INTERNATIONAL JOURNAL OF SCIENCE, TECHNOLOGY AND DESIGN

ULUSLARARASI
BİLİM, TEKNOLOJİ VE TASARIM DERGİSİ

On the Diagnosis and Analysis of an Automotive Fuel Pump Noise

Ayhan YAĞCI[1], Cem MERİÇ[2], Aytekin ÖZKAN[3]

[1] *Tofaş Türk Otomobil Fabrikası A.Ş., Ar-Ge Bölümü, Bursa, TURKEY, ORCID ID 0000-0003-0005-3164*
[2] *Tofaş Türk Otomobil Fabrikası A.Ş., Ar-Ge Bölümü, Bursa, TURKEY, ORCID ID 0000-0002-1737-4346*
[3] *Tofaş Türk Otomobil Fabrikası A.Ş., Ar-Ge Bölümü, Bursa, TURKEY, ORCID ID 0000-0002-8418-5713*

Corresponding Author: Ayhan YAĞCI, ayhan.yagci@tofas.com.tr

Abstract

This study aims to solve a low-frequency tonal fuel pump noise involving a roller-cell type of fuel pump located inside a metal fuel tank. Firstly, possible noise transmission paths are investigated. Then, the contribution of each component and/or the boundary condition to the fuel pump noise phenomenon is investigated step by step mainly with experimental methods. The effect of the differences in the structural design of the pump, sub-components ve interfaces are tested and analyzed. Finally, the solution alternatives are discussed and the proposed solution is tested and verified through objective NVH tests. It is shown that a 10 dB improvement in noise level can be obtained with the application of the proposed solution.

Article Info

Research Article
Received: 06/05/2020
Accepted: 11/08/2020

Keywords

Fuel Pump Noise, Tonal Noise, Vibration Damping

Highlights

- *Diagnosis and analysis methods of an automotive fuel pump noise.*
- *Experimental examination of a tonal noise caused by a roller-cell type fuel pump.*
- *Test and validation of the Vibration Damping Pads solution.*

Bir Otomotiv Yakıt Pompası Gürültüsünün Diyagnoz ve Analizi Üzerine

Özet

Bu çalışma, metal bir yakıt deposu içinde yer alan makaralı-hücre tip bir yakıt pompasının ürettiği düşük frekanslı tonal gürültü sorununun çözümü ile ilgilidir. Öncelikle olası gürültü iletim patikaları araştırılmaktadır. Sonrasında her bir komponent ve/veya arayüzün katkısı deneysel yöntemlerle adım adım incelenmektedir. Pompanın yapısal tasarımındaki farklılıkların, alt komponent ve arayüzlerde yapılan bazı değişikliklerin probleme etkisi test ve analiz edilmektedir. Son olarak, çözüm alternatifleri tartışılmakta ve önerilen çözüm objektif NVH ölçümleri ile test edilip doğrulanmaktadır. Önerilen çözümün uygulanmasıyla gürültü seviyesinin 10 dB iyileştirilebildiği gösterilmektedir.

Anahtar Kelimeler

Yakıt Pompa Gürültüsü, Tonal Gürültü, Titreşim Sönümleme

Öne Çıkanlar

- *Bir otomotiv yakıt pompa gürültüsünün teşhis ve analizi.*
- *Makaralı-hücre tipi bir yakıt pompasının ürettiği tonal gürültünün deneysel olarak incelenmesi.*
- *Titreşim sönümleyici yama çözümünün test ve doğrulanması.*

1. Introduction

Fuel pumps generally create a distinctive tonal noise. This noise is easily audible unless it is masked by another noise source.

Usually, a noise source emits sound energy that has a broadband frequency content. Whereas, some noise sources generate noise that has a narrow band spectrum. The latter is referred to as tonal noise. If the sound energy is concentrated at a single frequency, then it is referred to as a pure tone.

According to ISO 1996-2:2017 - Annex K, to denominate a sound as tonal noise, the sound pressure level in the one-third octave band of interest should exceed the level of its two adjacent bands by a constant quantity defined based on the frequency range as follows:

- 15 dB in the low-frequency range (25 Hz to 125 Hz)
- 8 dB in middle-frequency bands (160 Hz to 400 Hz)
- 5 dB in high-frequency bands (500 Hz to 10000 Hz)

There are three common types of fuel delivery pumps in the automotive industry: Roller cell, internal gear, and peripheral (Figure 1).

Generally, the operating frequency of the roller-cell type of fuel pumps lies somewhere in the middle-frequency range. Hence, the fuel pump noise is said to have a tonal character if the one-third octave band containing it has an 8 dB or higher amplitude when compared to its two adjacent bands. On the other hand, an internal gear type of a fuel pump containing a propeller/gear inside having around 45 teeth generate noise in the high-frequency region. For this kind of noise, a 5 dB difference between the operating frequency band and its adjacent is enough to be perceived as a tonal noise.

Figure 1. Three types of fuel pumps commonly used in the automotive industry

There are relatively few studies on the automotive fuel pump noise issues in the literature. Most of the research papers are on the high-pressure side of the fuel systems rather than the low-pressure side, which contains low-pressure pumping of the Fuel Delivery Module (FDM). Scarselli et. al 2010 studied the acoustic characterization of the automotive fuel pumps and tanks both numerically and experimentally. Wang et. al 2016 conducted a research activity on noise optimization of a regenerative (peripheral) automotive fuel pump. Ge et al. 2018 carried out an interesting study, in which they try to reduce the noise of a fuel pump by the application of TRIZ theory.

In this study, a noise problem generated by a roller-cell type of fuel delivery pump is examined. Roller-cell fuel pumps are widely used in passenger cars. The FDM containing the pump is mounted inside the fuel tank so that it is submerged in the fuel. The suction (inlet) side is at the bottom and the pumping (outlet) side is at the top. It is in contact with the inner bottom surface of the tank. On the top side, it is assembled to the tank with a flange using fasteners. This way, the flange is in continuous contact with the upper panel of the tank (Figure 2). So, any vibration generated by the fuel pump module is structurally transmitted to the tank through these contact surfaces.

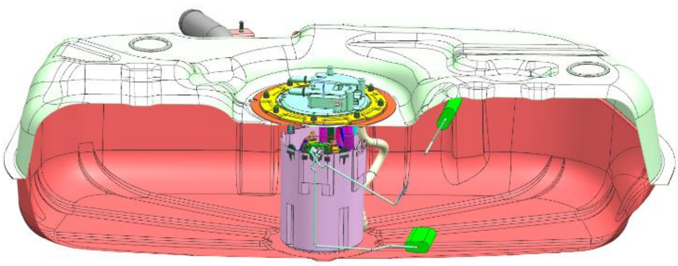

Figure 2. Fuel tank with fuel delivery pump mounted on it

2. Analysis of a Fuel Pump Noise Problem

In this section, the problem created by a noisy fuel pump on a passenger car is analyzed as an example. The fuel tank of this car is made up of sheet metal (steel). The noise level of the problematic pump was measured on a vehicle during the engine running in idle. To avoid any acoustic disturbance, all the tests were performed in a semi-anechoic chamber with a cut-off frequency of 50 Hz. Figure 3 shows the frequency spectrum of the noise data collected by the microphone at the Driver's Left Ear (DLE). The problem is a very distinctive tonal noise around 180 Hz. It is a disturbing noise and dominant over the whole spectrum.

Knowing the inner structure of the pump, especially the number of rotating parts, and the pump motor rpm, the excitation order of the pump can be calculated.

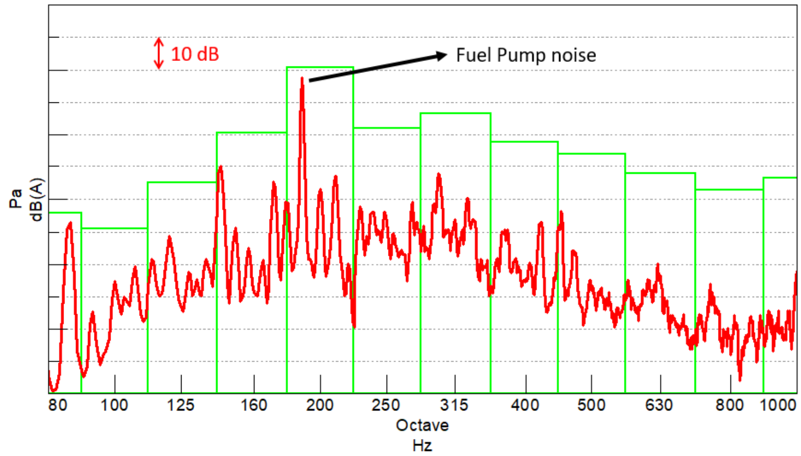

Figure 3. The frequency spectrum of noise measured by the microphone at the DLE.

For the cases where this kind of information is missing, an rpm sweep measurement may reveal important orders. To do this, the pump is fed from an external power supply and the noise of the pump is measured during a run-up from, say, 9 to 15 V.

Figure 4 shows the internal structure of a roller-cell fuel pump. The problematic pump has five roller cells. The pump motor contains 12 commutators. Therefore, 5th and 12th orders are important for investigation. The peak around 180 Hz corresponds to the 5th harmonic of the rotational frequency of the pump. This is the operating frequency of the pump. Consequently, it is the dominant noise source. Its harmonics (10th, 15th … orders) also generate local peaks in the spectrum. However, their effects on auditory annoyance are minor.

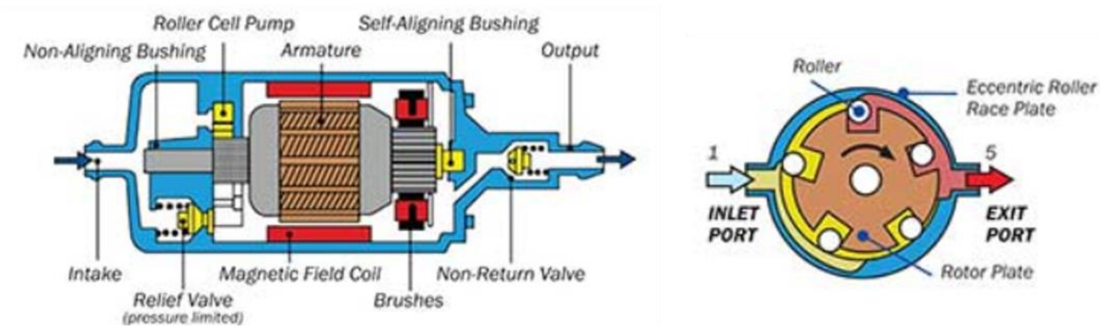

Figure 4. Internal structure and operation principle of a roller-cell type of fuel pump

The combined group of the fuel tank and the FDM, together with the interfaces between the components can be seen in Figure 5.

Although the noise problem arises mainly from the rotational frequency of the roller cells, the root cause of the problem needs to be investigated. Even if the noise source is known, the noise transfer path from the source to the receiver ear may be more important for some cases since the noise may be amplified along the transfer path. In this section, the effect of each interface to the phenomenon is investigated.

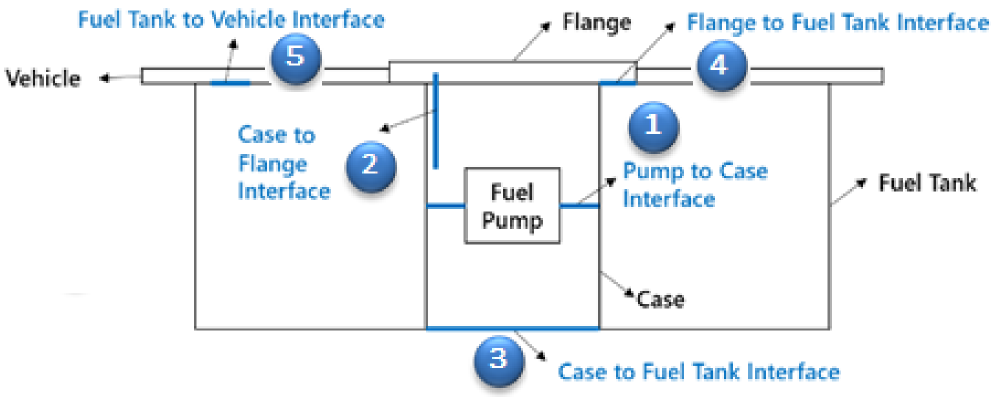

Figure 5. Schematic of the FDM-Fuel Tank-Vehicle Group

2.1 Pump-to-case interface

To demonstrate the effect of vibration filtration from the pump to the case, two different FDM structures are tested and analyzed in comparison. One of them is called FDM A and the other is denoted as FDM B. The only difference between these FDMs is the Pump-to-case interface. The pumps of the two FDM modules and their operating frequencies are the same. Nevertheless, the structural links from the pump to the FDM case have different designs as shown in Figure 6.

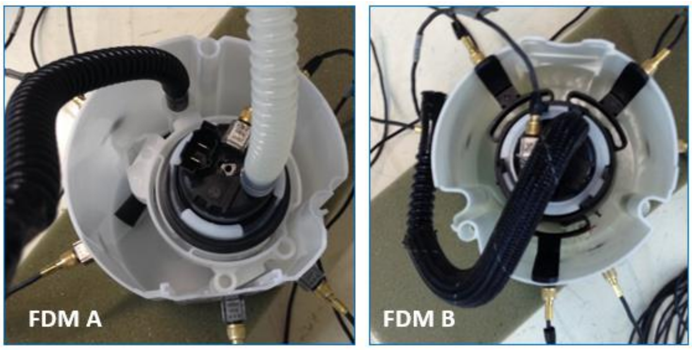

Figure 6. FDM A and FDM B modules (viewed from the top)

As a standard, the tank is filled to the one-quarter level of its total volume during all the tests. When FDM A and B were tested in the same tank and on the same vehicle, a level difference of more than 20 dB appeared at the operating frequency of the pump. Figure 7 shows the frequency spectra of two FDM units in comparison.

Another experimental setup was constructed to study the difference in the noise levels between the two deeply. A metal pan was semi-filled with fuel. The FDMs were seated inside it. Proper hoses, connections, and adaptors for inlet/outlet and a flow-regulating valve were utilized to set up a closed-loop flow. Since the diesel fuel was in use, the risk of fire was not a problem. The FDM unit was fed with a power supply externally with a constant voltage. Six vibration sensors were attached at different locations on the case wall of the FDMs. FDM A and FDM B modules were tested with this setup and the vibration levels were compared. As seen in Figure 8, the vibration level on the case for FDM B was around 4 times lower in amplitude compared to the FDM A.

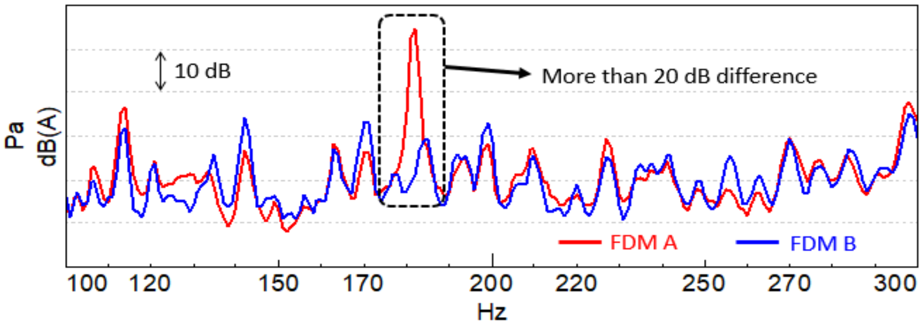

Figure 7. Frequency spectra for the noisy and the silent FDMs

Another experimental setup was constructed to study the difference in the noise levels between the two deeply. A metal pan was semi-filled with fuel. The FDMs were seated inside it. Proper hoses, connections, and adaptors for inlet/outlet and a flow-regulating valve were utilized to set up a closed-loop flow. The FDM unit was fed with a power supply externally with a constant voltage. Six vibration sensors were attached at different locations on the case wall of the FDMs. FDM A and FDM B were tested with this setup and the vibration levels were compared. As seen in Figure 8, the vibration level on the case for FDM B was around 4 times lower in amplitude compared to the FDM A.

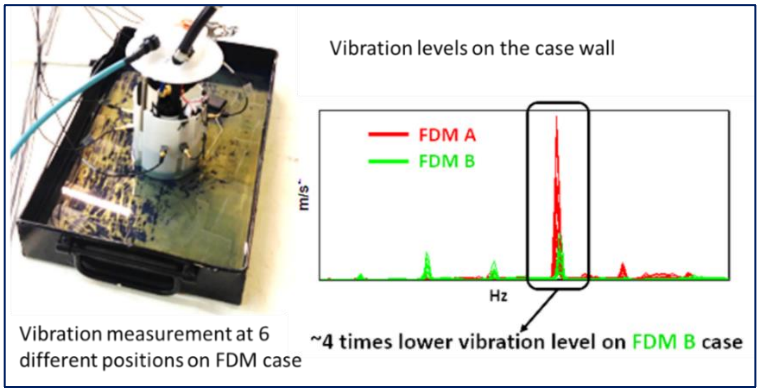

Figure 8. Vibration levels on the cases of the two FDMs on bench

For further analysis of the problem, the noisy FDM (FDM A) is used.

2.2 Case-to-flange interface

The Case-to-Flange interface of the FDM in this study consists of a spring and a support rod as shown in Figure 9. Three different springs with different stiffness values were tested to evaluate the effect of the case-to-flange interface. Not to create an additional variable, the same FDM and the same vehicle were used. Measurement results indicate that the spring force has a minor effect on the vibrations transferred to the tank and on the noise level, as shown in Figure 10.

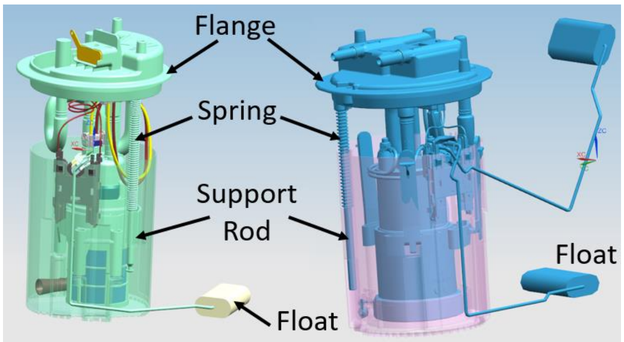

Figure 9. Structure of the two FDM units

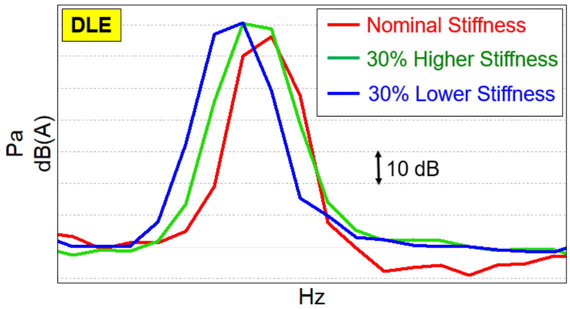

Figure 10. Effect of spring stiffness on the noise level at Driver Left Ear (DLE)

2.3 Case-to-fuel tank interface

The effect of adding a cushion between the FDM bottom and the tank bottom panel was also tested as shown schematically in Figure 11. This is a cushion made up of PUR material. As seen in Figure 11, cushion addition lowered the noise level at DLE by 2 dB.

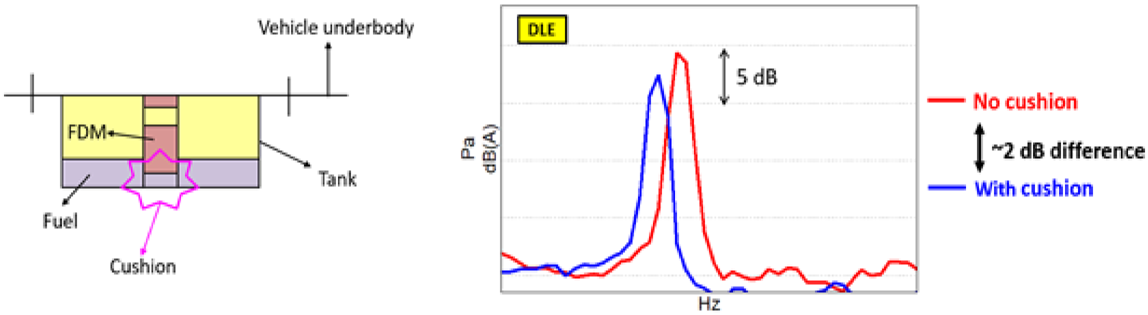

Figure 11. Effect of cushion addition between FDM & tank bottom

2.4 Flange-to-tank interface

Aneja et al. 2017 state that the flange and the torque values of the fasteners fixing the flange to the tank may also affect the vibration transfer from FDM to the tank in some cases. For the noisy FDM under examination, the effect of different flange fastening torques was tested as well. However, those different torque values had a very minute effect on the vibration and the noise levels (Figure 12).

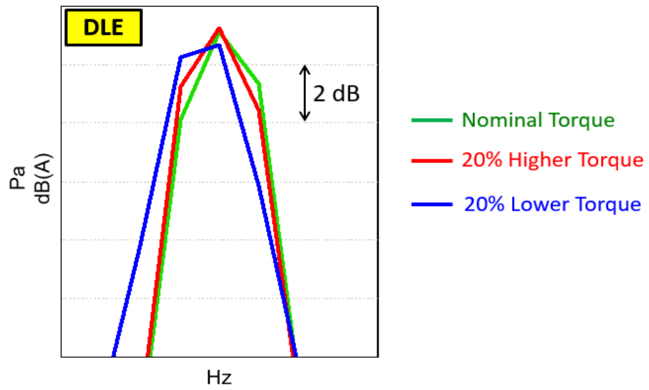

Figure 12. Effect of Flange Fastening Torque Value

2.5 Case

Also, an FRF measurement with an impact hammer was executed on the FDM Case (reservoir). As seen in Figure 13, no remarkable sensitivity was observed on the FDM case wall close to the problematic frequency.

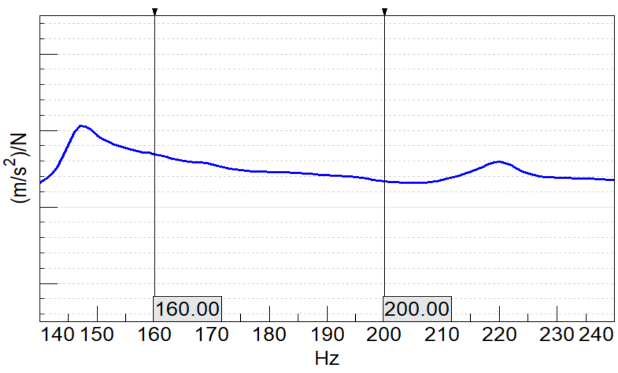

Figure 13. FRF Measurement result on the case wall of FDM A

2.6 Fuel tank

When a modal analysis is executed on the fuel tank, two structural modes close to the problematic frequency appear (Figure 14). This explains the amplification means of the noise generated by the FDM.

To dampen the vibration on large surfaces like the fuel tank panels, Vibration Damping Pads (VDP) are utilized in the industry. VDP is a viscoelastic treatment used on vibrating panels in the automotive, aircraft, and household appliances industries. VDP treatments are mainly classified into two categories: Free Layer Damping (FLD) and Constrained Layer Damping (CLD) (Mohan 2002).

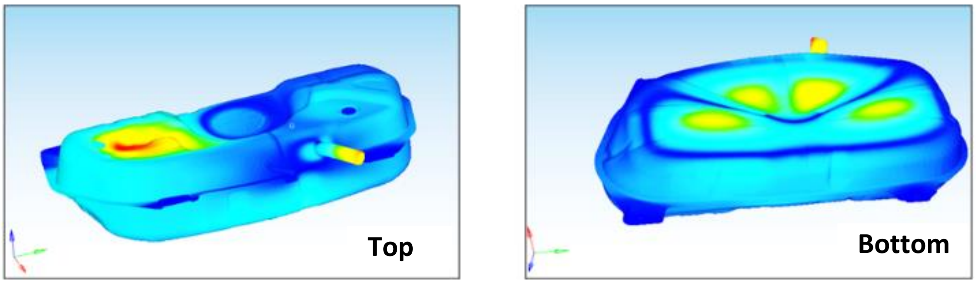

Figure 14. Two structural modes of the fuel tank (top and bottom) close to the rotational frequency of the FDM pump.

FLD makes use of viscoelastic material layers that can be either sprayed on the panel or attached to its surface through thermal bonding or pressure-sensitive adhesives. There are also magnetically attached FLDs for suitable surfaces.

CLD treatments consist of a sandwich of two outer elastic layers with a viscoelastic material as the core. Hence, CLD is also known as a sandwich-layer.

To investigate if the fuel tank modes shown in Figure 14 are excited to create a contribution to the noise phenomenon, FLD type of VDP treatments were applied to the fuel tank panels. The weight of the VDP application on the bottom of the tank is 0,63 kg and 0,25 kg on top. When VDP was applied only to the top panel, the sound pressure level at the rotational frequency of the pump decreased by 10 dB for the driver ear position. When the bottom panel was also treated with VDP, an additional noise reduction of 2 dB was obtained (Figure 15).

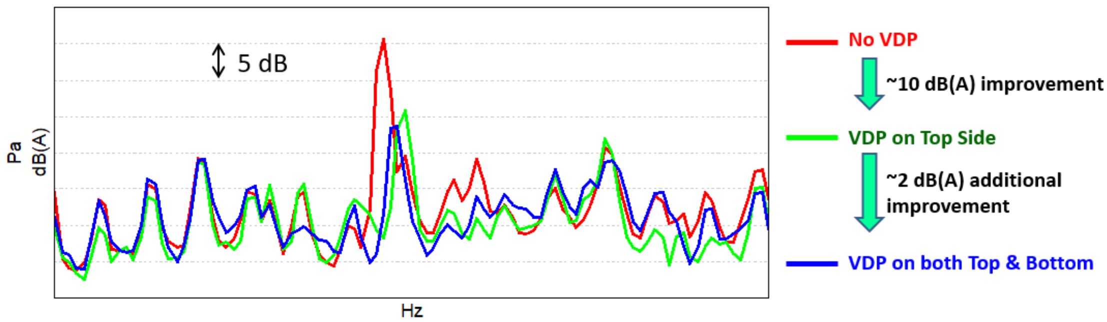

Figure 15. Improving effect of the VDP applications on the noise level (measured at DLE on the vehicle).

2.7 Fuel tank-to-vehicle interface

The fuel tank is assembled to the car underbody, usually under the rear seat area for the passenger cars (Figure 16). For assembly, either small brackets or supporting straps are used (Figure 17). Vibrations on the tank are transferred to the car body through direct contacts or fasteners.

The tank under investigation in this study is located under the rear seats as shown in Figure 16 and assembled to the vehicle underbody with fasteners as shown in the left picture of Figure 17.

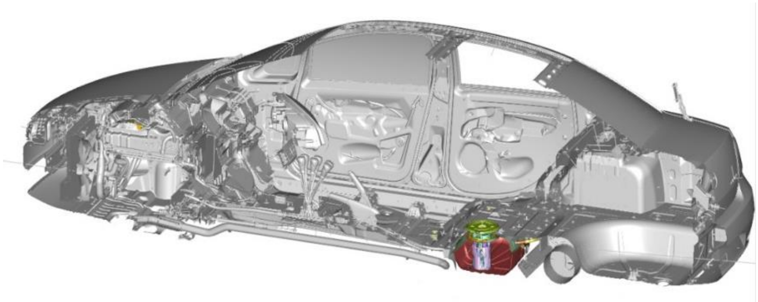

Figure 16. Location of a fuel tank on a passenger car

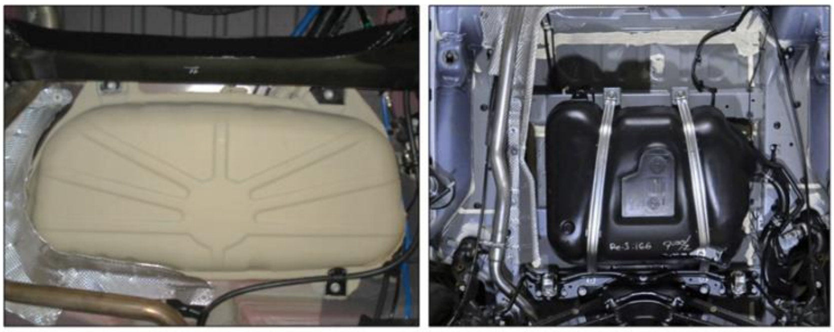

Figure 17. Assembling methods of fuel tanks to the underbody

To understand the effect of the fuel tank-to-vehicle interface, the fuel tank fastener connections to the vehicle body were removed. The tank was properly supported from the ground using some insulation materials. With the tank being disassembled from the body, another measurement was executed on the same vehicle under the same conditions. Disassembling the tank from the vehicle body turned out to not affect the noise level at the problematic frequency (Figure 18).

The results indicate that the vibration generated by the fuel pump is transmitted to the metal fuel tank panels via the pump-to-case interface and the noise generated by the fuel tank panels is transferred to the passenger compartment via air.

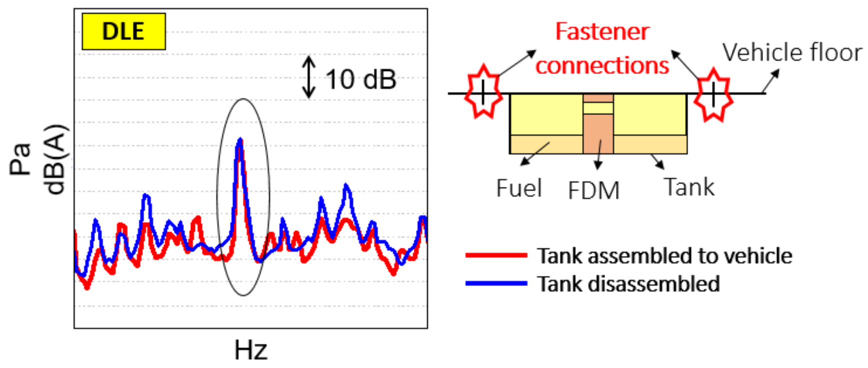

Figure 18. The effect of disassembling the fuel tank from the vehicle body

3. Solution Alternatives

Naturally, the first solution to apply for a fuel pump noise is to attack to the noise source. By changing the operating frequency of the pump, the number of rotating elements such as roller-cells, vanes, or impeller teeth can shift the excitation frequency so that the fuel tank is not excited at its modal frequency. Or, the problem frequency can be shifted to another frequency region, in which it is masked by other noise sources, like the engine. For an internal gear pump, irregularly spacing the gear teeth, or impellers can spread the tonal noise into many tones, which are not annoying as a single tone. Jiang et. al 2019 studied the effect of unevenly spacing the blades of a centrifugal fan for achieving lower tonal noise and reshaping the acoustic spectrum.

Other alternative solutions rely on dampening the vibration or sound along the transfer path. For example, Rana et al. 2011 examined a pulsation noise issue from fuel delivery pipes in a car and explained an experimental solution approach with different clip/bracket alternatives. For the noisy FDM with roller-cell fuel pump examined above, changing the structural linkages between the pump and the FDM case is a good solution. As explained in Section 2.1, dampening the vibrations transmitted from the pump to the FDM case results in lower vibration levels transferred to the fuel tank, and consequently lower sound levels arrive at the receiver ear.

Another solution alternative for the fuel pump noise under examination can be dampening the vibration on the fuel tank panels. To demonstrate the effect of dampening fuel tank panel vibrations by mass addition, bitumen-based vibration damping pads (VDP) were applied to the tank panels as explained in Section 2.6. This solution is favorable when ease of application, eventual acoustic impact, and relatively less complexity of modification are considered.

A systematic experimental approach may also be performed to determine the best or optimum alternative. Such a study was performed by Rosetti et. al 2013 using the DOE method. In this investigation, the length, shape, and the assembly method of fuel pipes, fuel type, and pump voltage are taken into account.

4. Conclusion

In this paper, the noise generated by a roller-cell type of fuel pump in a metal fuel tank has been investigated with several experiments. It is shown that the resulting noise issue is not purely dependent on the source (fuel pump) itself but also the acoustic radiation of the fuel tank panels. The emphasis has been given to the effect of vibration transfer from the pump to the FDM case and the effect of fuel tank panel vibrations. During the study effect of various alternatives has been analyzed and their comparison has been presented. Finally, a solution is proposed and its effect has been determined experimentally.

5. References

Anonymous, 2017. ISO 1996-2:2017 Acoustics - Description, measurement and assessment of environmental noise - Part 2: Determination of sound pressure levels. https://www.iso.org/standard/59766.html-(Erişim tarihi: 10.02.2020).

Scarselli, G., Lecce, L., Fortunato, F., Di Matteo, L., 2010. Numerical and experimental acoustical characterization of fuel pumps and tanks employed in the automotive field. International Conference on Noise and Vibration Engineering, 20-22 September, 2010, Leuven.

Wang, F., Feng, H.H, Mou, X.L., Huang, Y.X., 2016. Noise optimization of a regenerative automotive fuel pump. Second International Conference on Mechanical and Aeronautical Engineering (ICMAE), 28-30 December, 2016, Hong Kong.

Ge, M., Zhou, J., 2018. Application of triz theory in reducing noise of fuel pump. International Journal of Research in Engineering and Technology (IJRET), Volume 7 – Issue 4: 22-27.

Aneja, H., Tripathi, M., Singh, H., Parmar, A. 2017. Approaches of NVH improvements for fuel pump noise issues. SAE World Congress Experience, 28 March, 2017, Detroit.

Mohan, D., 2002. Recent applications of viscoelastic damping for noise control in automobiles and commercial airplane. Journal of Sound and Vibration, 262: 457-474.

Jiang, B., Wang, J., Yang, X., Wang, W., Ding, Y., 2019. Tonal noise reduction by unevenly spaced blades in a forward-curved-blades centrifugal fan. Applied Acoustics, 146: 172-183.

Rana, D., Rana, A., 2011. Reduction of fuel delivery system noise in a passenger car using EBD approach. Symposium on International Automotive Technology, 19-21 January, 2011, Pune.

Rossetti, T., Del Passo, M., Geremias, F., 2013. Fuel pump module noise optimization through design of experiments. 22nd SAE Brasil International Congress and Display, 7-9 October, 2013, São Paulo.

Abbreviations

NVH: Noise Vibration Harshness
FDM: Fuel Delivery Module
SPL: Sound Pressure Level
DLE: Driver's Left Ear
FRF: Frequency Response Function
VDP: Vibration Damping Pad
PUR: Polyurethane
FLD: Free-Layer Damping
CLD: Constrained-Layer Damping
DOE: Design of Experiment