Design Enhancement of EGR System for Improved Vibration Performance on Truck Diesel Engine

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Abstract: In the diesel engine Exhaust Gas Recirculation (EGR) components, valve and connecting pipes are the critical components and often fail during new engine development. These components are important for meeting NOx emission norms. Thus design of these components should remain robust. The compact packaging of complete EGR components on the engine, however, is counted as a designing challenge in which the consequent vibration-related failure plays a major role. Normally in pneumatic EGR valve, shaft spring stiffness is considered important for shaft opening and closing. But during emission testing in this layout, shaft is self-opened without feedback signal from sensor; this is due to resonance where the problem is solved by increasing the spring stiffness. The next key components are the EGR pipes; the flexible bellows on these pipes are useful for thermal expansion during hot conditions. In this case the bellow crack failure is observed due to vibration. Therefore, design improvements due to proper design of bellow geometry and bracket support for these pipes facilitated prevention of EGR pipe failure. This paper also describes the methodology of conducting proper failure investigation to identify the root cause for vibration-related failures of EGR system during new product development.

Keywords: Corrosion, Design, EGR Valve, Stress, Validation, Vibration,

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Biographical notes:

1 INTRODUCTION

The automotive industry frequently faces new challenges as the demand increases for inexpensive and at the same time, high quality components. Extreme care must be taken to ensure that such components are designed and manufactured with sufficient quality to withstand a variety of service environments. However, in the absence of material defects, improper design for the service environment can lead to failure. If a failure occurs in such a component, a meticulous approach is necessary to identify the failure root cause and to make appropriate design and manufacturing changes in order to prevent failure.

But it is quite interesting that the vehicles on the roads have less or no failures due to systemic analysis and test done in a robust product development process. This creates a need for structured method of identifying the cause of failure. Generally speaking, enjoying the entire background information is important before inspecting a failed component. This includes material composition, specification requirements, manufacturing history, heat treatment, operation and service history. With regards to service history, careful consideration should be given to details such as mechanical loading type and amplitude, environmental conditions, length of time in service and any anomalous events which may have occurred during the life of the part. Attention should also be given to the frequency of the failures and behaviour of mating components. During this stage the scope of investigation should be defined properly. Once the above information is analysed, the failure conditions are simulated then, based on the behaviour of the component, a comprehensive assessment of the failure and the relevant counteractive measures are made.

2 EGR VALVE INSTALLATION ON ENGINE

EGR valve installation on the engine is shown in Fig. 1. The EGR valve is connected by rigid casting pipe (1) at the bottom valve inlet side and by flexible pipe (2) at the top outlet side. The hot gas flows from bottom side and exits from the top side. Exhaust gas flow is controlled by means of shaft motion. This shaft is compressed by spring and actuated with the help of vacuum regulator.

The resonance in EGR valve is due to oscillation of spring with larger amplitude at few frequencies than at others. These are known as the system's resonant frequencies. In these frequencies, even small periodic driving forces can produce large amplitude oscillation, because the system stores vibrating energy. Hence spring stiffness improvement is made based on resonance study.

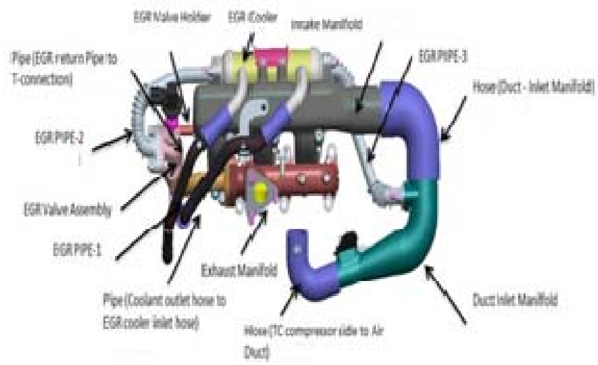

Fig. 1 EGR Valve Location on Engine

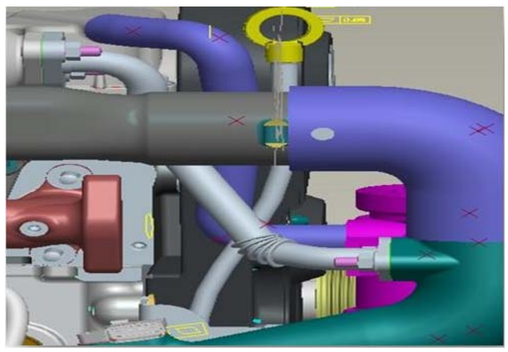

Fig. 2 EGR pipe-RH arrangement on engine

Normally EGR pipe thickness ranges from 0.4 mm to 0.8 mm. The design of this pipe, thus, is critical. In this case study of EGR pipe failures, vibration from the air-duct (connecting component of EGR pipe) is forced to act on the pipes causing vibration failure. In forced vibration, the frequency of vibration is defined by the frequency of force, with order of magnitude being dependent on the actual mechanical system. EGR pipe-3 (RH) arrangement on the engine is shown in Fig. 2. Therefore, packaging constraint highly affects the vibration-related problems.

3 MATERIAL AND COMPOSITIONAL ANALYSIS FOR EGR PIPE

To identify clearly the reason for such a failure in case of EGR pipe, not only vibration study, but also the material analysis is required as well. Thus, the component has been thoroughly documented, and sectioning is performed to study the material composition and properties. Due to the significance of cost and time, special considerations are made during selection of tests and evaluation methods to suit best the objective. Here microstructure and hardness study are made to conform to the properties. Further failed components are analysed for their composition using inductively coupled plasma/atomic emission spectroscopy (ICP/AES). The results are compared to the designed specification to provide a basis for better understanding the properties of the pipe material.

4 FAILURE SIMULATION ANALSYSIS FOR EGR PIPE

Once a failure-related hypothesis has been formed, computer simulation (FEA) investigation is made. Any recommendations should be as simple and practical as possible and directly address the cause of the failure. Here the thermal stress analysis is made to simulate the failure.

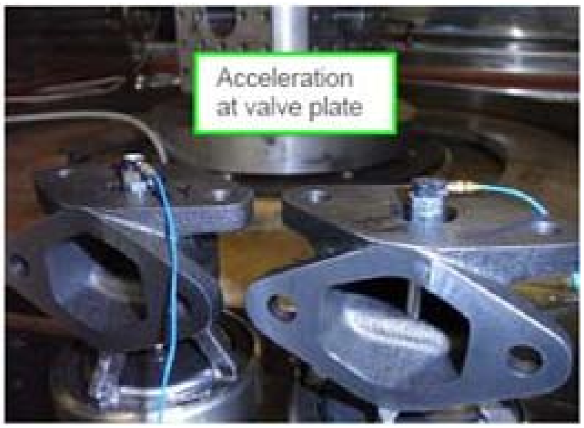

Fig. 3 Accelerometer Sensor arrangement on shaft

5 RESULTS & DISCUSSION

Valve Vibration Analysis for Self-opening

To identify the resonance on EGR valve, accelerometer sensor is placed on the valve in different locations before and after spring stiffness modifications. Fig. 3 shows the sensor arrangement on the EGR valve for acceleration measurement towards the direction of the shaft for both springs' stiffness. This arrangement is for valve open condition.

As Fig. 4 indicates, during valve open condition, valve resonance occurs at 113 Hz with maximum acceleration of 416m/s^2 for 2N/mm spring stiffness (red line). By increasing the stiffness, the resonance (green line in Fig. 4) did not occur and there is no self-opening of the valve.

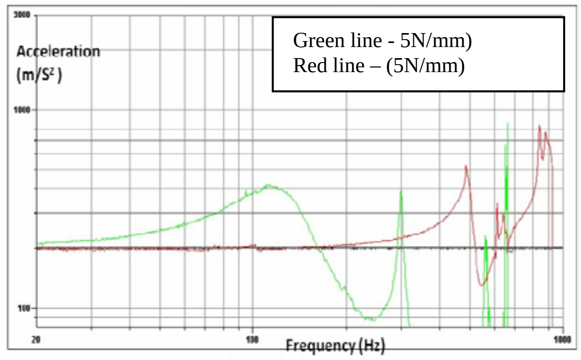

Fig. 4 Acceleration measurement on the shaft

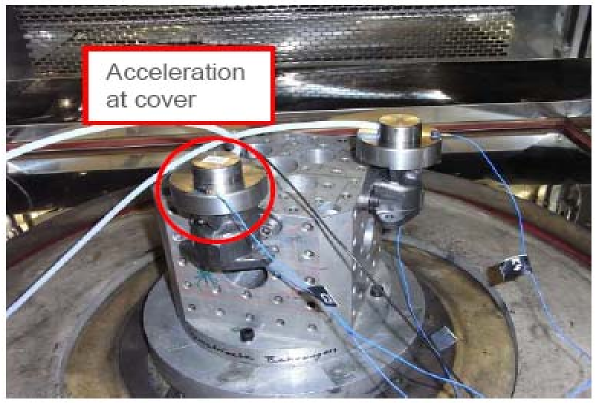

Fig. 5 Accelerometer sensor arrangement on the cover

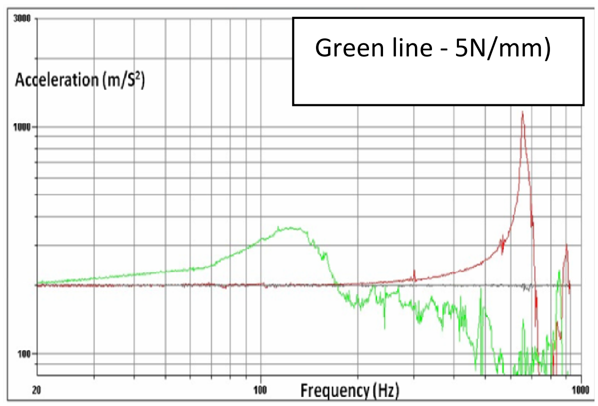

Fig. 6 Cover acceleration measurement

Fig. 5 shows acceleration measurement taken on the cover during valve operating condition. Based on Fig. 6 during valve open condition, valve resonance occurs at 123Hz with maximum acceleration of 362m/s2 for 2N/mm spring stiffness. By increasing the stiffness, the resonance did not occur concerning the fact that there is no self-opening of the valve.

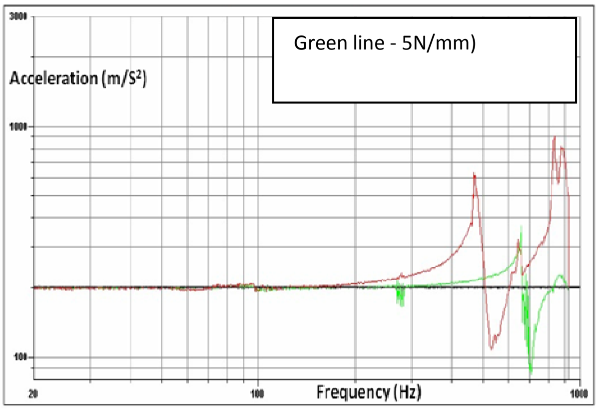

Fig. 7 Accelerometer measurement on the shaft

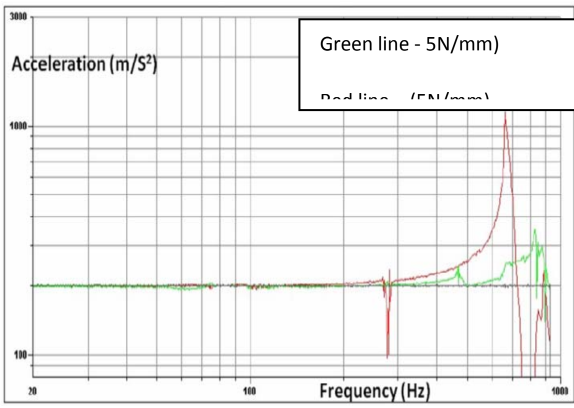

Fig. 8 Acceleration measurement on cover

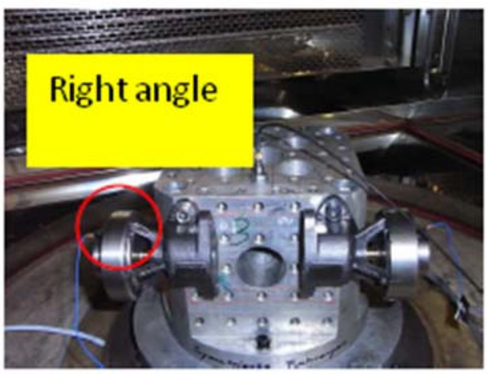

Fig. 9 Accelerometer sensor kept on the cover

As figures 7 & 8 show, during valve closed condition, valve resonance did not occur within 130Hz, which is an appropriate condition for self-opening of valve. Fig. 9 shows EGR valve with both springs' stiffness mounted at right angle for acceleration measurement.

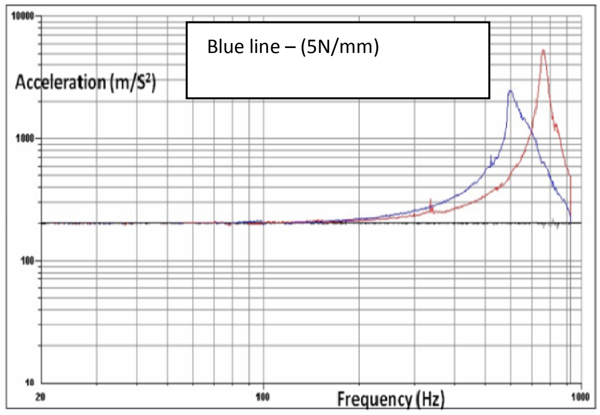

Fig. 10 Vibration measurement on the valve cover

Based on figure 10, during valve closed condition, resonance did not occur with 130HZ for both springs' stiffness.

EGR PIPE FAILURE ANALYSIS

Regarding the figures 11, 12, & 13, ring failure (0.4mm pipe thickness) is due to forced vibration from the EGR cooler side. To solve this problem full pipe thickness is increased to 0.6mm. This, however, created again a failure slightly at a lower point. As part of design improvement, the ring thickness alone changed to 0.6mm and overall pipe thickness is made 0.4mm, this solved the failure and thus, the durability in vehicle is increased to 100000km for RGR pipe-LH.

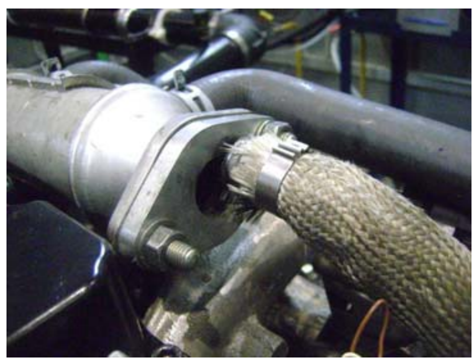

Fig. 11 EGR pipe-2 (LH) failures [0.4mm thickness]

Based on figures 14 & 15, EGR pipe-RH under investigation has exhibited an undesirable number of failures during durability test. With 0.6mm the thickness failure is observed near the lower points, so the thickness is reduced to 0.4mm and the location of the mentioned points is changed and the quantity of the points is reduced to 5 as well, however, the failure is still observed. The suspected reason for failure is probably due to material or thermal fatigue creep.

Fig. 12 EGR pipe-2 (LH) ring failures [0.4mm thickness]

Fig. 13 EGR pipe-LH failure at a lower point (0.6mm)

Fig. 14 EGR pipe- RH failure of a lower spot (0.6mm)

Fig. 15 EGR pipe-RH failure of a lower spot (0.4mm)

Table 1 Chemical composition of EGR pipe-RH

S. No	Observed		Spec	Parameters
1	Chemical Composition	%C	0.05	0.08 Max
		%Si	0.27	1.00 Max
		%Mn	0.90	2.00 Max
		%Cr	20.0	18-20
		%Ni	8.0	8-10.5
		%P	0.03	0.045 Max
		%S	0.02	0.030 Max
2	Material	AISI 304		Conforms to spec
3	Hardness		-	180-200 VHN
4	Microstructure		Austenite	Austenite

As the table 1 indicates, the composition of the part is analysed via inductively coupled plasma (ICP). The result is indicative of specified SS-304 and shows no compositional deficiencies. According to the Fig. 16, the microstructural analysis shows Austentic grains with carbide precipitation. The carbide precipitation occurs at the welding temperature near the welded zones and it may also occur during the service if the temperatures are of the order of 600^{o}C. The carbide precipitation decreases the strength of individual cracks and is responsible for a great deal of intergrannular propagation of cracks as the grains become Cr depleted. This is not observed for the second time, so this may be due to atmospheric conditions also.

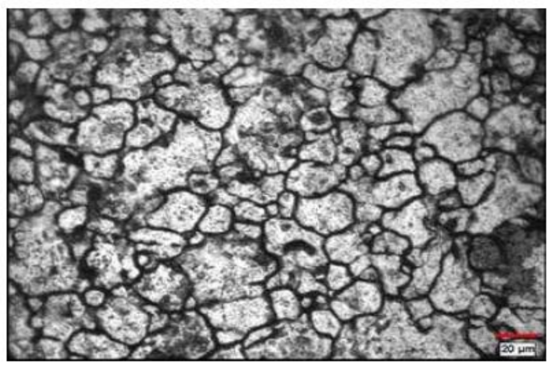

Fig. 16 Microstructure Analysis

Based on the Fig. 17 the stress level of maximum Von-Misses stress on the EGR pipe is 100MPa which is below yield limit (215MPa) of the pipe material. Hence it is concluded that the thermal load considered in this analysis is not the cause of the failure. According to the results of these tests, it is observed that the major cause for the failure in EGR pipe-RH would be because of excessive vibration. Hence to confirm this hypothesis, vibration measurements were taken at different loading conditions (idling, static run-up, maximum load and rated speed).

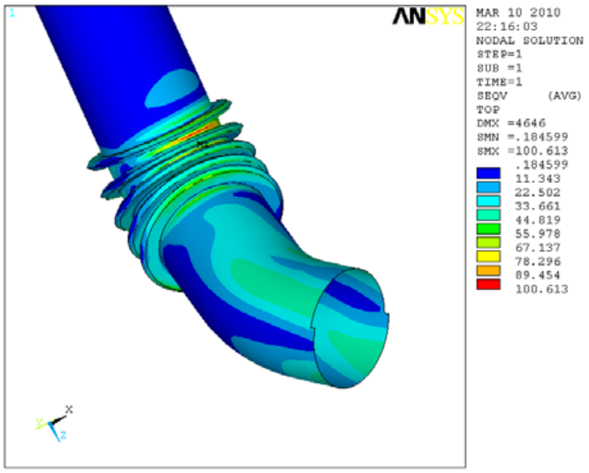

Fig. 17 Stress analysis of EGR pipe-RH

Fig. 18 Sensor arrangement on EGR Cooler

Fig. 19 Sensor arrangement on air duct bracket

Figures 18, 19 and 20 show the sensor (Tri-axial accelerometer) arrangement on air duct bracket, EGR cooler and air duct to study the vibration level in the connecting components and to identify the reason for the EGR pipe–RH failure.

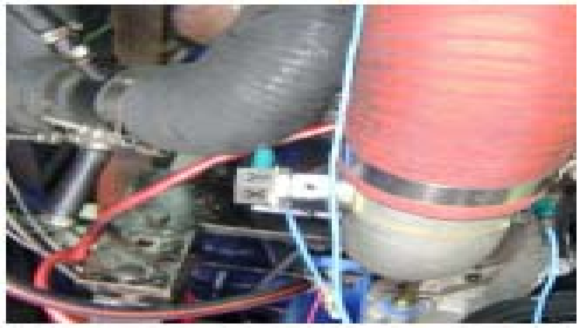

Fig. 20 Sensor arrangement on the air duct

The following were accomplished based on the obtained vibration data:

i. RMS comparison at idling
ii. Frequency analysis for idling condition
iii. Order analysis for static run-up condition

Fig. 21 shows the time domain RMS comparison at all locations within different test conditions. It is observed that the vibration levels during rated load RPM were found to be higher than other conditions. At rated load with rated RPM the vibration on vertical direction is found to be more than crosswise (56.7 %) and fore and aft direction (37.6 %) on the air duct.

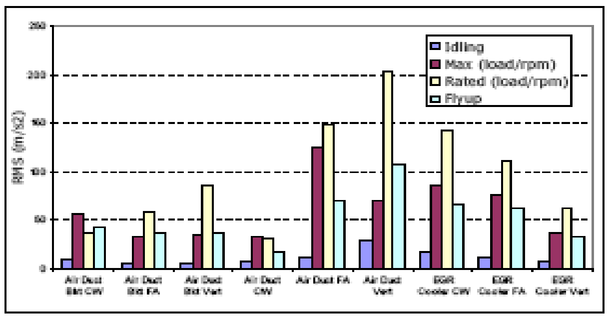

Fig. 21 Vibration levels at different locations

In figures 22, 23 and 24 the frequency spectrum of vibration signals in all three locations has been plotted. It is observed that peak amplitude occurs at 62.26 Hz. The crosswise direction at 62.26 Hz has higher peak than fore and aft and vertical directions, which doesn’t get excited much during rated load at rated RPM condition for air duct bracket. It is also observed that from frequency spectrum of the signals at 240 and 1328 Hz, the amplitude of vibration is found to be high in all directions for EGR cooler.

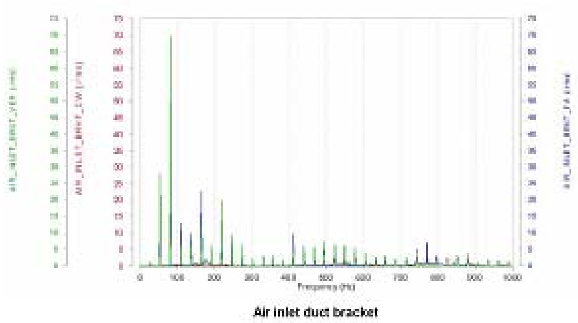

Fig. 22 Frequency spectrum at of air inlet duct bracket

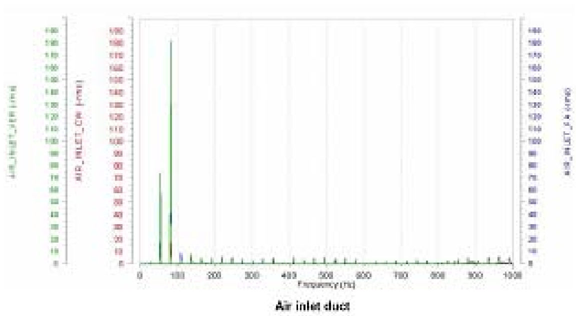

Fig. 23 Frequency spectrum of air duct

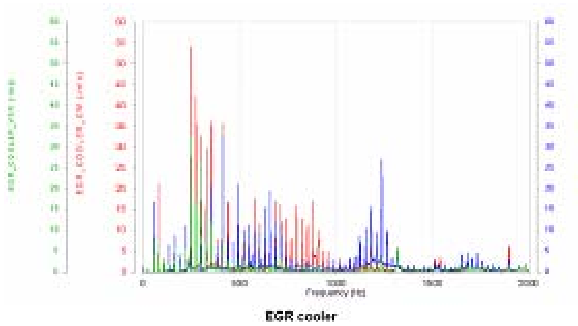

Fig. 24 Frequency spectrum of EGR cooler

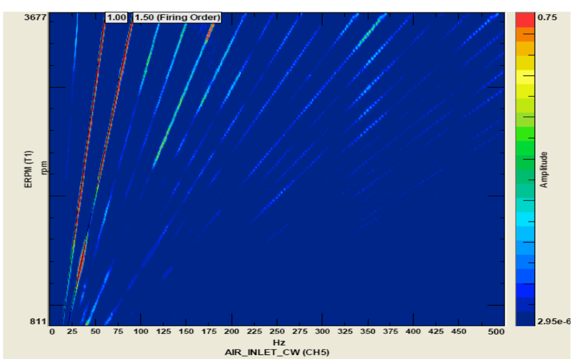

Fig. 25 Order plot for air inlet duct- Fore and Aft direction (0-500Hz)

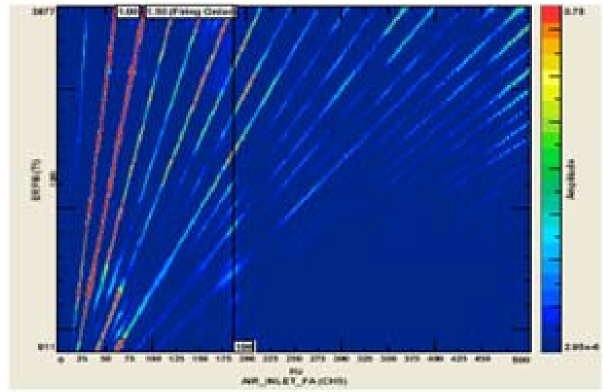

Fig. 26 Order plot for air inlet duct- crosswise direction (0-500Hz)

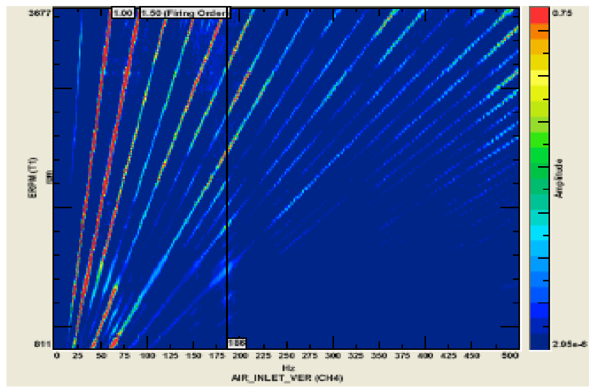

Fig. 27 Order plot for air inlet duct- vertical direction (0-500Hz)

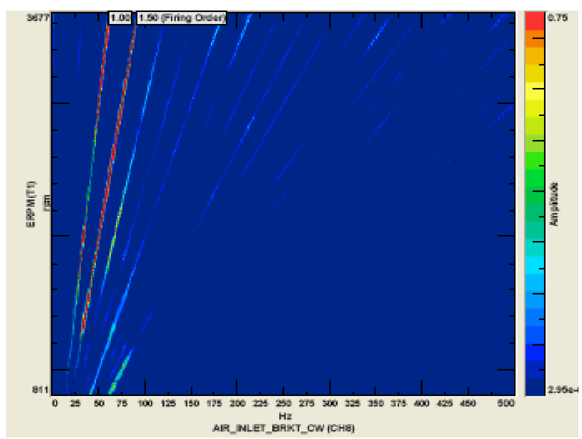

Fig. 28 Order plot for air duct bracket- for crosswise direction (0-500Hz)

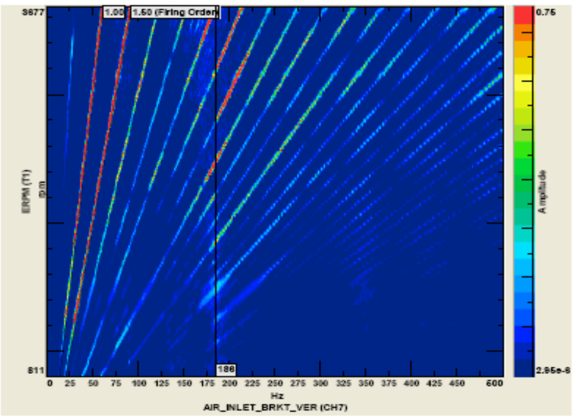

Fig. 29 Order plot for air duct bracket- for Fore and AFT direction (0-500Hz)

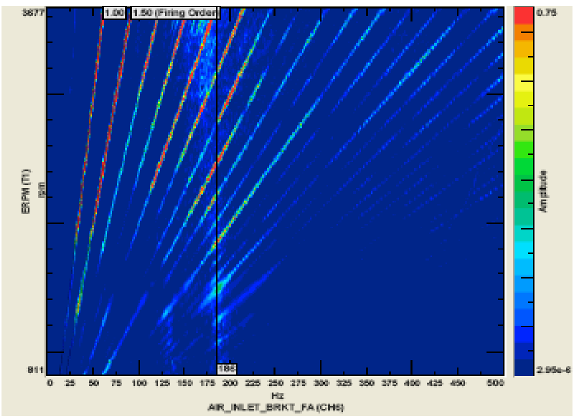

Fig. 30 Order plot for air duct bracket vertical direction (0-500 Hz)

Figures 25–30 show the order plot for air duct and air inlet duct bracket. It is observed that in all firing orders and its harmonics, the vibration amplitude at air inlet duct and air inlet duct bracket is found to be high. Vertical line with higher amplitude is observed, which indicates that the resonance of either air inlet bracket or air inlet duct occurs at 180 Hz in vertical and fore and aft direction.

6 CONCLUSION

According to the vibration test on EGR valve, it is identified that the self-opening of the EGR valve is due to resonance on the valve owing to lower spring stiffness of 2N/mm. Based on vibration analysis, the stiffness is increased to 5N/mm to deal with EGR valve self-opening for rated speed load conditions.

Related to EGR pipe LH, the failure at a lower spot is solved by changing the position and increasing the durability to greater than 100000km. Furthermore, there is no suspicion for EGR pipe-RH failure with respect to thermal stress, and full engine assembly with respect to pipe mating components for vibrations are studied as well. EGR pipe and connecting component (air duct) amplitude level is found to be high due to improper air duct bracket support.

As a result, the vibration is transferred to the EGR pipe which results in failure within two hours of engine running. By increasing the stiffness of the bracket the pipe, no failure is observed after 100 hours of engine running. Through conducting structured failure analysis, factual failure, thus, is identified and necessary design modifications were implemented without increasing the cost and performance of the component within stipulated time during new product development.

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