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Regarding the NVH Behaviour of the more Electric Vehicles. Study Case of a Small PM Motor

The noise and vibration behaviour of electric and hybrid vehicles is dramatically different from conventional vehicles. The noise and vibration mechanisms of the individual components (combustion engine, electric motor, transmission etc.) are known in principle, but an electric or hybrid powertrain features additional and different components as well as new operation modes compared to a conventional powertrain. This results in new interactions which are uncommon in this form for conventional vehicles. In the case of the electric traction, the electric motor becomes an important noise and vibrations source. Depending on the design of the motor, the electromagnetic (EM) pulses and corresponding torque pulses from the motor can be very strong. These can be radiated as noise directly from the motor housing and can also be transmitted structurally to the support structure through the motor mounts. However, the EM forces are generally lower than the combustion and reciprocating mass forces of an IC engine, and significantly, they are at a much higher frequency. On the other side, the electric drives are quite numerous in cars. Lot of smaller motors are involved in X-by-wire systems or other comfort oriented systems. As a study case, the paper is focused on the NVH produced by a 0.25kW PM motor.

Keywords: noise, vibrations, electric motors.

1. Introduction

Nowadays, the tendency towards the more electric cars is obvious. But Electric (EV) or Hybrid Electric Vehicles (HEV) bring new noise, vibration, and harshness (NVH) challenges such as: high frequency electric motor generator noise, power control unit high frequency switching noise, power-split system gear whine and engine start/stop noise and vibration. In the same time, increased vehicle light weight material applications such as plastics and aluminium structures along with the migration from Body-on-Frame to Uni-Body structures are key actions to further improve fuel economy. These pose new NVH challenges such as road noise and powertrain noise as they become more noticeable.

But speaking about more electric cars also means the more extensive utilization of different electric systems for drive safety, comfort, communications etc. Among this, several electric drives became common solution for assuring a higher comfort: drive-by-wire or break-by-wire systems, electric windows, electric seats, heating and ventilation systems and so on. The most suited motors for the mentioned applications are considered the permanent magnet motors, induction motors and switched reluctance motors. Due to their very important characteristics of high power density and high efficiency, the permanent magnet synchronous motor (PMSM) has become the preferred choice in various electric drives applications, including in classical, electric or hybrid vehicles [1].

The paper first discusses the NVH issues of the more electric vehicles, focusing deeply on the noise and vibrations produced by the electric motors. Then, as an example, the case of a 0.3 kW PMSM motor is analyzed. The motor has been designed to be used for X-by-wire systems in cars. The possible noise and vibrations have been identified by FEM analysis and confirmed by experimental measurements.

2. Noise and vibrations in more electric vehicles

First, the technology used in electric and hybrid vehicle concepts is significantly different from conventional vehicle technology with consequences also for the noise and vibration behaviour, which is dramatically different from conventional vehicles. NVH refinement is an important aspect of powertrain development and the vehicle integration process, being often critical to satisfy customer expectations. Particular attention should be paid to the NVH performance of the vehicles, especially in relation to the subjective perception by driver and passengers.

Second, the extensive use of electric drives and actuators brings different sound than in the former cars. Especially in EV or HEV, where the conventional combustion engines are replaced or doubled by electrical motors, new types of components are introduced in the cars. These components often generate noise of higher frequency. At the same time, the masking effect from the engine noise is lost for EV and random for HEV, meaning that noise from these new components will be more dominant.

Figure 1 quantifies this noise issue of electric vehicles. At low and medium vehicle speeds, the electric vehicle is about 10 dBA quieter, i.e. about 25% of the noise. At higher speeds, the shares of wind and tire noise (which are independent of the powertrain concept) are increasing, causing the difference to be reduced.

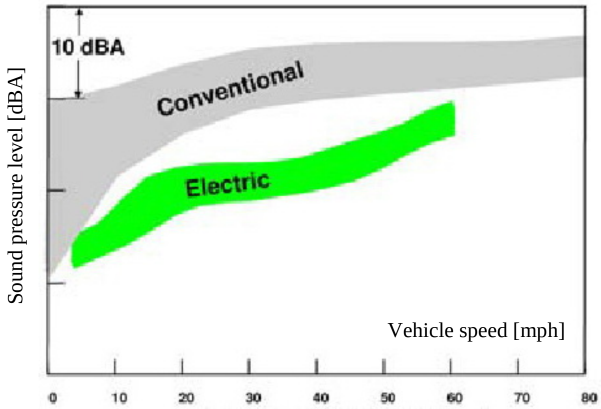


Figure 1. Vehicle interior noise (at driver's ears) for conventional and electric vehicles [3]

Mechanical noise can be produced by unbalanced rotors, overall rotor condition, rubbing and rolling bearing motions, and mechanical resonances of the stator core and end shields. Stator cores, end shields and fan covers may respond in two ways to the internal transmitted noise. First, they act as an acoustical enclosure, reflecting the noise energy back into the system. Secondly, they act as an acoustic transmitter and radiator, converting the noise energy to airborne noise radiation or to structure-borne vibrations [2].

EM forces generated by electric motors are generally lower than the combustion and reciprocating mass forces of an IC engine, and significantly, they are at a much higher frequency. As a result, the rubber isolation systems used to mount the electric motor to the body can be tuned more efficiently and achieve a much higher level of isolation than with an IC engine. Also, the noise radiated directly from the motor is generally quite high in frequency (>1000 Hz), which is easier to block and absorb with conventional acoustical materials than to lower frequencies [4].

In addition to the motor itself, other parts of the electromotive system create noise, in particular, the gearbox and the power electronics unit. For gearbox and power electronic unit systems, the radiated noise spectrum is very high in frequency. Normal levels of wind noise and tire/road noise will suddenly become unacceptable due to the absence of engine noise, especially at low to moderate speeds (less than 50 MPH). This means that achieving a new balance between electric motor noise, wind noise and tire/road noise will be the fundamental job at hand for EVs [4].

Compared to a conventional powertrain, HEV or EV powertrain features additional components such as electric engines, electronic control units and a high-voltage battery, resulting in these components. Each hybrid vehicle configuration brings unique NVH challenges that result from a variety of sources. The main acoustic and vibration problems with a negative effect on comfort, which results as consequence of the additional components and different new interactions between these, have been synthesized by [5]:

- Low-frequency vibrations of the powertrain during start/stop of the combustion engine at load change;
- Modified moments of inertia and eigen-frequencies in the powertrain;
- magnetic noise of the engine/generator during electric driving and regenerative braking;
- Aerodynamic noises of the battery cooling system;
- Switching noise of the power control unit.

In hybrid concepts, the driving condition is often decoupled from the operation state of the combustion engine, which leads to unusual and unexpected acoustical behaviour. Very often there will be no clear connection between vehicle speed and engine speed, because the last one is both influenced by the load demand and the state of the battery. So, start/stop event happens frequently and influence the noise and vibration behaviour.

Two proven metric to describe vibration during transient events such as ICE start-up have been defined [6]. The Vibration Dose Value (VDV) has the expression [7]:

$$VDV = \sqrt[4]{\int_{ts}^{te} a^4(t) \cdot dt} \tag{1}$$

where $a(t)$ is the frequency weighted acceleration (in m/s^2), and the difference between the start moment t_s and the end moment te represents the total measurement period (in seconds).

The VDV can be used for vehicle benchmarking, target setting, and to track the ICE start/stop performance of a vehicle during the HEV and/or range extended EV development phase. But it does not provide additional insights that might be needed to focus development efforts. That is why, the Energy Spectral Density (ESD) of vehicle steering wheel vibration has been defined as [7]:

$$ESD = \frac{G_s(\omega)}{\Delta f} \Delta T \tag{2}$$

where $G_s(\omega)$ is the autopower spectrum of steering wheel vibration, while Δf and ΔT are the frequency resolution and time period for the ESD calculation respectively. The ESD metric allows for development of scatter bands based on benchmarking the state-of-the-art HEV for their ICE start/stop behaviour. In addition, the ESD based analysis can provide insights into the ICE start/stop measurements on a development vehicle and assist with focusing refinement efforts [6].

3. Specific noise and vibrations produced by electric motors

The electric machine torque ripple can excite the propulsion system resonance when the frequency of the torque ripple is close to the propulsion mount resonance frequencies. This results in NVH issues and unacceptable performance for the electric-drive propulsion system.

Depending on the design of the motor, the electromagnetic (EM) pulses and corresponding torque pulses from the motor can be very strong. These can be radiated as noise directly from the motor housing and can also be transmitted structurally to the support structure through the motor mounts.

The noise from electric machines such as motors and generators manifests in the form of whine noise, i.e., tonal noise (typically in the 400 Hz – 2000 Hz range). The tonal nature of the whine noise from the electric machines can be annoying to the customer [6].

Noise and vibrations develop from various energy sources that appear when the motor armatures rotates, and most noise stems from the magnetic field. The attraction due to magnetic field is the main cause of vibration in rotating electrical machines. It occurs in the direction of the flux lines and is due to the sinusoidal flux in the air gap. It changes as the motor rotates and is characteristically harmonic [2]. Even though the radial force vectors are undesirable, they are unavoidable. The radial forces result in the mechanical vibration modes and it is documented in the literature that the low order modes, 2^{nd} and 4th in particular, are the main contributors to the noise creation [8].

Ripple torque, cogging torque, and magnetic radial forces are the main electromagnetic sources of noise and vibration in most of the electrical machines.

The ripple torque is produced from the harmonic content of the current and voltage waveforms in the machine [9]. In the case of multi-phase motors, torque ripple is a crucial factor in the performance and operation because it determines two important performance parameters, the magnitude of the machine's vibration and acoustic noise. The pulse-width modulation (PWM) strategies add many harmonics of the air-gap Maxwell forces spectrum, leading to possibly harmful noise and vibrations. Stator windings induce in rotor currents additional time harmonics which can also significantly enrich the electromagnetic forces spectrum, especially when running at high slip. Audible electromagnetic noise spectrum therefore results from a complex combination of both PWM time harmonics and winding space harmonics. To get a correct torque ripple analysis is necessary to perform an integrated transient study of the entire system, by combining the inverter circuit simulation with FEA (Finite Element Analysis) motor modelling [10].

The cogging torque is produced by the magnetic attraction between the rotor mounted permanent magnets and the stator teeth. Based on energy method, it can be seen that cogging torque is the negative derivative of the motor magnetic field energy W relative position angle α [11].

$$T_{cog} = -\partial W / \partial \alpha \tag{3}$$

Different cogging torque minimization techniques have been analyzed for various electromechanical machines [9]: magnet strength variation, radial shoe depth variation, magnet arc length decreasing or increasing the magnetic leakage flux that exists between pole pairs by varying the offset of one or more pole pairs. Many other methods, such as a fractional number of slots per pole, slot skewing, magnet skewing, auxiliary slots or teeth, magnet segmentation, etc. have been proposed to reduce the cogging torque [12], [13].

However, Islam et al. [14] have shown, based on an analytical model to study the radial displacement of the stator, that the radial forces are the major contributors to noise and vibration in these PMSMs, not the torque ripple or the cogging torque. These radial forces are increasing with the load increase. Studying PM motor drives operating over the entire torque-speed range Yang found that under load condition, harmonic components of radial force density are richer than those on no load condition [15].

In the interior permanent magnet (IPM) machines, the torque ripple can be unacceptable high if poor choices are made for the arrangement of flux barriers inside the rotor, contributing to both acoustic noise and vibration [16]. Beside this, high stator core losses can pose a significant problem in interior permanent-magnet (IPM) machines operating over wide constant-power speed ranges. At lower speeds, the torque ripple can be undesirably large in some IPM machine designs, contributing to acoustic noise and vibration. Han et al. shows that the conditions for reducing stator core losses during flux-weakening operation, dominated by harmonic eddy-current losses in the stator teeth, can conflict with the conditions for reducing the torque ripple of IPM machines [16].

To reduce NVH in IPM motors, Zhang proposed a compensation torque command. This is generated based on the modelling of the torque ripple and added to the average torque command, being able to reduce the selected harmonic component by more than 80 per cent. This compensation torque command is a function of the fundamental current component to produce the average torque, the rotor position, the winding distribution function and the rotor structure [17].

The simple and rugged construction of the switched reluctance motor (SRM) together with the low weight, easy cooling, high efficiency and high operational temperatures compared to other types of electric motors, make the SRM an attractive alternative to power electric vehicles. SRM applications are limited by their torque ripple and NVH issues. These drawbacks are caused mainly by the pulsed excitation of the stator poles and can be reduced by optimizing the motor design [18] and the excitation control of the stator poles [19], [20] or active compensation with current injection into auxiliary windings [21]. Mininger et al. proposed to decrease the SRM vibrations by placing piezoelectric actuators (PZT) actuators on the outer surface of the stator, with an adequate supply, imposing an opposite strain [22].

On the other side, a change in the design or the control will affect both the thermal losses of the SRM (and therefore also on the required dimension of the cooling system) and the global vehicle parameters such as efficiency and vehicle autonomy. That is why Gillijns proposed an early design stage for trade-offs between NVH and energy management, by coupling a functional SRM motor model to detailed electromagnetic and vibro-acoustic models on the one hand, and to a vehicle thermal model on the other hand [23].

4. Study case

4.1. Motor presentation

The motor investigated in this study has ten permanent magnets on the rotor and nine stator slots with a concentrated dual layer winding. Each phase consists of three coils in series with 38 wires on each coil. The motor was designed for small hybrid traction drives with the following parameters:

1) rated torque: 3.8 Nm;
2) rated power: 250 W;
3) rated speed: 600 rot/min;

The main geometric parameters are presented in Table 1.

The vibration analysis was conducted in two cases: BLDC and PMSM under-load motor operation. Figure 2 presents the four measure points for the acceleration caused by vibrations. Two horizontal (point 1 and 3) and two vertical points (points 2 and 4) were used. The vibration analysis is completed by results obtained by F.E.M. using a dedicated software package.

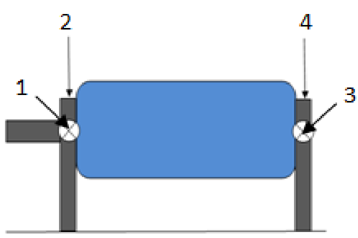
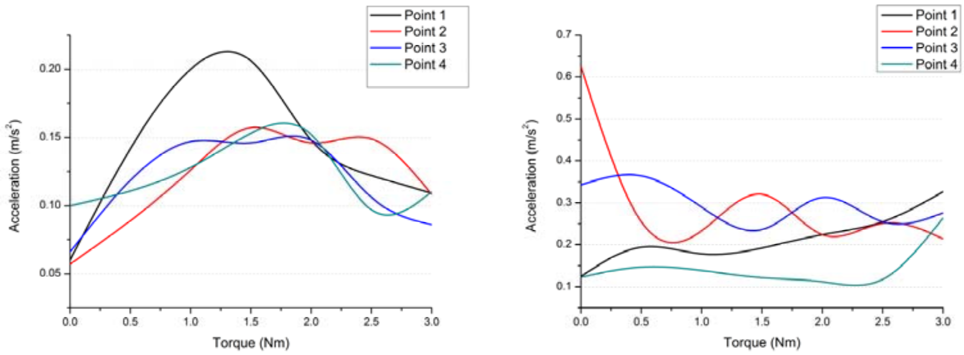


Figure 2. Motor representation with the four measurement point

Table 1. Main geometric parameters

Parameter	Value	unit
Stator outer diameter	96	mm
Stator inner diamenter	58.2	mm
Rotor outer diameter	57	mm
Rotor inner diameter	44	mm
Machine length	45	mm

Figure 3 presents the results based on experimental studies for BLDC motor operation (a) and for PMSM operation (b).



a) Motor operating as BLDC b) Motor operating as PMSM

Figure 3. Acceleration versus loading torque

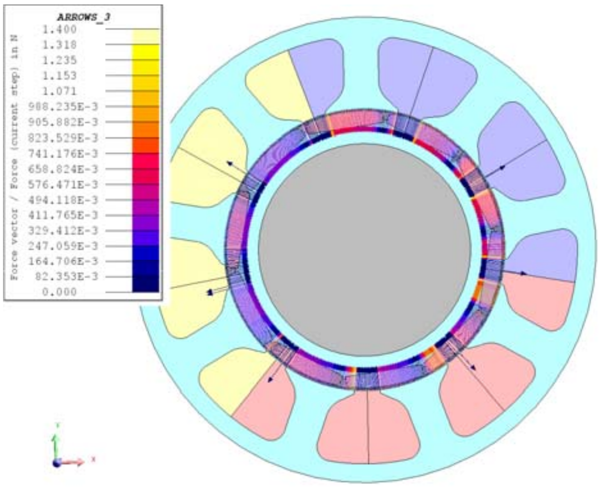
For BLDC motor operation the lowest acceleration values are obtained for no load operation (or small loads). This values increase approximately linearly with the load increase until the resistant torque reaches a value close to 1.5 Nm. The highest increase can be noticed for point 1. One explanation can be that point 1 is closer to the mechanical coupling. For higher load values, a certain decrease of vibrations can be noticed, for resistant torque values close to 3 Nm, the accelerations values are similar to those registered at no load. A particular situation can be noticed for point 4. In this case for increased load torque values, the acceleration values are smaller than those obtained at no load operation.

In the case of PMSM operation, the motor is fed from a static frequency convertor. For all four measure points an increase in acceleration values can be noticed at no load, compared to the previous case. Due to the fact that the speed in this case is constant the vibrations maintain an almost constant behaviour. The two studied cases have different vibration behaviour due to the fact that in BLDC motor operation the self-driving technique is used, where in the PMSM case the speed is maintained constant. The frequency converter has a current regulator which may cause additional vibrations by maintaining a rigid mechanical characteristic. Smaller vibrations may be obtained for PMSM operation if an adapted converter is used, also increasing the peak torque developed by the machine.

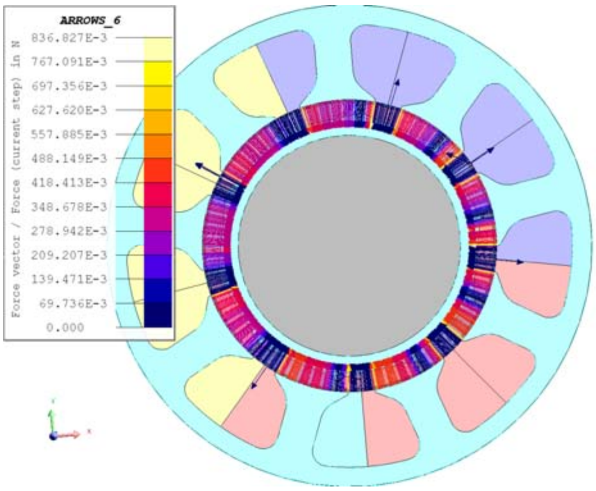
By means of F.E.M. analysis the electromagnetic forces, in the two operation cases, were computed. The software package calculates the forces starting from the magnetic radial and tangent pressures from the air-gap, as following:

- for the normal component $$F_n = \frac{1}{2}\frac{1}{\mu_0}B_n^2 - \frac{1}{2}\mu_0 H_t^2 \quad (4)$$

- for the tangential component $$F_t = B_n H_t \quad (5)$$



(a) Motor operating as BLDC



(b) Motor operating as PMSM

Figure 4. Electromagnetic forces developed in stator at 600 rpm

where B_n represents the normal component for the magnetic flux density, H_t represents the tangential component for the magnetic field and μ_0 is the permeability constant ($4\pi\cdot10^{-7}$H/m).

In Figure 4 the computed electromagnetic forces are displayed. The maximum values for the electromagnetic forces are obtained in areas where the magnetic flux density in the air-gap has increased values.

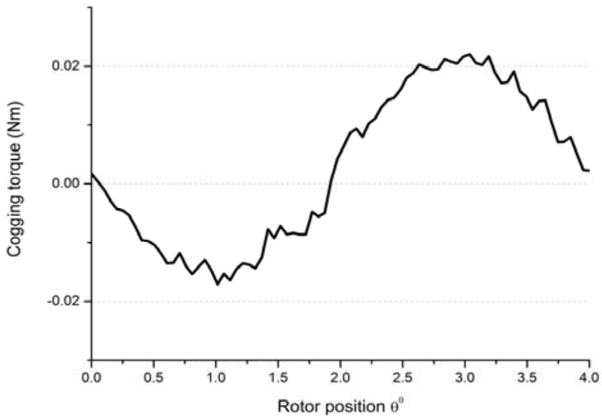


Figure 5. Cogging torque evolution with rotor position

Also in the case of BLDC motor operation, due to the fact that at each given moment only 2 phases are fed, the electromagnetic forces are not arranged symmetrically.

Another vibration source accounted for by means of F.E.M., is represented by the cogging torque evolution. As a simple rule, the cogging torque period is given by the lowest common multiple between the slot number and the rotor magnets number. In this case the period for the cogging torque is 4^0 mechanical degrees. Although the cogging torque frequency is high in this case, the maximum values are reduced.

5. Conclusions

The NVH behaviour of the more electric cars is substantial different to the one of the conventional ICE vehicles. Even though electric motors used for traction make lower noise than the IC engines, there are enough other annoying sources. Among the new components used in EV or HEV, the small motors bring their contribution to the NVH behaviour of the new structures. Designed for small hybrid traction drives, the motor described in the study case shows different behaviour when operating as BLDC and as PMSM.

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