



NVH investigation of automotive HVAC brushless motors

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ABSTRACT

In the automotive industry, thermal systems are of critical importance in securing optimum vehicle operating, preserving battery capacities and ensuring passenger comfort. These systems involve a wide range of components with various technologies, designs and consisting of more innovation.

Currently, thermal engine market shares are decreasing in parallel to increasing electrification trends worldwide. Consequently, thermal systems may become major sources of noise and vibration issues that may emerge inside the car cabin. This may cause significant discomfort to passengers and can create major disturbances to passersby outside the car.

System supplier ensure NVH compliance according to internal standards as well as OEM specifications during development and production stages. However, as electrification trends involve more and more innovations with less technical background, ensuring NVH compliance becomes a formidable challenge to deal with. Among the main NVH sources, the HVAC Brushless motor is highly critical as implanted inside the car cabin.

This paper focuses on the main NVH topics encountered on HVAC BLDC motors. First, the NVH sources are analyzed from mechanical and magnetic design perspectives. Furthermore, solutions to control the NVH behavior are presented which sets the product intrinsic limitations and operating conditions. Finally, from a technical compliance perspective, specification design implications are discussed.

1. INTRODUCTION

NVH compliance in the automotive business has become a critical part of design and development processes to ensure passenger comfort at vehicle level. Nowadays, as overall noise reduction trends are ongoing and automotive market electrification is quickly increasing, NVH sources possibly raising concerns at vehicle level are progressively linked to the embedded equipments.

Among the sources that may induce discomfort to passengers inside the vehicle and to passers-by outside, thermal systems remain one of the major contributors of the assessed NVH behavior. These systems include well-known products such as HVACs, heat pumps, compressors and fan system but also new products and innovations induced by automotive electrification trends such as brushless motors and High Voltage thermal conditioners. In addition, the required thermal performances of these systems are increased while seeking improved efficiencies for battery optimization requirements. Consequently, OEMs NVH requirements and system suppliers specifications are highly reinforced at both component and vehicle levels to ensure NVH compliance for the final customer.

Within the HVAC system, the Brushless DC motor (BLDC) is the alternative approach to regular DC motors ensuring the required aeraulic performances of HVACs while providing higher electrical

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and overall efficiencies. As BLDCs operate without mechanical brushes and commutators like traditional brush motors, NVH issues linked to contacts, such as Ticking noise, are removed which should significantly improve NVH comfort.

However, as BLDC motor operating consists of magnetic driving, specific NVH emergencies can occur linked to the electromagnetic design of both rotor and stator, which possibly leads to specific NVH issues. Furthermore, BLDC motors implications on NVH topics are consequently linked to design and process limitations. This is putting considerable risks on newly developed products as specific standards and test procedures require implementation in order to highlight such targeted behaviors.

This paper aims to provide an overview of the main possible NVH issues involved in automotive HVAC BLDC motors. With this observation, solutions to reduce such NVH behaviors are presented and design intrinsic limitations highlighted. Finally, from a compliance perspective, both OEM requirements and system suppliers specifications are analyzed and discussed to ensure a relevant compliance definition.

2. AUTOMOTIVE HEATING VENTILATION AND AIR CONDITIONNING SYSTEM

2.1. System description

The automotive Heating, Ventilation and Air Conditioning system (HVAC) is a complex structure designed to ensure thermal comfort inside car cabin areas using air circulation through ducts and thermal regulation through thermal exchangers. As shown Figure 1, HVAC systems are composed of numerous parts, many of which involve continuous innovation to improve overall performances and quality. Each HVAC is specifically developed to reach OEM requirements, mainly consisting of thermal and aeraulic performances within a limited allocated packaging usually under the dashboard.

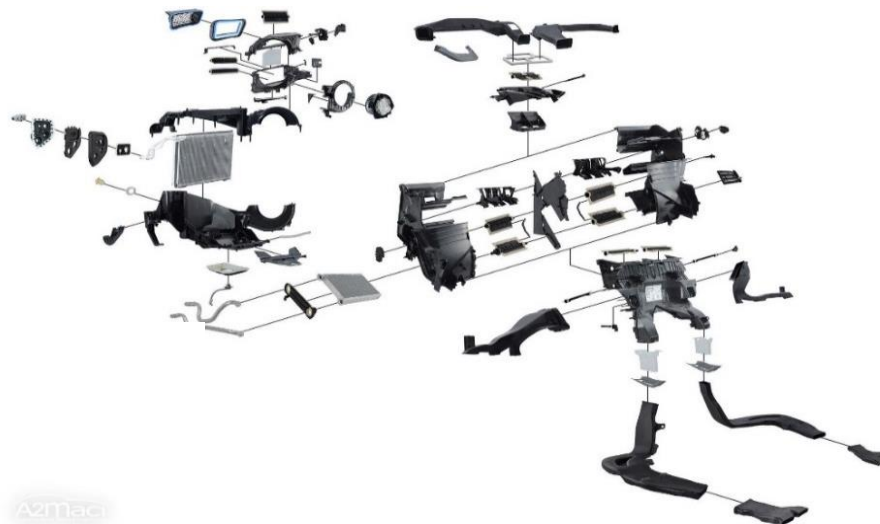


Figure 1 : Exploded view of a half centered HVAC unit.

System suppliers ensure mastering all possible occurring NVH issues of their products as detailed in previous work [1, 2, 3, 4]. HVAC airflow noise for instance, is mainly linked to blower rotation speed, flowrate and aeraulic turbulences generated by interactions between airflow and HVAC sub-components. What's more, the selected HVAC distribution mode and target airflow and/or temperature can induce a significant impact on both overall noise levels and noise spectral content by changing the pressure loss and the turbulence rate.

2.2. BLDC blower

The automotive HVAC blower is a subcomponent of the HVAC system designed to ensure flowrate requirements and consisting of a centrifugal fan driven by an electric motor. Blowers are usually required to fulfill specific operating conditions of flowrate and counter pressure while complying with packaging and power consumption requirements. Within this scope, the BLDC blower shown Figure 2, is designed to be an improvement of regular brush motors by complying by the same aeraulic requirements while reaching higher electrical and aeraulic efficiencies within a reduced packaging.

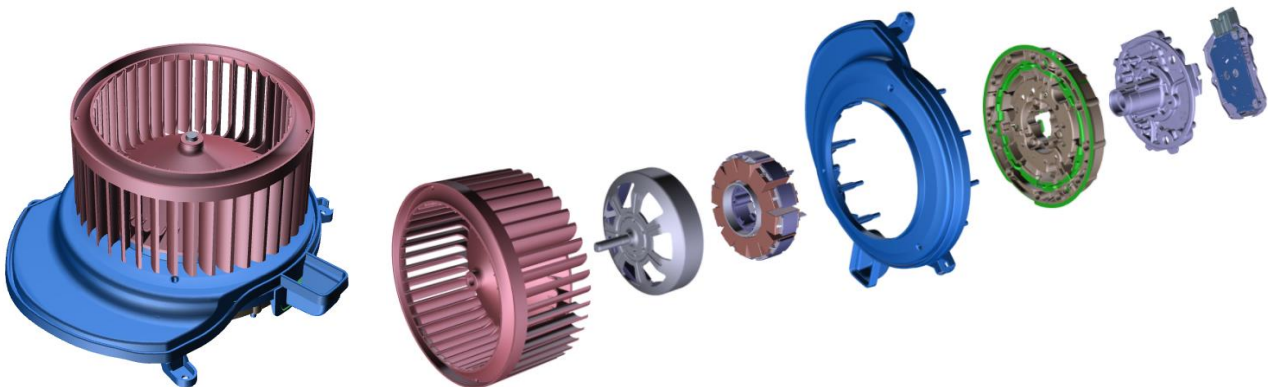


Figure 2 : HVAC BLDC blower unit and exploded view.

3. BLDC motor design

3.1. System description

Like regular brush motors, a BLDC motor essentially consists of two parts : rotor and stator as shown Figure 3. Motor operating is based on electromagnetic driving of permanent magnets placed on the rotor using electromagnets placed on the stator. One of the key design points to consider is the correct alignment and concentricity of both stator and rotor.

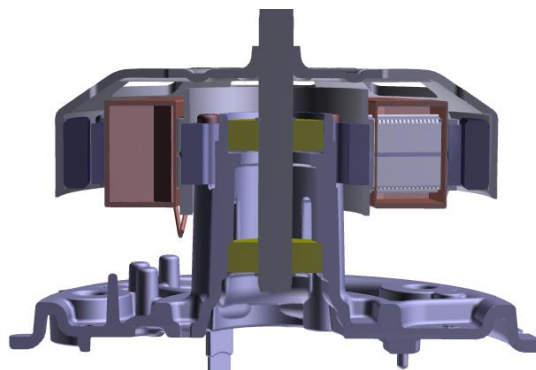


Figure 3 : Rotor and stator side view.

BLDC motors design choices are based on an intentional selection of a number of magnets and electromagnets to reach a compromised performance between the developed torque and rotation speed. However, the rotation speed is also chosen according to the required aeraulic performances of the blower. In this paper, the considered motor design example for NVH assessment consists of 8 magnets and 12 electromagnets as shown Figure 4.

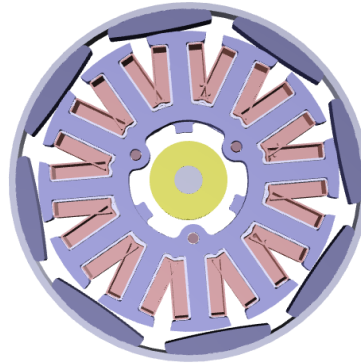


Figure 4 : Rotor and stator top view.

3.2. NVH behavior

Due to its design and usual implementation inside the car cabin, BLDC NVH issues opposing a comfort challenge are summarized as follows :

- Mechanical balancing,
- System resonances,
- Motor orders,
- Electronic chopping frequency.

3.2.1. Mechanical balancing

The HVAC blower is a rotating machine mainly consisting of a plastic wheel assembled to a motor at its center through a shaft. Due to its design parameters, wheel injection and assembly processes, the HVAC blower displays a mechanical unbalance. This intrinsic unbalance generates a centrifugal force proportional to its mass, the wheel diameter and square the rotation speed as represented Figure 5. As standard blower fixations to HVACs are not stiff, low frequency vibrations are created by the unbalance during operating and transmitted to the HVAC, the dashboard and the steering wheel while also emerging as noise inside the car cabin.

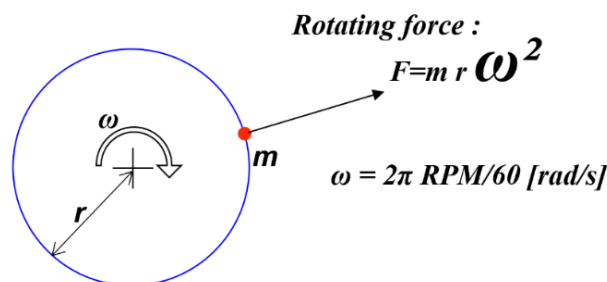


Figure 5 : Representation of the centrifugal force generated by blower mechanical unbalance.

3.2.2. System resonances

Due to their specific designs and parameters, motor components and assembly of components display eigenfrequencies in the operating speed range raising high resonance risks. For instance, the yoke and shaft assembly showed Figure 6, as part of the rotor, displays a static eigenfrequency. However, considering the gyratory effect occurring during blower operating, the single static eigenfrequency is split in two dynamic eigenfrequencies for any fixed speed. During operating, the yoke orders may match the dynamic eigenfrequencies at the corresponding fixed speeds, which will induce two possibly objectionable resonances as illustrated in the Campbell diagram example Figure 6.

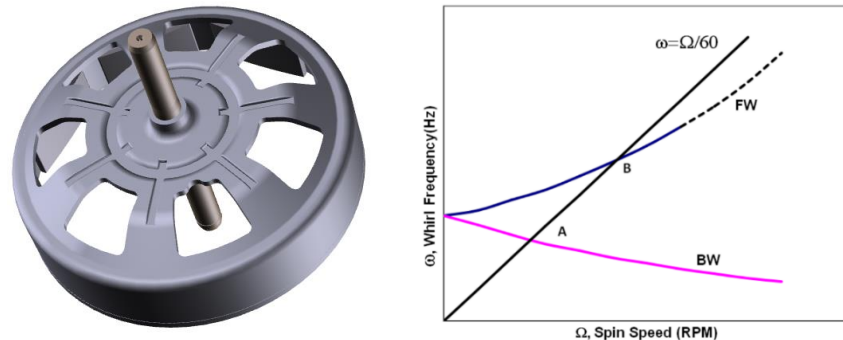


Figure 6 : Yoke/shaft assembly and Campbell diagram computation.

3.2.3. Motor orders

Both rotor and stator are composed of specific numbers of magnets and electromagnets placed regularly from one another as shown Figure 7. During motor operating, the rotor is moved by electromagnet activation, which generates cogging torque fluctuations [5, 6]. Cogging torques occurrence during operating generate motor orders linked to magnets and electromagnets numbers as well as the least common multiple if existing. These orders may appear as noise and vibration with different levels depending on motor design parameters such as coaxiality and alignments.

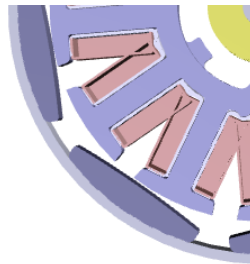


Figure 7 : Rotor and stator top view.

3.2.4. Electronic chopping frequencies

The specific operating of BLDC motors requires electronic control parts to regulate rotation speed. For this purpose, additional electronics are added to the blower such as chopper circuits which require chopping frequencies. The latter frequencies can induce noise radiation of the electronic components which can emerge as pitch noises inside the car cabin.

4. BLDC NVH issues control and solutions

In order to ensure BLDC blower NVH comfort inside the car cabin, numerous solutions are investigated and are already applied at serial production level.

4.1. Decoupling system

A decoupling system often consists of a soft material placed in between the motor and the blower, as shown Figure 8, to ensure vibration transfer dampening. The process of developing such system requires understanding the motor design to set a relevant decoupling frequency. For this purpose, considering a fixed motor design fulfilling the required aerodynamic performances, the operating range and the main motor orders must be assessed.

Usually, the decoupling frequency is strategically placed after the first order frequency range to avoid any increase of the mechanical unbalance and should be placed below the first motor order as shown in the transfer function example Figure 9.

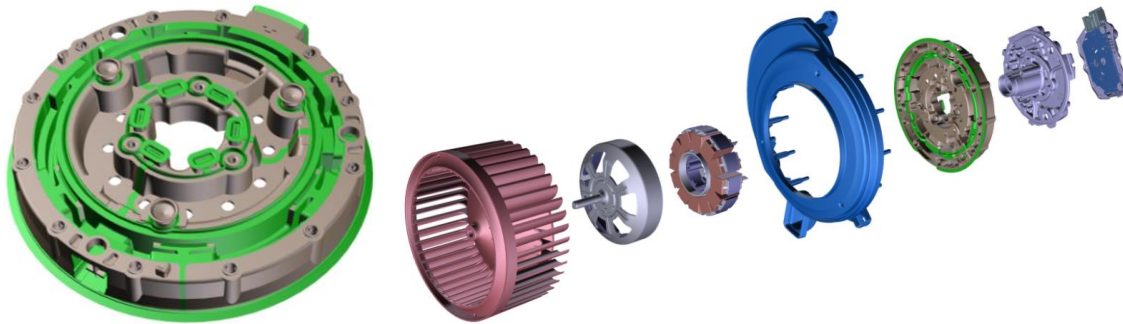


Figure 8 : Blower decoupling system.

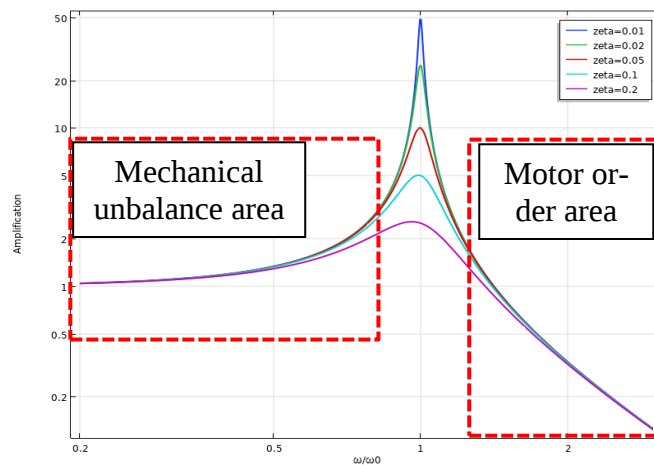


Figure 9 : Blower decoupling system transfer function example.

In the following example, the decoupling system impact on blower and motor orders is highlighted considering two different material parameters. In the first case, the material choice is made to ensure correct placement of the decoupling frequency. In the second case, the material choice is made to stiffen the decoupling system beyond design recommendations to eradicate any decoupling function. For the purpose of this study, ramp up measurements are performed at HVAC level. The microphones are placed at specific positions from the HVAC ventilation outlet to simulate a position in between passenger, and driver heads as shown Figure 9. Mechanical unbalance and motor orders noises are extracted using a 25rpm step and summarized Figures 10 and 11 (red : Soft decoupling, blue : stiff decoupling).



Figure 9 : Blower decoupling system transfer function example.

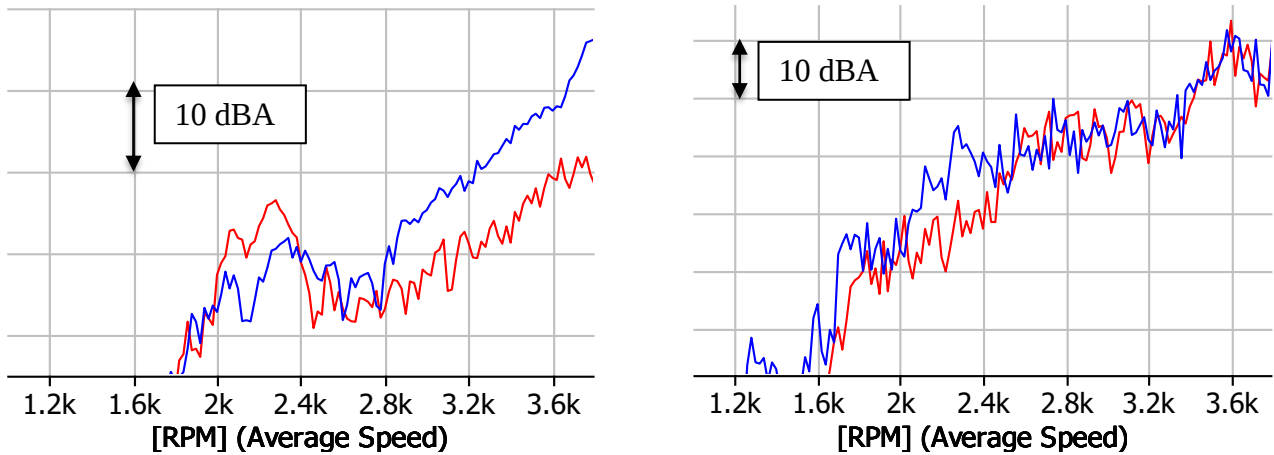


Figure 10 : Order extraction (order 1 left, order 8 right. Red : Soft, blue : stiff).

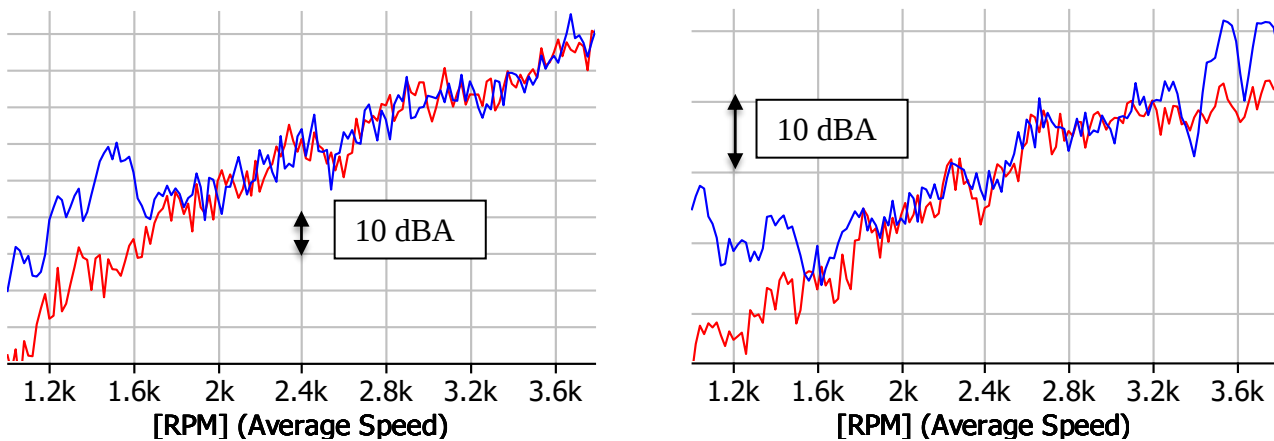


Figure 11 : Order extraction (order 12 left, order 24 right. Red : Soft, blue : stiff).

Order extractions show a significant increase of all levels when using a stiff decoupling system. Keeping similar airflow noise, order levels increase would result in objectionable specific frequencies emerging inside the car cabin. This highlights the critical interest of using a decoupling system and of correctly setting the decoupling frequency.

4.2. Motor design parameters

In order to reduce motor NVH orders, several design parameters must be mastered at both design and process levels. At design level for instance, reducing cogging torque requires changing magnets and electromagnets shapes in order to induce progressively smooth rotor movement. In addition, at serial production level, the process must ensure components alignment and coaxiality in a fixed range to limit order levels. However, as the required precision of motor assembly process induces significant cost, it would be advisable that the design reaches enough robustness that process discrepancies do not induce any issue. As an example, voluntary misplacement of a magnet induces high motor order levels as shown Figure 12.

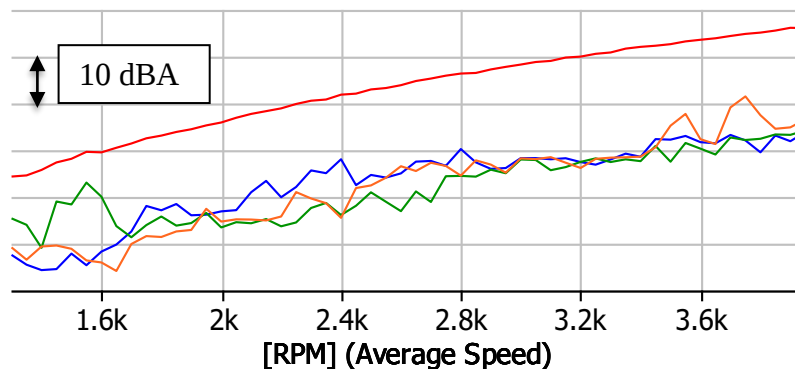


Figure 12 : Order extraction for a misaligned motor.

5. Compliance and specifications

5.1. Durability

The decoupling system is currently the main solution to ensure vibration transfer reduction from motors to HVACs and vehicles. As previously stated, to do so, the decoupling system is carefully designed to fulfill a compromise between low frequencies linked to mechanical unbalance and high frequencies linked to motor orders.

However, in addition to vibration transfer performances, decoupling systems are also designed according to other criteria. For instance, vibration durability tests are required to assess performance changes of HVACs and/or blowers induced by mechanical fatigue over vehicle lifespan. To perform durability tests in short time, vibration profiles are set using severity coefficients, which increases the vibration input level the shorter the time is, as shown in the example Figure 13.

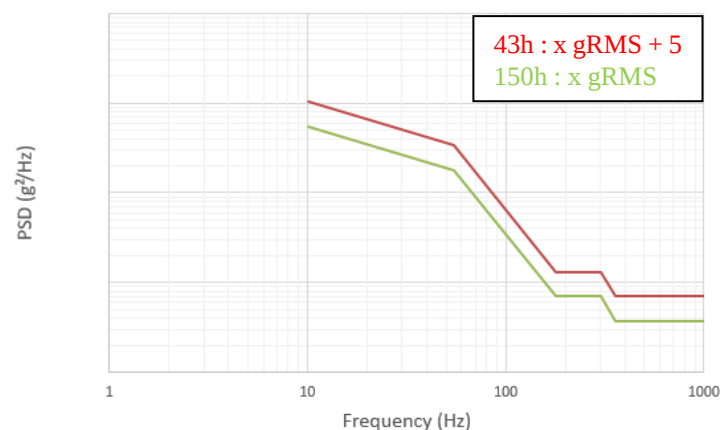


Figure 13 : Vibration input level example for durability tests.

Severity coefficients are based on logarithmic scaling depending on the part that is applied to. Mechanical and electronic parts severity coefficients for instance are different. Because of this difference, parts equipped with a decoupling system subject to unrealistic severity coefficients tend to fail durability tests. When failing these tests, complying with customer requirements then requires improving the decoupling system usually by increasing its stiffness. This solution often solves durability issues but also reduces the decoupling efficiency in reducing high motor orders which are then transmitted to the HVAC and emerge inside the car cabin. Durability requirements must be adapted to the tested component in order to achieve acceptable performances and avoid product overquality.

5.2. Microphone position

HVAC validation criteria defined by OEMs and system suppliers are usually based on regular metrics as third octave band spectra and overall noise levels in dBA for specific testing conditions such as distribution mode and flowrate. In addition to these parameters, microphone positions are defined according to OEMs and suppliers knowledge to get the closest possible to final customer's subjective assessment. For example, at HVAC level, testing setups require a microphone placed at a specific position from the HVAC ventilation outlet to simulate a position in between passenger and driver heads.

However, among customers, some may require additional microphones placed close to noise sources for investigation purposes or to set requirements. In this case, a microphone was chosen to be placed very close to the blower from below, as shown Figure 14, to investigate motor orders and a threshold was set at fixed speed on any motor order emergence.



Figure 14 : Microphone position for blower noise assessment.

Such parameters raise several concerns considering the lack of representation of car passengers' assessment. What's more, setting a fixed threshold over the hearable frequency range is biased, as a dBA scale does not take into account human frequency sensitivity with enough accuracy.

6. CONCLUSIONS

In this paper, the conducted analysis of automotive HVAC BLDC motors highlighted the critical challenges raised by such innovation in a competitive continuously evolving industry. Within this scope, BLDC motors represent a significant improvement providing higher efficiency in a reduced packaging.

However, as any component, it is crucial to master both design and process stages to avoid any NVH risks emerging inside the car cabin at serial production. For this purpose, it is of great importance to understand the fundamental phenomena occurring at component level and the possible transmission mechanisms, which are codependent. The suitable solutions to implement at each stage must fulfill the improvement targets while complying sometimes with contradictory requirements and specifications.

These findings highlight the codependency of design choices in putting NVH phenomena under control. Components must be carefully investigated to establish reasonable thresholds before considering system integration. It is then mandatory for system suppliers and integrators to work jointly in addressing the NVH topics using appropriate and realistic requirements.



Within this set blueprint, the joined work involving BLDC and NVH skills currently promotes development of more robust BLDC motors. In addition, technical expertise involvement with system integrators ensures potential NVH risks management.

7. REFERENCES

1. Bennouna, S. NVH integration impact of thermal systems components in serial vehicle production. *SIA2021 international Automotive NVH comfort conference*. Le Mans, France, 2021.
2. Bennouna, S. & al. Aeraulic and aeroacoustic experimental characterization of academic and industrial HVAC flaps. *International Styrian noise vibration and harshness conference*. Graz, Austria, 2016.
3. Bennouna, S. Caractérisation aéroacoustique d'éléments et associations d'éléments de systèmes de ventilation d'air pour l'automobile. *Ph.D thesis*, Université de Technologie de Compiègne, France (2016).
4. Naji, S. & Ailloud, F. HVAC and battery cooling noises for hybrid/electric vehicles and its impact on the end user comfort. *International conference on automotive and railroad comfort*. Le Mans, France, 2010.
5. Yaz, M., Cetin, E. Brushless Direct Current Motor Design and Analysis. *COJ Electronics Communication*. 2(2).COJEC.00534.2021.
6. Akar, M. & al. BLDC Motor Design and Application for Light Electric Vehicle. *Afyon Kocatepe University Journal of Sciences and Engineering* 025203 (326-336). Turkey , 2021.