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Isolator selection for imbalanced three-cylinder diesel engine

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Abstract

Application of three-cylinder engines in off-highway vehicle segment is minimal and three-cylinder engines are cost effective compared with four-cylinder engines. Major challenge is to dampen vibrations of three-cylinder engine. Engine isolators plays major role in restricting inherent vibration, improving operator comfort and component reliability. This paper explains the methodology followed to select right isolator and placement for three-cylinder engine for off- high way vehicle application and lessons learned throughout the process. These design aspects include the dynamic mode that is most disturbing, support structure requirement, isolator location and orientation, factors that affect fatigue life and analysis procedure.

Introduction

Six cylinder and four-cylinder engine are powerful and smooth operation due to its balanced firing frequency. Making better choice for heavy off highway machine. However, it comes with heavy weight more parts and higher emissions and bring low fuel economy. As competitive market every off-highway machine manufacture target to attract the customer with provide powerful machine, cost effective and comfortable operation.

3-Cylinder engine is compact size, lighter weight, less part and fuel efficiency and emission control. These features brought competitive value of 3cylinder and every Off-highway machine manufacture trying to offer machine with 3-cylinder engine. With benefits I t brings some challenge of less power and torque, higher noise level and higher vibrations. Engine engineers bring new calibration techniques to overcome power and torque.

Higher vibrations concern to customer comfort as well as machine part failure can take way from the competitive advantage and cost effectiveness. Hence it is necessary to reduce the vibration and meets the customer expectations as per higher cylinder engine machine. In this process engine integrate with machine with Isolators.

Isolators play critical role to reduce the vibration level at machine level and in restricting noise and vibration transferred to the structural components and operator cabin.

Hence to design isolator for 3cylinder engine its dynamics or inherent properties were studied and explained isolator design and validation and set the isolation selection process for 3cylinder engine for off highway machine.

Design Requirements:

As depending on number of cylinders the engine dynamic characteristics based on power stoke called disturbance or firing frequency. During power stroke for 4cylinder engine 2 pistons are going up and two pistons move down hence they are balance in natural. similar case found in six cylinders as three pairs move up while 3pairs move down and balance each other and cancels the rocking motion and 2^{nd} balance with crank arrange in planes offset to 120 degrees.

As elimination of cylinder number create impact on balancing of disturbing forces which higher vibration observed on 3cylinder engine. Low frequency and multiple directions of excitation make three-cylinder engines more challenging to isolate.

Good amount of attention is required to select correct isolator and position with respect to engine geometry, weights, centre of gravity, inertial properties and other components getting mounted on engine such as transmission, pump etc.

Engine performance tuning changes can also be implemented to improve vibration.

Tremendous efforts were put on analytical calculator to verify supplier data which includes excitation forces, displacement, isolator stiffness and transmissibility. Various static and dynamic NVH tests based on machine application and duty cycle are conducted to understand the behaviour of isolator performance at same time durability of isolators.

Engine Mounting System:

Two types of disturbance originate within the engine.

- Disturbance generated by firing pulse.

- Disturbance due to imbalance forces due to reciprocating (Pistons) and rotating (Crankshaft and rods) masses within engine.
  - Predominately 1st order
  - Inertia loads are due to engine design.
  - Imbalance loads are due to engine and transmission part-to-part variation.

These must be identified to position isolator correctly and to select the isolator with the characteristic required for isolation. Mount location, combined Center of gravity and its effect on increasing isolation ration. The correct position of the mounts can vary the vibration modes and reduce the natural frequencies of the suspended element, increasing the isolation ratio.

All the mounts should support the same static load. So, in “X” direction, the mounts should be installed symmetrically to the total COG. To achieve the lowest natural frequencies possible and better dynamic load distribution, in “Y” direction, the mounts should be installed symmetrically to the total COG. To minimize the dynamic forces transmitted by the mounts, it is recommended to install the mounts on the imaginary NTA, which connects the front and rear mounts with the total center of gravity.

The imaginary rotation axis of the harmonic motion (explosions of the pistons) is referred to as the NTA. It does not coincide with the crankshaft axis or the with the main axis of inertia of the engine/transmission unit. If the mounts are soft (in order to minimize the transmitted forces) and they are installed on the NTA, the dynamic forces can be effectively isolated.

Interaction with support Structure:

Regardless how carefully the stiffness characteristic and isolator location are selected, the whole exercise can be zero if the interaction with the support structure is not considered.

A general rule of effective isolation is that the stiffness of the engine bracket and frame side support structure should be at stiff enough than the isolator if not it will nullify the effectiveness of the isolator and Failure to meet requirement.

Isolation is possible only when the engine and its accessories are allowed enough room for its relative motion within the vehicle frame.

The motion must occur in space permitted. If too little space can place the isolator s, we can be forced to shift part around. we may be limited in deflection between fan and the radiator shroud.

There are multiple mount arrangements available to mount engine and transmission to the vehicle main frame. Majorly used mount arrangements are 3 Point, 4 point which can be either focal or flat type mounts.

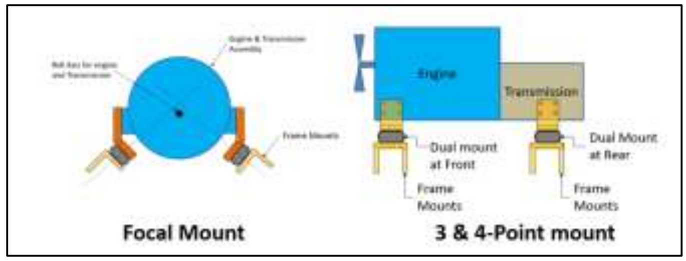


Fig 1: Mount Systems

Shock Loading:

The degree and direction of shock loading the engine mounts will have to withstand is depends on the application. In construction applications, heavy shock loading can occur in the fore-aft and side to side directions due to machine operations. Shock loading is usually expressed as the maximum expected acceleration level in “G” s.

Vibration Modes:

Any solid object can vibrate in six modes with respect to its centre of gravity called rigid body modes. Rigid body is structure does not deform but its moves. These are not only depending on the dynamics of the structure properties but it boundary condition, stiffness and damping of the suspending element (isolator). Can be consider as spring and damper system.

Out of 6 modes, three are shaking modes (vertical (Z), horizontal (Y), and axial (X)) and other three are rotating modes (pitch, yaw, and roll). For each rotating mode, the object will tend to move around the axis where the moment of inertia is lowest. The location of these axis for a typical engine / transmission assembly is shown in Figure 2. Most diesel engine vibration can be separated into pitch, yaw, roll, and vertical shaking.

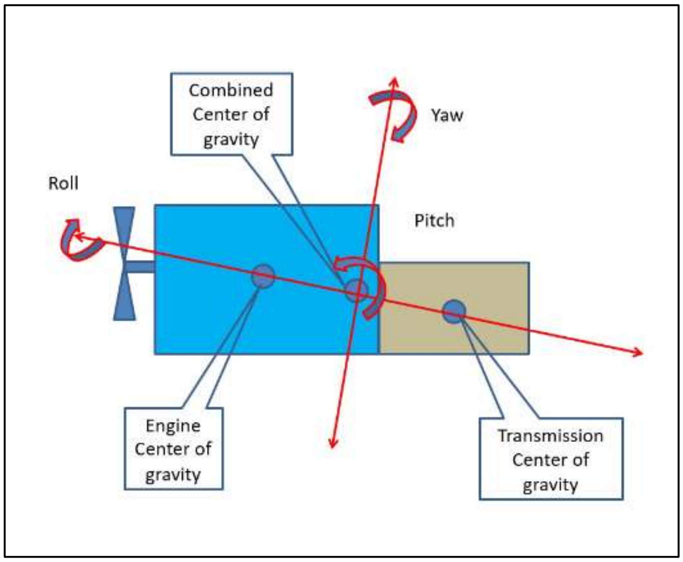


Fig 2: Degrees of freedom

Transmissibility Ratio's :TR

Transmissibility is a ratio of the energy exiting a system divided by the energy entering the system. Thus, a Transmissibility equal to 1 means that there is 'perfect' transmission: no reduction or amplification is occurring, and the energy is passing through unaltered.

Transmissibility less than 1 must be before idle RPM. Transmissibility above 1 means that there is amplification happening; transmissibility below 1 means that there is reduction taking place. For example, a transmissibility of 0.01 means that only 1% of the incoming displacement is being transmitted, in other words there is 99% reduction at that point.

Transmissibility is usually expressed in a transmissibility graph. The transmissibility level is on the Y axis. Frequency stated in hertz or Engine RPM is along the X axis.

The transmissibility graph is the primary measure of an isolation system's performance. It shows you how an isolation system performs across a broad frequency range.

The transmissibility graph tells you where a system's natural resonance can occur, how much amplification occurs at that point, how quickly it picks up performance, and how much reduction it provides at maximum performance.

A steep descent after the resonance, usually called a fast roll-off, indicates that the system achieves good isolation within a few hertz of the resonance. Some systems provide only a small resonance but do not achieve great reduction at peak performance, others provide a low natural resonance with a gradual roll-off. These performance characteristics will be summarized in a system's transmissibility graph. The line on the graph is referred to as a system's performance curve.

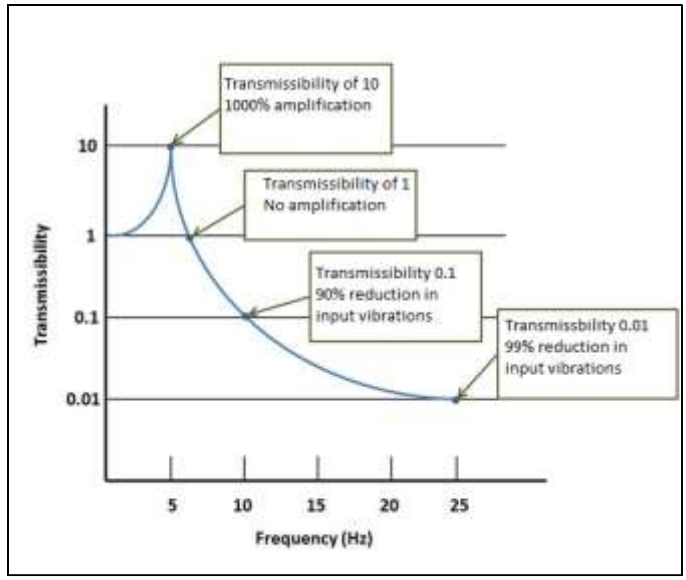


Fig 3: Transmissibility

*Values shown are only for representation purpose.

Isolation Efficiency:

The effectiveness of the isolator, expressed in percent is:
% Isolation = 100 (1-T) %
% Isolation is the percentage of the vibration isolated from Source.

Imbalanced 3 Cylinder Engine Isolation Requirements

A body free to move in space has 6 degrees of freedom – 3 Translational and 3 Rotational. This freedom is determined by the isolation system. The ideal mounting system should provide isolation in all 6 natural modes throughout the operating range. There is a misconception that isolation is solely depends on stiffness of isolator. A very soft isolator will allow engine to float freely relative to the support structure.

The major difference between a 3 Cylinder engine and a 4-cylinder engine is that when crankshaft of 3-cylinder engine rotates two cycles, the 3 cylinders ignite once respectively, so the excitation from the gas pressure is 1.5th order. There exist moments around y-axis and the major torque component is 1.5th order. Only roll mode should be controlled for the 4-cylinder engine, however, both roll mode and pitch mode should be controlled for the 3-cylinder engine. The roll mode frequency of the 3-cylinder engine must keep away from the 1.5th order excitation and its pitch mode should be avoided to occur resonance with the 1st order excitation.

Generic Isolator Selection Process

Isolator Selection process can be split into two - for existing machine and for a new machine. For an existing machine, measurement of vibrations getting transferred to the engine mounts and isolators can be already available. This can be a direct input to the suppliers for the new isolator selection. There may not be many efforts required to select the location and orientation of engine and transmission mounts.

In case of new machine, information regarding the engine & transmission properties to be used to perform mount stiffness-analysis. This will define the orientation and location which plays a major role in evaluating the isolator performance and selection.

For the above two scenarios, the details such as machine C.G, weight details, mount locations and moment of inertias required to be shared with supplier to perform their analysis to select a suitable isolator for the proposed machine. Often our existing mount location may not work if we are transitioning from a 4 Cylinder engine to a 3 Cylinder engine. The important parameter which needs to be considered is the transmissibility, which needs to be less than 1 to have a good isolation system.

Parameter to consider for isolator selection.

Centre of Gravity, Moment of inertia of engine and transmission assembly to be defined by help of 3D model and with the help of supplier database. Reactions coming on mounts and force coming on mount in normal and shear direction, to be calculated as per static and dynamic load condition.

The torque roll axis of engine & transmission assembly and elastic center position to be estimated. Orientation and location of mounts to be located as close as possible to the nodes for chassis frame (Modal Analysis to be done in Finite Element model considering various major aggregate connected and with body structure connected). Reported mode shape must be above natural frequency of the mounts and below low idle frequency.

Transmissibility in all directions, that is X, Y and Z direction, to be limited to less than 1 for the highest value of stiffness of mount (considering manufacturing variations.).

Structure used for placing the rubber mounts should be designed to have stiffness in respective direction minimum 10 times the stiffness of rubber mounts to avoid significant effects on transmissibility calculated considering rigid foundations. Loading condition:

We must look at three normal loading conditions as we prepare to select the engine isolator.

Static load (weight of engine, transmission, and other accessories) Dynamic loads (transient shock levels): dynamic load is the shock load from outside due to vehicle operation. Torque load: Deflection of mounts & strength load cases for mount structures- Vehicle Frame side Mount & Engine and Transmission mount to be designed considering below criteria in addition to the transmissibility aspect.

Static condition – under static 1g load the deflection. verify static deflection with supplier calculation.

Dynamic condition –
Vertical- 5g load condition
Lateral- 5g load condition
Longitudinal – 5g load condition

Torsional– output torque of transmission
Engine and Transmission packaging should have enough space considering all these deflections with lowest tolerance limit of mount stiffness (considering manufacturing variations), combined with stack up of geometrical tolerance in various mounting and surrounding components.

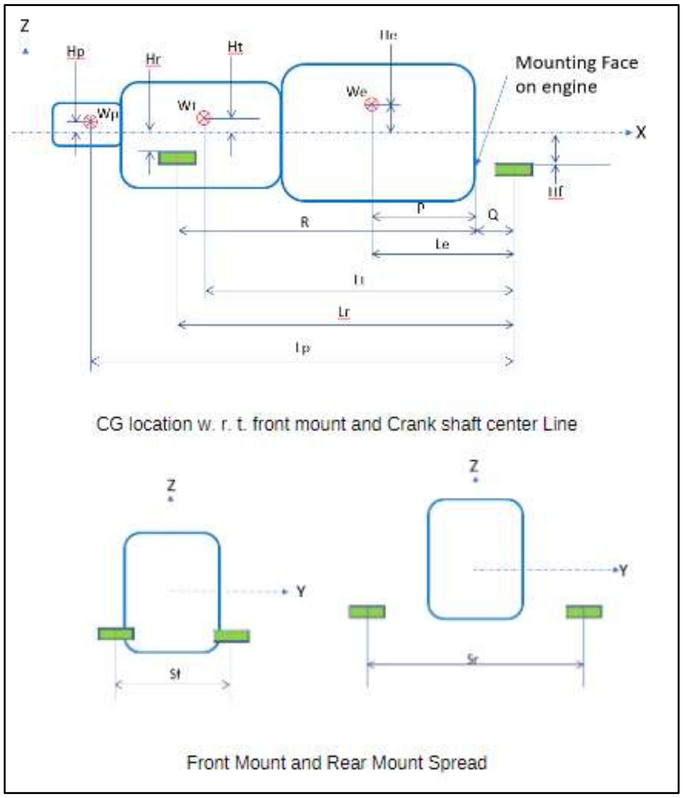


Fig 4: C.G and Mount Locations

Center of Gravity:
1. Engine C.G. Height above CSCL (He)= ...... mm
2. Engine C.G. Location Behind Front Mount (Le) = ... mm
3. Transmission C.G. Height Below CSCL(Ht) = ... mm (below)
4. Transmission C.G. Location Behind Front Mount (Lt) = ...

mm
5. Hydraulic Pump C.G. Height above CSCL (Hp)= ....mm
6. Hydraulic Pump C.G. Location Behind Front Mount (Lp) = ... mm

Position of mounts:
1. Front Mount Location Below CSCL (Hf)= ....mm (Below)
2. Rear mount Location Below CSCL (Hr) = ... mm (below)
3. Rear Mount Location Behind Front Mount (Lr) = ... mm
4. Rear Mounting Spread (Sr) = ... mm
5. Front Mounting Spread (Sf) = ... mm

Powertrain generated Excitations come from many sources: Combustion, Inertia, Imbalance, and Accessories. Excitations are proportional to Engine Speed and are called Orders. Awareness of Powertrain Orders allows for an intentional misalignment of Powertrain Modes and Excitation
The primary disturbance for an inline three-cylinder engine is

- 1st order pitch
- 2nd order pitch
- 1st order yaw
- 3/2 order roll

Design Calculation

Natural Frequency:

Natural Frequency = {(Engine RPM) / (60 sec/min)}x {(number of cylinder)/ Firing Order)}

Acceptance criteria:
First natural frequency of the bracket should avoid engine operating frequency range

Engine Torque Reaction Force per mount

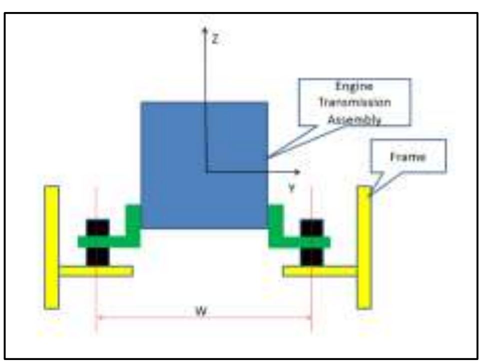


Fig 5: Reaction forces

Torque reaction force can be determined by the following formula:

TORQUE REACTION = PEAK ENGINE TORQUE / W
Multiply the loads due to static weight by the appropriate "G" factor for your application. Make sure that the sum of total torque reaction does not exceed the supplier's dynamic load rating for the mounts selected.

Verification and Validation

As per off Highway machine requirement and load case .and criteria analysis model developed and based on that Mounts have been selected. Different supplier provided the different mounts for same requirement with different performance with different cost structure.

To meet the cost and performance requirement onboard 2-3 suppliers with 2-3 different type of isolators.

Evaluate the performance of the isolator with critical machine operations like transportation, trucking, bumpy road, Digging, rough transportation. Vibration measurement done at isolator location as well as operator tactile location in machine vertical direction (Z), lateral direction (Y) and longitudinal Direction (X).

Isolator performance evaluated based on the vibration level at engine side and frame side as well as vibration transfer to the operator.

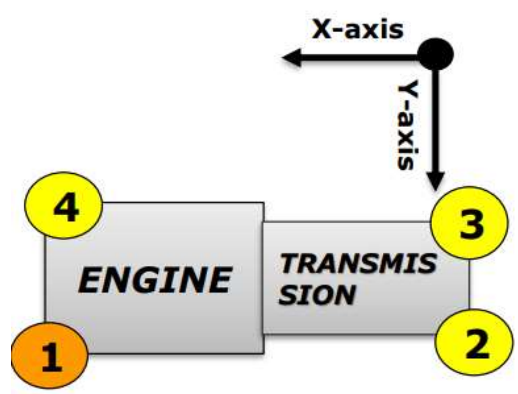


Fig 6 a: Mount Locations

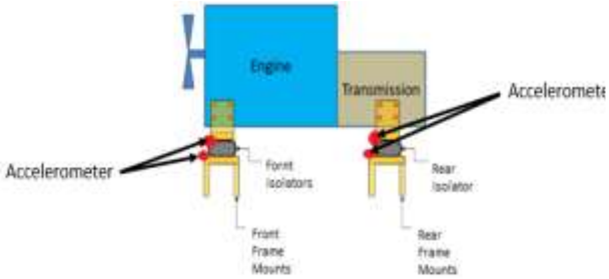
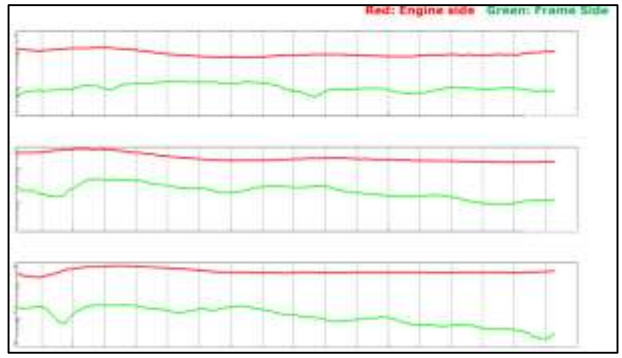


Fig 6 b: Mount Locations



X Axis – RPM, Y Axis - mm/s

Fig 8 b: Vibration attenuation level with engine speed at mount location

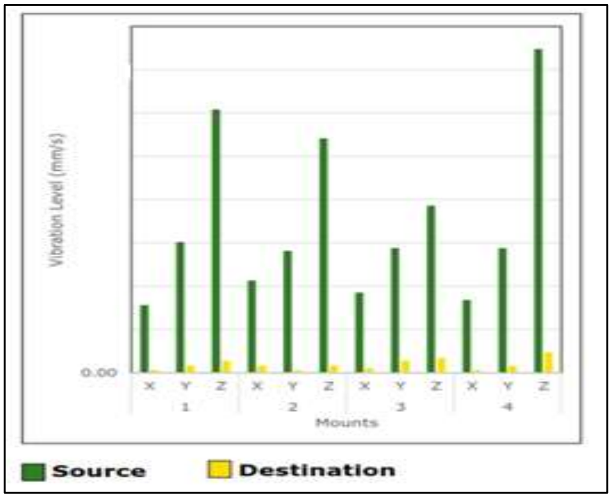


Fig 7: Vibration level at engine (Source) and Frame (Destination) Mount Locations

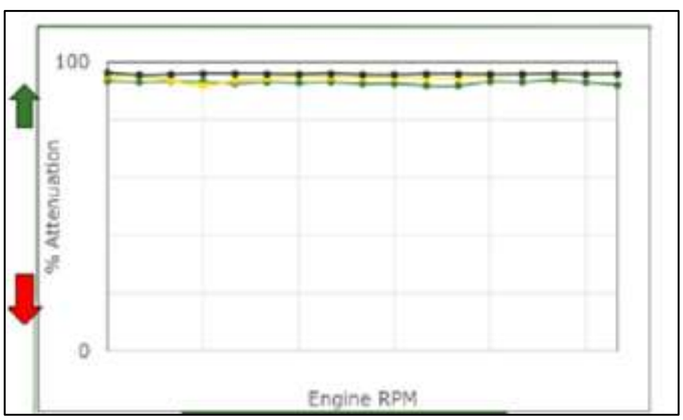


Fig 8 a: Vibration attenuation with engine speed at mount location

Deflection Measurement:

Deflection is measured at all 4-mount locations using transducers. Displacements need to be measured in X, Y and Z axis at all operating conditions. At all conditions deflection of isolators where within the acceptable limits. Once you have the deflection values, use it to evaluate the durability of isolators. Fatigue life simulation is used to see how the mounts would respond to the cycle life.

Correlation

- Transmissibility:
  The below Fig. Shows comparison between Analytical calculator and NVH test results. Variation in results within 5% which is acceptable.

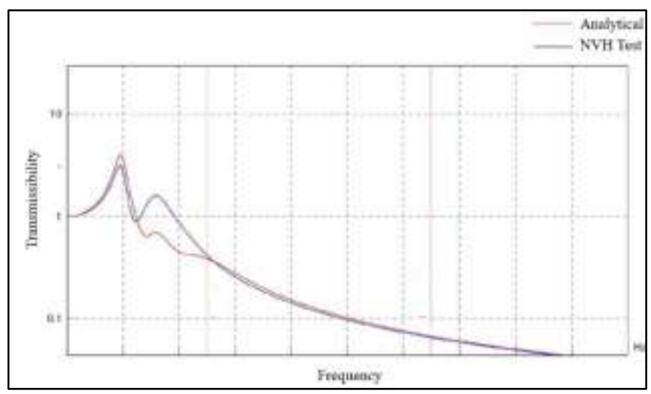


Fig 9: Transmissibility Curve – Analytical vs Physical Test

- Frequency

3 Cylinder engines typically have a natural pitching motion at the first order frequency. Due to the odd number of cylinders causing unbalanced motion. Cylinder engines have a roll motion at 1.5 Order/ firing frequency, Roll moment due to cylinder pressure. These are two critical parameters to be considered for 3 Cylinder engines. Even though these are critical parameters, we must ensure

Vehicle operating frequency away from Natural frequency of Isolator at all six degrees of freedom. Below Table 1 shows correction of analytical Vs Actual test data.

Frequency	Analytical Calculator (Hz)	Test Data (Hz)	% Difference
F1	9	9.81	8%
F2	11.71	11.61	-1%
F3	13.91	14.18	2%
F4	18.23	17.81	-2%
F5	20.85	19.55	-7%
F6	21.18	23.17	9%

Table. 1: Frequency -Analytical vs Test Data

*All values are for representation only. To represent the % difference between Analytical Vs Actual test data.

Results show 95% correlation between Analytical Vs Actual test data and meets the acceptance criteria. This helped us in building confidence on the analytical tool which we developed, thereby reducing the number of iterations and physical tests.

Summary/Conclusions

The above approach helped in overcoming the challenges associated with the 3-cylinder unbalanced engine and standardizing our process of isolator selection. The test data shows a good correlation with analytical analysis. Selected isolator which meets customer expectations and comfort.

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