promote oxidation of several exhaust gas components by oxygen, which is present in sample quantities in diesel exhaust. When passed over an oxidation catalyst, the following diesel pollutants can be oxidized to harmless products, and thus can be controlled using the DOC:

- carbon monoxide (CO)
- gas phase hydrocarbons (HC)
- Organic fraction of diesel particulates (SOF)

The emission reductions in the DOC occur through chemical oxidation of pollutants occurring over the active catalytic sites. A DOC consists of a catalytic coating on a cordierite or metallic substrate for oxidizing exhaust PM. It operates in a passive-only mode that requires no active regeneration or special duty cycle requirements [1].

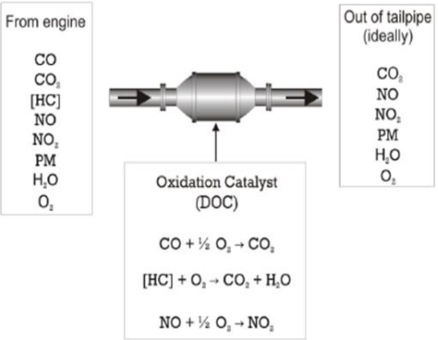

Figure 2.2 Diesel Oxidation Catalyst

3) *Diesel Particulate Filters*

DPFs are effective at removing over 90% of Particulate Matter (PM). The use of passive and active regeneration also allows more control in oxidizing and cleaning the filter.

DPFs, combined with DOCs, use wall-flow substrates typically made of porous ceramic media that capture exhaust gas and remove PM or soot particles. A typical filter consists of an array of small channels for exhaust has to flow. Adjacent channels are plugged at opposite ends, forcing the exhaust gas to flow through the porous wall, capturing the soot particles on the surface and inside pores of the media. As soot accumulates in the filter, a regeneration event will provide sufficient heat to oxidize and capture the soot. The remaining ash can be removed during regularly scheduled cleaning events based on the recommendations of the engine manufacturer [1].

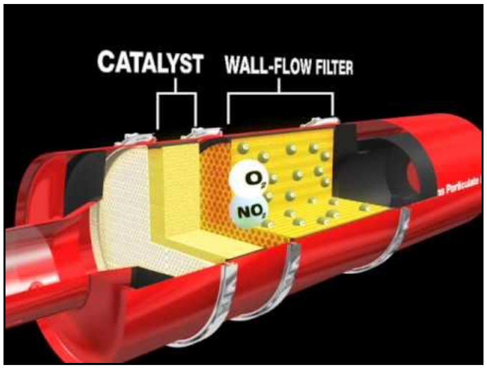

Figure 2.3 Diesel Particulate Filter

4) *Selective Catalytic Reduction System*

SCR technology is based on reduction of NOx by ammonia, which has to be generated on-board from a suitable reductant, since a transportation of pure ammonia is not desired or advisable. Today the usage of urea and water solution (“Adblue”) is most common for SCR systems. Aside of the liquid urea also alternative system concepts based on ammonia carbamate or solid urea are under development.

For passenger car and light-duty applications current ideas are using non-air assist urea injection systems and zeolite type catalysts. SCR catalysts are described by complex procedures of ammonia storage; NOx conversion as well as ammonia slip is required with a specific end goal to accomplish high NOx conversion rates while keeping up low ammonia slip under transient working conditions [21].

III. NEED FOR VIBRATION ANALYSIS

Vibration is the motion of a molecule or a body or a system of associated bodies dislodged from a position of equilibrium. Most vibrations are undesirable in machines and structures because they deliver increased stresses, energy losses, cause added wear, increase bearing loads, induce fatigue, create passenger discomfort in vehicles and absorb energy from the system [2].

Thus, to overcome from the above mentioned effects of vibration; vibration analysis of the system or components of vehicles is done before they can be certified ready for production. After-treatment System is one of the vehicle component which needs to be pass the random vibration analysis in order to survive on the vehicle without any fatigue and may provide the extended service.

1) *Random Vibration Analysis*

Random vibration analysis is dynamic in nature. If the magnitude of the excitation (force or motion) is unknown for all time, but averages and deviations are known, the excitation is said to be random. For this particular case, the response is also random and cannot be determined exactly at any instant of time. The vibratory response of the system can be described only in terms of statistical quantities such as the mean and mean square values of the excitation.

One of the main goals or uses of random vibration testing in industry is to bring a Device Under Test (DUT) to failure. Random vibration is also more practical than sinusoidal vibration testing, because random vibration simultaneously incorporates all the forcing frequencies and “at the same time excites all our product’s resonances”. To simulate these vibrations shaker is used and operate product under those conditions. Testing the product to failure will tell us many important things about product’s weaknesses and ways to improve it [2].

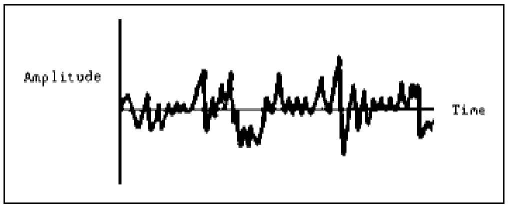

Figure 3.1 Amplitude-Time History of Random Vibration

2) *Various Methods to Solve Random Vibration Problems*

2.1 Miles Equation:

- Perform modal analysis to find natural frequency of system.
- Use Miles Equation to discover 3 Sigma GRMS for the system.
- Multiply 1.0 G by the 3 Sigma GRMS value and apply that product as acceleration in desired direction.
- Perform a static structural analysis to find deformations and stresses.

Miles Equation:

$$3\sigma_{GRMS} = 3 * \sqrt{\left(\frac{\pi}{2}\right) * Q * f * PSD} \tag{3.1}$$

$$Q = \frac{1}{2 * \zeta} \tag{3.2}$$

2.2 Random Vibration analysis in Workbench:

- Perform modal analysis to find natural frequency of the system.
- Perform a random vibration analysis utilizing the modal analysis as the initial condition environment, with the PSD Base Excitation applied in the desired direction.
- Evaluate desired stresses and deformations at 3 sigma values [5].

3) *Modal Analysis*

The experimental approach is based on the “Modal Analysis” concept [17]. Modal analysis is a process or a technique of determining the dynamic characteristics (modal parameters) of a given structure, namely the mode shapes, modal frequencies and modal damping by measurement or computational techniques, and to develop a mathematical model simulating the dynamics of the structure.

- Any physical system can vibrate. The frequencies at which vibration normally occurs, and the modal shapes which the vibrating system expect are properties of the system, and can be resolved analytically using Modal Analysis.

- Hypothetical [Finite Element Analysis(FEA)] and Experimental Modal Analysis(EMA) have been exceptionally separate engineering activities aimed at solving above mentioned regular issue.
- Modal analysis is most fundamental of all the dynamic analysis types.
- In order to carry out model updating, modal parameters of a structure need to be estimated. In Finite element modeling, a single equation of form (3.3) is generated for each degree of freedom (DOF) in the model [13],

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{f(t)\} \quad (3.3)$$

From which we get well known frequency relationship

$$\omega=\sqrt{\frac{k}{m}} \quad \text{(Natural Frequency)} \qquad (3.4)$$

IV. NEED OF VIBRATION TEST FIXTURE

Almost all advanced machineries and dynamic mechanical systems urge accuracy in its performance. The dynamic nature of the After-treatment system leads to the generation of vibrations within the system. These vibrations causes fatigue to the mechanical components in the long run as well as disturb the sound working of the After-treatment systems and its components in the long run.

If the generated frequencies match with the natural frequencies of any of the components, resonance occurs. The effect of resonance might permanently damage the complete system. So, the vibration testing of the After-treatment systems and its components employed in a mechanical system is very important for its proper working. Thus, to carry out the vibration testing of After-treatment system, vibration test fixture is needed [6].

A vibration test fixture is the interface between the device under test and the vibration equipment. However, the test fixture should be more stiff and rigid than the related part utilized for mounting on the vehicle, since vibrations during accelerated testing are considerably more serious than vibrations during true operation of the component. The manner in which a DUT is mounted during a vibration test can have the effect between the component passing or failing a test. The manner in which it is mounted should neither add nor subtract energy from the applied test [7].

A. Mounting Bracket

Mounting bracket is the bracket, finally used on vehicles to mount the system and for testing purpose in labs to validate the results of vibration test fixtures. There is a need to study the mounting brackets and its features considering the durability performance under dynamic random loads imposed by engine excitation [20].

1) Types of Vibration Test Fixtures

1.1 Head plates and expanders:

These fixtures increase shaker’s available surface area, horizontal mounting is provided. This allows testing of large test articles or multiple items.

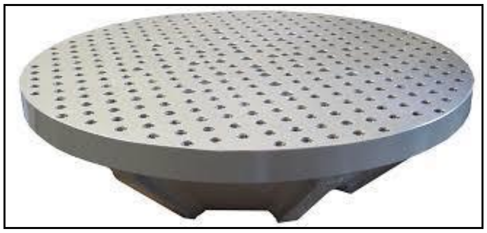

Figure 1.3 Head Plates and Expanders

1.2 ‘Cube’ Type Fixture:

Cube type fixtures provide up to 5 mutually perpendicular mounting surfaces that enable three simultaneous axes of vibration or six axes of shock while attached to the vibration exciter, horizontal slip table or shock machine.

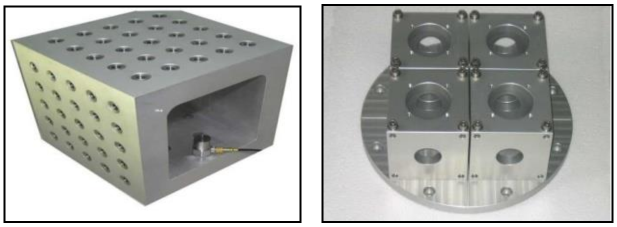

Figure 1.4 Cube Type Fixtures

1.3 Custom made fixtures:

In every fixture some custom changes are made as per requirement. But in some special cases entire fixture has to be designed as per the test specimen. These are called Custom made fixtures.

Figure1.5 Custom Made Fixtures

1.4 'L' and 'T' Type Fixtures:

Single vertical mounting surface is provided 'L' and 'T' fixture for most test applications. 'T' fixtures are relatively simple in design and require less material [6].

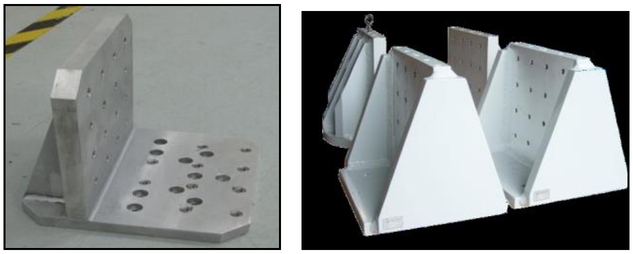

Figure1.6 'L' & 'T' Type Fixtures

2) Basic Concepts of Vibration Test Fixture Design

To design a fixture, vibration test fixture designer must consider the following inputs for test article and test equipment [8]:

- Shaker table details such as pattern of the bolting holes, bolt size and thread sizes must be known to which the fixture is mounted.
- Details of test equipment such as size, configuration, weight and centre of gravity.
- Details of the test equipment such as the mounting interface, Proximity coupling device (PCD) and its dynamic characteristics.
- Dynamic test specifications details.
- Test axis of test equipment for which fixture is designed.
- Identify the mass that can be hold by shaker table without causing any damage.
- Available shaker rating.
- The required necessary pre load between the shaker table and fixture.
- Possibilities of the shaker resonances must be ensured.
- Ensure the anticipated/repeated usage of the fixture.

To size and configure the fixture, preliminary information such as size and configuration of test equipment is required. To match the centre line of shaker table with fixture and test equipment; it is required to estimate the location of weight and C.G of the test equipment so that combined C.G of the test specimen and the fixture can be calculated. The direction of motion such as axial, vertical or lateral should be defined relative to the test equipment or to the complete assembly which will provide the service. The intensities of test must be known for two reasons,

- The inertia force acting on the test equipment $F=W_tA$ must be with stood by the bolts or other fasteners connecting the test item to the shaker.
- As weight W_a and W_t are fixed hence there is a limit for weight of the fixture that can be allowed without exceeding the force rating of the shaker table.

3) Dynamic Characteristics of Test Fixtures

3.1 Mechanical Impedance:

The concept of mechanical impedance helps to explain the interaction between vibration shaker, fixture and specimen. A simple definition of mechanical impedance is that it is the force required to produce a desired motion to the specimen. For light weight structures, the mechanical impedance of the equipment and of the mounting structure are typically comparable whereas the complex vehicles test fixtures will exhibit resonant and anti-resonant frequencies in the testing frequency band. At anti-resonant frequencies, force exceeding the capability of vibration equipment is necessitated to maintain the required test level. The extra force requirement leads to infinite mechanical impedance. So, the test fixture has to be designed in such a way that it should not induce mechanical impedance to the specimen during testing.

3.2 Transmissibility:

The fixture must be as stiff as possible so that it does not deflected by the load and transfers motion with high constancy. This quality is called transmissibility, which is a comparison of the output to the input. At a transmissibility of 1.0, the output faithfully follows input. Ideally, a dynamic test fixture couples the movement from the vibration shaker table to the specimen with zero distortion at all amplitudes and frequencies. Practically, the ideal can't be met and the limitation of the fixture must be known. The essential fixture shortcoming is lacking stiffness. In theory, with an infinitely stiff fixture, the natural frequency of the fixture-specimen system can be made as high as important to prevent resonance in the testing frequency band and to provide a transmissibility of 1.0 [15].

3.3 Cross axis Response:

The After-treatment system is designed to have high stiffness at right angles to the vibration axis. Designing all fixtures to be light and stiff will help in preventing undesirable cross axial motion. The centre of gravity should be precisely calculated and each fixture should be rigidly coupled to the shaker table. If C.G of the payload is kept low and aligns with the shaker table centre then cross axial stress will be minimized. However if the payload C.G is high or offset, then a turning moment is introduced during vibration.

3.4 Fixture-Specimen Resonance:

A simple way to model the fixture-specimen dynamic system is to assume that the test specimen is an ideal, resonant-free mass that loads the fixture. An idea of the fixture design problem in terms of how stiff the fixture can be obtained from the formula

$$D = (3.13/F_n)^2 \qquad (4.1)$$

D = the fixture static deflection caused by the specimen that produces the desired, F_n in inches

F_n = the desired resonant frequency of the specimen-fixture system.

Ideally, F_n is higher than the test range, however for the most part this ideal is impractical or impossible. For example, many specifications call for testing up to 2,000 Hz. If, to keep transmissibility close to 1.0, F_n is targeted for 3,000 Hz, the above equation shows that the fixture must not deflect more than 1 milli inch under the weight of the specimen. In most cases, such a stiff fixture is not feasible [9].

V. SYSTEM DYNAMICS

System dynamics is a part of systems theory as a strategy to understand the dynamic behavior of complex systems. System Analysis is the taking apart these systems to understand the causalities, detect and discover their structural arrangement and understand the effects emerging from the vibrations acting in the system. System Dynamics is the use of the results of System Analysis in order to improve the system causalities. The use of System Dynamics involves assessing the performance of improved factors and design variables of the system and to predict future behavior [10].

1) Design Variables affecting System dynamics

As Vibration testing is a necessary part of many programs, but the one thing every test has in common is that the energy must be transmitted into the test specimen with some kind of fixturing. The best fixturing is rigid, simple, lightweight, and economic [6]. The following is a list of general guidelines to aid in choosing the best fixturing for our test sample [13].

1.1 Rigidity:

A fixture should be very stiff in order to transmit the vibration without including additional noise. A flexible fixture can resonate at test frequencies, influencing the measure of energy transmitted to the test sample, and thus test quality. A very flexible fixture may be difficult to control and will require a more powerful vibration system, affecting both quality and price. At 2000 Hz, a 1 g sinusoidal input just requires 0.000005” of shaker displacement. It doesn’t take much fixture bending to influence that [16].

1.2 Weight:

A fixture with extra mass will require more force to vibrate at given amplitude (g-level). Low mass fixtures will enable different samples to be tested at the same time, enhancing costs per part and test throughput. Fixtures ought to be low profile and keep the sample as close to the system input as possible. Eliminate unnecessary features, but don’t skimp on material if it will influence stiffness. Weight can also be reduced using geometry change of fixtures [11].

1.3 Material Selection:

Unfortunately, vibration fixtures are not constantly made of the most economical materials available. Steel and Aluminum have generally a similar strength to weight properties, so it may make sense to pick steel as the more affordable option. However, aluminum has a density much lower than that of steel, and features can be made much bigger and stiffer with no weight penalty. This makes it the superior material for high-frequency vibration. For very high-performance fixtures, magnesium will sometimes be used as its performance is even better than aluminum. The tradeoff is difficulty in machining and much higher fixture costs. [13] [11] [15].

1.4 Complexity:

The best vibration fixtures are simple, with the minimum number of features. Vibration testing is not just unpleasant to the sample, but in addition to the fixturing. Extra features and thin sections can include more potential for undesirable resonances, and more components that can fatigue and break. Simple fixtures are usually less costly up front, and cost less over the long run [6] [11].

1.5 Other Considerations:

Most vibration testing is performed in a single axis, and repeated in each orthogonal axis (X, Y, & Z). Vibration systems can either be vertical or horizontal, and fixtures are regularly rotated 90° to perform two of the three axes on a horizontal surface. If we only have one vibration system accessible, it might sense to design a fixture with mounting holes on more than one surface so it can be rotated for each axis of testing. T.S. Reddy et.al. also worked on orientation of the testing fixture [9] [16].

1.6 Validating a Fixture:

When a fixture is utilized out of the blue, it is great practice to perform a resonance scan keeping in mind the end goal to check for any undesirable responses. It is validated through drive point FRF measurement using impact test method. In this method, accelerometer is mounted on fixture and mounting bracket and impact excitation is provided through hammer. The response is then evaluated on the accelerometer and stiffness is validated [12].

VI. PROBLEM SOLVING APPROACH

Modal participation analysis is one of the approaches to solve and calculate the fatigue life due to random vibration. This method also uses the calculated natural frequencies, normalized mode stresses, modal participation factors and modal damping ratios to synthesize a representative time history which can then be processed through existing damage calculation algorithms such as rainflow counting [18] [19].

VII. CONCLUSION

From the above Literature survey we find that there are many researchers done analysis on vibration test fixtures and the mounting bracket. The various factors like materials, mounting location and change in geometry of test fixtures; are considered by them to do the fatigue analysis on test fixtures and mounting bracket.

Finally, we reached on conclusion to do the research and understand the system dynamics of the vibration test fixture and mounting bracket on After-treatment system. We will carry out a comparative study and consider four different parameters such as material, mounting location, change in geometry of fixture and the mounting bracket i.e. mounting bracket is used instead of test fixture. Here, we will use the Mass participation factor method to identify the mode shapes. It also tells how many frequencies we need (modes) to accurately capture the dynamic response of the system. Further, we will perform modal analysis and Power Spectral Density (PSD) analysis to compare the effect of different parameters on the system dynamics.

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