Characteristics of Vibration Propagation on Passenger Car Monocoque Body Structure at Static Small Turbocharged Diesel Engine Speed Variation

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ABSTRACT. The use of diesel engines in small passenger cars began to be common by vehicle manufacturers. The direct contact with humans with all the consecquencies is one of the important things to be considered in the vehicle design aspect of vibration. This research of the vibration propagation characteristics on passenger car structure has been done. Eventhough is not so many been done, especially on monocoque body structures types, in the world of the automotive industry, This research was conducted by tracking the measuring point which is considered to have a relatively large vibration response compared to other points on the body. Retrieval of vibration data in the form of RMS velocity amplitudes and of the frequency spectrum data at the measuring point. The RMS velocity amplitude data is obtained and then refered to the IRD Severity Chart vibration standard to determine the vibration severity level, as well as the transfer path analysis is performed to determine the vibration reduction that occurs in the vehicle structure. Spectrum analysis is also carried out to see what excitations that provide vibrational responses to the vehicle body structure. From the measurement and analysis results, the characteristics of vibration propagation on the monocoque body structure are determined, which the vibration response of the monocoque body structure as a whole can be concluded.

1. Introduction
Nowadays small passenger cars are built as monocoque cars body structure. This type of automotive body has a particular structure, so therefore will have a particular vibration propagation characteristics as well. In automotive body structure the propagation of vibration is an important matter for safety driving, structural strength, vehicle life time as well as passengers comfort. This street vehicle characteristics of vibration are still interesting for research since the knowledges are still developed as the problems and the demand for higher comfort are still increasing [1]. The design of monocoque body is a vehicle body that is built by integrating many particular parts or body segments. The so called monocoque is derived from French which means “one shell”, and has an integrity like an egg shell. Very efficient in the manufacturing process since the products are relatively small particular body parts, so also very suitable for automotive mass production. . This type of automotive body structure was first introduced in 1923. This automotive body does not use trunk chassis like its predecessor types, but otherwise it builds by combining and integrating the particular body parts by
spot welds as well as other conventional welds, e.g. CO2 welds [2]. The integration of the body parts will hold all the load of the body statically and dynamically as well as all vibration propagation from the engine as the vibration main source. The particular body parts are assembled to be a shell structure that be lighter in weight, relatively less stiff but able to distribute the external and internal forces as well as vibration.

Vibration effects on passengers especially the driver is very important in the context of safety driving and comfort as well. Vibration affect people physically as well as psychologically so therefore the knowledge of how vibration can propagate from the source to the people become interesting. Moreover it is believed that Diesel engine generates high vibration compared to other engine types due to the Diesel combustion. This research is investigating how vibration transmitted from a Diesel engine as the main source to the whole vehicle body, in the case of a Diesel passenger car. On a monocoque structure body, the vibration wave go through all the particular body parts which every body parts will response individually. These various responses will accumulate and interfere each other so resulting uneven propagation depends on the size, shape, thickness, material of every body parts as well as how they are connected and assembled.

2. Methodology

The study was conducted with a literature study and measuring process. Using a vibrometer at a certain point in the engine compartment with the transfer path analysis (TPA) method. Transfer path analysis (TPA) is a procedure based on tests or simulations that can record vibroacoustic flow paths from source to destination locations that have been determined through a known body structure and air-bone transfer pathways. The TPA in vehicles is categorized based on noise paths and their geometric location [1]. The principle of the TPA is to summarize all vibration paths (sources) into a combined vibration response on the vehicle. Sources of vibration include the forces on the damping, power train, combustion engine, and components that provide excitation to the vehicle body. The main problem of TPA is to get force input. There are four principal methods used: Force Method, Stiffness method, Matrix method, and TPA Operational. This procedure is carried out to determine the direction of vibration propagation that occurs in a system. Knowing the direction of the vibration propagation can be done further action whether a system requires an additional damping system or not.

Spectrum analysis is a method used to detect errors that occur in a system or machine. Spectrum analysis changes the vibration data taken on a time-based basis into a frequency-based graphical plot. By processing data using the fast Fourier transform (FFT) method, time-based data can be converted to frequency-based. By knowing what frequencies are operating on a machine it can be detected an error or damage that occurs in a part of the machine. Determination of Measurement Points. To determine the location of the measurement point is carried out by tracking the vibration which is indicated to be quite severe. Using an electronic stethoscope that is connected to the earphone, follows the direction of the propagation of vibration from the source, engine mounting, to some designated point. Measuring point search is done when the engine is idle. The following is the specified measurement point.

Vibration Measurement Vibration measurements are carried out using a vibrometer connected to the probe because the measurement location is relatively difficult to reach by researchers. There are eight points taken as a place to measure vibration. The first point is the source of vibration (engine mounting) and then forward to the point that has been tracked using an electronic stethoscope. Vibration data retrieval is done in a static condition where the vehicle is only in a steady condition without moving. Variable data divider is varied from engine speed on the vehicle, namely at RPM 800, 2000, 3000, and finally free vibration by slamming the car door in an engine off condition. The vibration characteristics measured in this study have the RMS value of the velocity amplitude of vibration that occurs and the retrieval of spectrum data at a predetermined measurement point. Then do the measurement data obtained by measuring the vibration severity chart, Rathbone Chart, and IRD Severity Chart.
3. Results and discussions

3.1. Spectrum analysis

The vibration spectrum at 800 RPM (idle) indicates that there is a large excitation at a frequency of 26.25 Hz. At these frequencies, it has a maximum amplitude value of vibration velocity of 0.65 mm/s. The frequency is the operating frequency of order 2 of the driving machine on the vehicle because in order 2 the engine operating frequency of the combustion process occurs in the combustion engine so that it gives great excitation to the vehicle body structure. This frequency can be categorized as a muffled frequency ($\omega_d$) because the system has an integrated damper. It can also be seen in the frequency of multiples there is a harmonic motion with decreasing amplitude of excitation. At 3.75 Hz frequency, there is also a spike in the spectrum.

![Figure 1. Spectrum at idle RPM](image)

The vibration spectrum at the condition of 2000 RPM showed a great excitation at a frequency of 66.25 Hz. At that frequency, it has a maximum amplitude value of the vibration velocity of 0.15 mm/s. The frequency is the operating frequency of the driving machine on the vehicle. This frequency can be categorized as a muffled frequency ($\omega_d$) because the system has an integrated damper. It can also be seen in the frequency of multiples there is a harmonic motion with decreasing amplitude of excitation. At 3.75 Hz frequency, there is also a spike in the spectrum.

The vibration spectrum at conditions of 3000 RPM showed a large excitation at a frequency of 97.5 Hz. At this frequency, it has a maximum amplitude value of vibration velocity of 0.07 mm/s. The frequency is the operating frequency of the driving machine on the vehicle. This frequency can be categorized as a muffled frequency ($\omega_d$) because the system has an integrated damper. It can also be seen in the multiple frequencies there is a harmonic motion with a diminishing amplitude of excitation. At 3.75 Hz frequency, there is also a spike in the spectrum.
The vibration spectrum of free vibration excitation shows the highest vibration response at a frequency of 3.75 Hz. Seen at all measurement points the highest amplitude response occurs at that frequency. At this frequency, the vibration acceleration value has the largest value of 2.71 mm/s. The vibrational response continues to experience harmonic motion at the frequency of the multiple amplitudes of the largest response as seen in the spectrum graph above.

3.2. Transfer path analysis

The TPA analysis has two parameters namely the red-colored line which represents line 1 and the yellow-colored line which represents line 2 vibration propagation on the vehicle body. On the propagation line 1, it appears that the vibrations that propagate on the vehicle body have damping. The vibration amplitude is significantly reduced from the source point (which has been reduced by engine mounting damper) by the body structure. From the amplitude of 5.19, 1.19 and 1.58 mm/s it was reduced to 0.27, 0.3 and 0.28 mm/s in the idle, 2000, and 3000 RPM sequential conditions. Then the RMS value of vibration velocity increased in amplitude to 0.53, 0.14, and 0.56 mm/s.

On the propagation line 2, it appears that vibrations that propagate on the vehicle body have experienced damping. The vibration amplitude is significantly reduced from the source point (which
has been reduced by engine mounting damper) by the body structure. From the amplitudes of 5.19, 1.19, and 1.58 mm/s it was reduced to 0.27, 0.23 and 0.33 mm/s under idle, 2000 and 3000 RPM sequential conditions, respectively. Then the RMS value of the vibration velocity increases in amplitude to 0.53, 0.14, and 0.56 mm/s. This is due to the addition of vibration sources such as a gearbox.

![Spectrum - Free Vibration](image1)

**Figure 4.** Spectrum door slamming engine off

The direction of propagation of vibration that occurs evenly spread on the body, but at some point, has decreased the value of the amplitude. This decrease in amplitude is caused by the difference in structure profiles and manufacturing processes. These two factors have different particle structures and with a cylindrical shape can concentrate on the propagation that occurs in the monocoque body. The type of welding joint used in this type of monocoque structure mostly uses point welding which causes a lack of contact between the components on the monocoque body.

![Vibration propagation path](image2)

**Figure 5.** Vibration propagation path
With a vibration amplitude value of 5.19 mm/s, the results obtained from the IRD Severity Chart are vibrations that radiate on the body of the monocoque body into the categories that are still allowed to be allowed. Monocoque bodies produce vibrational responses at sources 5.19, 1.17 and 1.58 mm/s under conditions of 800, 2000, and 3000 RPM, respectively. It can reduce vibration to, with an average value of 0.45, 0.23 and 0.31 mm/s. Only using the original structure of the body shows that this type of structure can provide attenuation to the vibrations that spread to the monocoque body. The vibration results that have been muted compared with vibrations from sources that give the magnification factor of 0.08, 0.18, and 0.19. The propagation that occurs in the monocoque body structure is the transfer of vibration from one body element to the next body element in the monocoque body structure. Thus, the monocoque body structure causes the natural frequency \( \omega_n \) structure to be small, namely in the test vehicle, only 3.75 Hz. Monocoque body structure causes the natural frequency \( \omega_n \) structure to be small, namely in the test vehicle, only 3.75 Hz.

4. Conclusion
1. Monocoque type vehicle structure is effective to reduce the vibration response that occurs due to excitation from the operation of the driving machine.
2. The shape of the monocoque body part determines the attenuation or the transmission of the vibration propagation on the part.
3. The monocoque body parts with a profile cross section provides a large attenuation, in other words, produces a small response to the vibration excitation of the propagation.
4. From the transfer path analysis, it’s revealed that the vibration attenuation is significantly large on the structural parts of the cabin structure so that the vibrations severity level is low on the the cabin structure.
5. The vibration severity of the vibrational response as a whole that occurs on the monocoque vehicle structure falls into the category between smooth and slightly rough which is still within the permissible limit.
6. Passenger cars that require comfort besides safety, can be made with a monocoque structure.
Figure 7. IRD severity chart
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