Vibro-Acoustic Analysis of an Electric Powertrain: An Evaluation of the Relative Contribution of Gear Whine Noise and Electromagnetic Excitations on the Overall Response

Vibro-acoustic analysis of an electric powertrain: an evaluation of the relative contribution of gear whine noise and electromagnetic excitations on the overall response

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Abstract The NVH (Noise, Vibration, Harshness) performance of electric vehicles is gaining critical importance nowadays. Sources of different nature are responsible for the production of vibrations and noises in electric powertrains: namely, mechanical and electromagnetic excitations are worth investigating, both leading to relevant vibroacoustic responses. The mechanical source considered in this paper is the transmission error (TE); radial and tangential forces acting on stator teeth, as well as torque ripple acting on the rotor are the electromagnetic sources included. The modelling and simulation of the vibroacoustic performance of an electric powertrain for vehicle traction is carried out using a specialised commercial software, Romax. The NVH problem is first approached with the aim of weighting separately the contributions to the acoustic response due to mechanical and electromagnetic excitations. The difference between spur and helical gears is analyzed in terms of TE excitation harmonics, and the benefits brought by microgeometry corrections discussed. Waterfall and operational deflection shapes analysis has been used to identify the cause of some resonances (e.g. stator breathing mode) excited by the different vibrational sources.

Keywords: Electric powertrain, NVH, vibro-acoustic analysis, transmission error, gear whine, microgeometry optimization, electromagnetic excitations, torque ripple, dynamic system modelling, frequency domain simulation.

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1 Introduction

In recent years, the growth of electrical vehicles has driven research into the design and optimisation of electric powertrains, to be adopted for traction purposes. Initially, the designers focused independently on the electric motor and the mechanical transmission, but when the two systems are coupled, various dynamic problems may arise. Furthermore, the aspect of Noise, Vibration and Harshness (NVH) performance is becoming increasingly important, [1], with the aim of increasing passenger comfort. Replacing the internal combustion engine with an e-drive unit eliminates masking noise, but at the same time secondary noises, such as gear whine, emerge and new ones are added, such as the electromagnetic tonal noise of the electric motor [2]. In the literature, many studies focus on just one excitation source, either mechanical or electromagnetic, explaining the causes and possible solutions, but without having a complete overview of the whole system. [3], [4], [5] deeply investigate the sources of vibrations and noises of electromagnetic origin, especially focusing on PMSM motors. On the other hand, many studies focus more on the noise and vibrations generated by the gearbox and its optimization by modifying gear teeth [6]. By contrast, the present work applies an integrated and comprehensive approach, considering both mechanical and electromagnetic sources. In literature, very few papers use this kind of methodology. For instance, [7] and [8] consider both mechanical and electromagnetic excitations but, unlike the present work, does not highlight the improvements brought about by microgeometry optimization and also does not provide many details on transmission error analysis. Moreover, in the present paper, the considered electromagnetic excitations have been obtained by simulations performed in SyR-e [9] of a typical electric motor for automotive traction. Furthermore, the present work aims to weight separately the contributions to the acoustic response due to mechanical and electromagnetic excitations. This paper is organised as follows. Section 2 provides a description of the EV powertrain model considered and of the main Romax hypotheses. In section 3 an analysis of the different acoustic sources is performed. In section 4, the optimisation of the gear tooth microgeometry is proposed, while in section 5, the vibro-acoustic analysis is carried out for both excitation sources.

2 Case study and model assumptions

The dynamic analyses, performend in Romax [10], are based on a model included in the training material [11]: it is an electric powertrain with single-speed dual stage transmission, shown in Fig. 1 with (on the left) and without (on the right) the housing. The mechanical power source originally available in the model was replaced with an Internal Permanent Magnet (IPM) Distributed Windings (DW) eletric motor, a typical electric vehicle traction motor described in [12]. The electromagnetic excitations for the stator and the rotor were firstly computed using an open-source software for

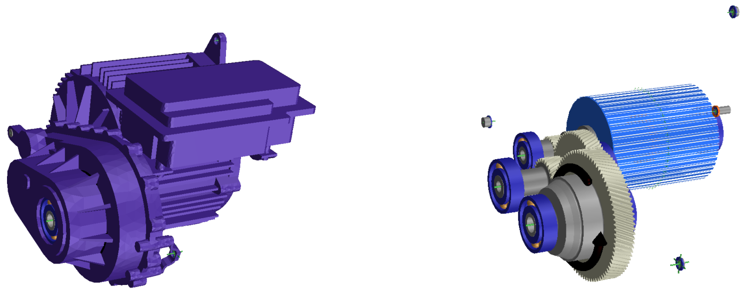

Fig. 1: e-Powertrain Romax model

electromagnetic analysis of electric motors (SyR-e [9]) and then uploaded in Romax. The main parameters of the e-powertrain are reported in Tab. 1.

Gearbox parameters	
Layout	Two-stage parallel
Nr of teeth (1^{st} stage)	22/65
Nr of teeth (2^{nd} stage)	27/83
e-Motor parameters	
Number of stator slots	48
Number of pole pairs	2
Number of phases	3
Rated torque-power	120 Nm - 50 kW
Max input speed	12000 rpm

Table 1: e-Motor and gearbox parameters

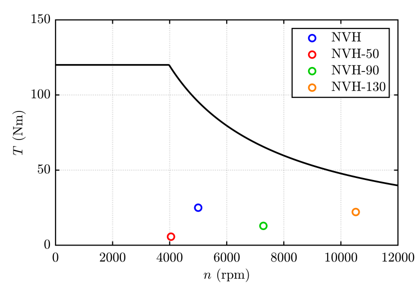

Fig. 2: NVH target points

To define the load cases (see Fig.2) to be analysed in the following, the application of the e-powertrain to a city car having 1200 kg of mass, aerodynamic drag coefficient $C_x = 0.35$ and rolling resistance coefficient $RRC = 7kg/ton$ is considered. The first load case, *NVH*, corresponds to a vehicle speed of about 60 km/h and a relatively low torque, representing a light acceleration phase in an extra-urban cycle. The second, third and fourth points refer to steady-state (constant speed) conditions (the number in the point name refers to the vehicle speed in km/h).

The main hypotheses used by Romax to define the e-powertrain model are now reported. Axisymmetric shafts are modelled as Timoshenko beam elements; bearings are modelled as fully coupled non-linear 5DoF stiffness representations; gears are accounted for as equivalent 6 DoF non-linear stiffnesses and, after the resolution of the static analysis of the whole system, the software calculates TE and teeth loads as a function of micro- and macro-geometries; electric machine rotor includes mass and inertia, applied to rotor shaft together with the torque ripple EM excitation; electric machine stator involves a 3D FE representation: radial and tangential excitations are applied to each of the stator teeth using weighted RBE3 connections; the gearbox housing is modelled as a finite element part where bearings are fitted and where the electric machine's stator is connected using a conformal mesh. When the NVH analysis is launched in *Romax Spectrum*, the static analysis is performed at the desired input torque for different speed points, the resulted deflections of the components and the linearized stiffness matrix are then used in the dynamic analysis around the selected working condition. Undamped natural frequencies and mode shapes are consequently calculated. In this activity a constant modal damping of 5% was applied, a detailed analysis of the effect of damping on the system response can be found in [13].

3 Analysis of excitation sources

3.1 Gears

The most relevant type of noise related to the transmission system in electric vehicles is gear whine, a tonal noise generated by the meshing forces of the gears which generate harmonic oscillations of the transmitted torque [14]. The whine noise is due to a parametric excitation of the dynamic system attributable to a non null transmission error (TE). TE is a measure of the deviation of the relative angular position of two meshing gears from the ideal kinematic coupling (gear ratio), accounting for the flexibility of the mechanical system (gear teeth, shaft, bearing and housing), micro-geometry profile modification, manufacturing and assembly errors [15].

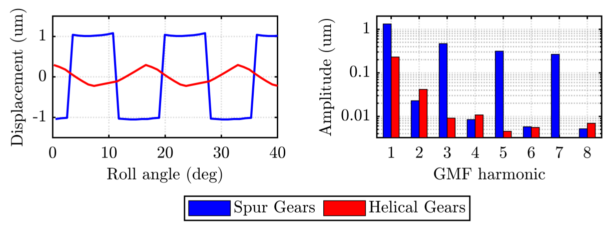

Fig. 3: Static Transmission Error vs involute roll angle and its harmonic decomposition for spur and helical gear sets

In this work, the TE is evaluated as a displacement on the line of action (LOA) versus the roll angle on the involute profile. It is interesting to note the difference in gear mesh frequency (GMF) harmonic contributions relative to different gear types (Fig. 3). Spur gears exhibit a square-wave trend of the TE with respect to involute roll angle, which corresponds to supremacy of odd-order harmonics of the meshing frequency in the spectrum. On the contrary, cylindrical gears with helical teeth, beside presenting a well lower peak-to-peak amplitude of transmission error, they show a more sinusoidal trend, thus resulting in a lower content of super-harmonics in the spectrum (please note that a logarithmic scale on the y-axis is used). This is due to the helix angle that increases the total contact ratio thanks to the contribution of the overlap contact ratio, thus allowing a smoother and quieter power transmission.

One of the most effective ways to reduce the negative effects of gear meshing, including reduction in TE, is represented by tooth microgeometry modifications, as will be discussed in section 4.

3.2 Electric machine

EV drivetrains are typically equipped with induction motors (IM) or, as the one analysed in this work, with permanent magnet synchronous motors (PMSM) [12], [16]. The operating principle of a synchronous motor is based on the interaction between the rotating magnetic field, synchronous with the rotor (generated either by permanent magnet or suitable stator current distribution) and the stator current distribution in quadrature with the magnetic field waveform. The interaction between the rotating magnetic field and the stator currents induces a distribution of forces (Maxwell forces) at the airgap, which allows for the generation of an instantaneous torque acting on the rotor. However, this distribution of forces excites the stator structure and the rotor during operating conditions, generating noise and vibrations. A further source of noise is torque ripple, defined as the instantaneous torque oscillation generated by the electric machine, acting on the rotor and stator as torsional excitation. Detailed investigations about sources of vibrations and noises of electromagnetic origin are provided by [3], [4], [5]. The radial forces waveforms computed in SyR-e [9] and their spatial harmonic content (wavenumber) are represented in Fig. 4.

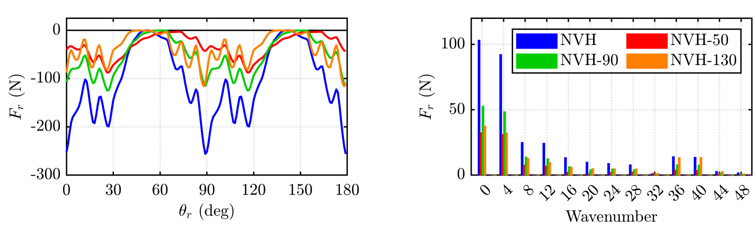

Fig. 4: Waveforms (left chart) of the radial force applied to a single stator tooth as a function of the rotor position and their spatial harmonic spectrum (right chart) evaluated in four different test points

4 Gear teeth microgeometry optimisation for noise and vibration reduction

At the design stage, optimising gears from the point of view of durability, efficiency and noise requires appropriate modifications to the micro-geometry of the tooth surface. However, selecting properly the microgeometry parameters is not an easy task: it is sometimes based on the experience of gear designer or may be based on a dedicated microgeometry optimization tool like the one available in Romax. In this study the optimisation problem was set to improve the NVH performance at motorway speeds of the electric vehicle, by minimising the 1^{st} harmonic and the peak-to-peak value of the TE of both gear sets. The outcomes of the micro-geometry design lead to the results shown in Fig. 5, in which the peak-to-peak transmission error of the input gear set is shown. A similar optimization was also set up for the output gear set. Furthermore, Fig. 5 highlights the improvement in terms of gear contact patch obtained by adding microgeometry modifications, showing the overall contact to which a flank is subjected to during a whole rotation of the gear. Looking at the normal load per unit length distribution it is clear how the contact patch is more concentrated in the center of the tooth face in the case of optimized profile.

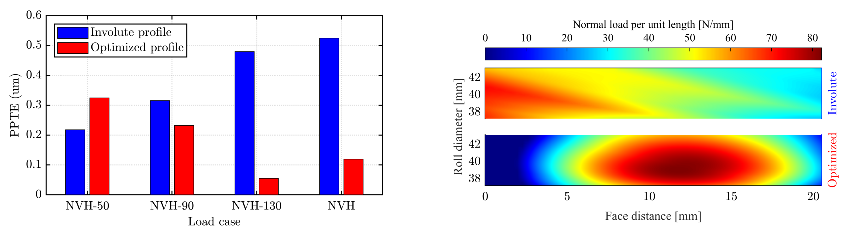

Fig. 5: PPTE for input gear set and normal load per unit length with involute and optimized profile (microgeometry modifications)

5 Vibro-acoustic analysis

The spectrograms shown in Fig.6 are used to compare and evaluate the influence that sources of different nature have on the e-powertrain acoustic response. They were obtained from a simulation with *Actran* software embedded into *Romax Spectrum*, applying mechanical and electromagnetic sources separately and selecting the *NVH* load case with a constant torque of $T = 25\,Nm$. On the left side of Fig.6 the GMF harmonics of the input and output gear sets can be clearly identified. A resonance peak, excited by the 1^{st} order of the input gear set (1X in), circled in red, is visible at a speed of about 8500 rpm. This resonance condition will be investigated in the following.

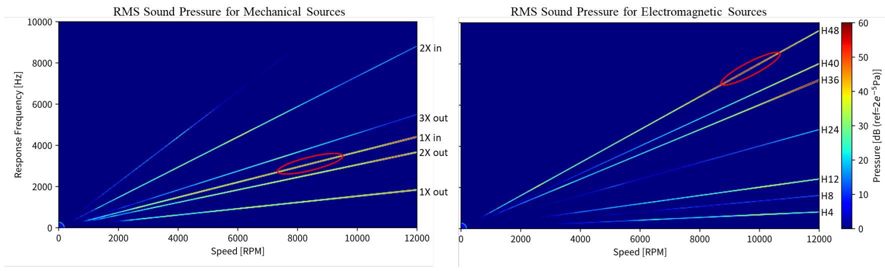

Fig. 6: SPL spectrogram of the system response to mechanical and electromagnetic sources

On the other hand, the sound pressure spectrogram on the right of Fig.6 contains the harmonics of the electromagnetic sources. Unlike the previous case, here the harmonics with prevailing amplitude are those of higher order, which excite the structure at higher frequencies. In particular, harmonic 48 has the greatest response in the 6-8 kHz range (8-10 krpm), while the 36^{th} at maximum motor speed. Several articles, such as [17], have demonstrated that the stator breathing mode, whose order is equal to the least common multiple of the number of slots and the number of motor poles, [18], is generally the main acoustic problem in the PMSMs of today's electric vehicles. In this machine there are 48 slots and 4 poles, therefore the order 48 causes breathing mode.
Moreover, comparing the two charts, it can be noticed that the two sources, i.e. mechanical and electromagnetic, lead to acoustic pressure peaks of the same orders of magnitude. Therefore careful design is required on both sides to enhance acoustic comfort of electric vehicles. The linear dynamic transmission error (LDTE), which is the sum of the dynamic response of the gear mesh and the static transmission error, is plotted in Fig. 7 versus the input shaft speed. A resonance peak is evident at 8448 rpm; this resonance mainly involves radial deformation of the right bearing that supports the intermediate shaft causing relevant gears misalignment, as highlighted by the operating deflection shape (ODS) shown on the right.

To deepen the analysis on the 48^{th} harmonic of the electromagnetic forces the equivalent radiated power (ERP) due to tangential forces, radial forces and torque ripple is reported. The ERP provides an estimate of the airborne noise radiated from the vibrating surface of the housing; the results shown are A-weighted and thus include the sensitivity of the human ear. The contribution to the powertrain acoustic response due to tangential forces is prevalent at low speeds, whereas radial forces become predominant at high speeds; the contribution due to torque ripple is instead very limited across the entire speed range. The peak at 9225 rpm is investigated through ODS analysis: the breathing mode excites the structure around the stator

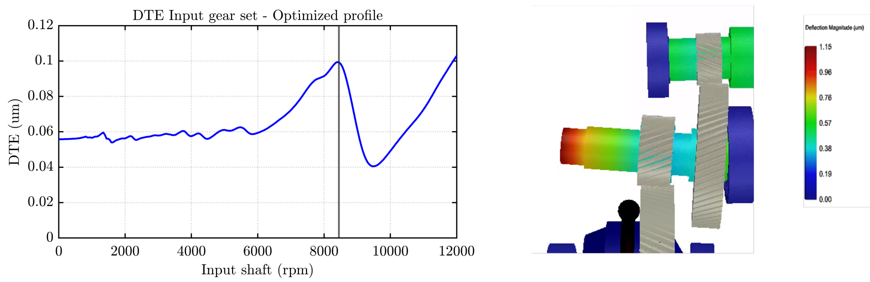

Fig. 7: Linear DTE for input gear set with optimized microgeometry and the ODS for the peak in the response at ω = 8448 rpm

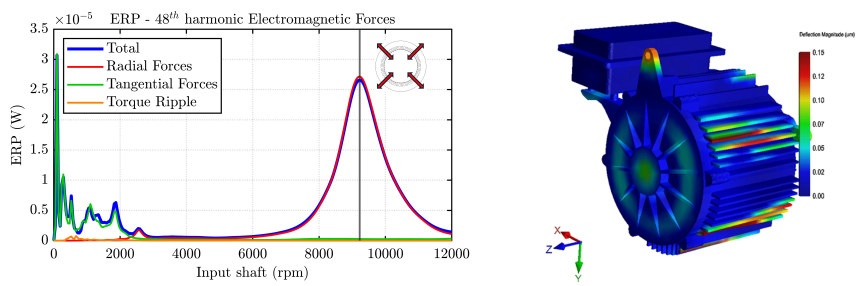

Fig. 8: ERP (A-weighted) considering the 48^{th} harmonic of electromagnetic forces and the ODS for the peak in the response at ω = 9225 rpm

of the electric machine, causing deflections of the cooling fins and of a powertrain mount.

6 Conclusion

This paper presents and applies a methodology for assessing the NVH performance of an electric powertrain that aims to weight separately the contributions to the vibro-acoustic response due to mechanical and electromagnetic excitations. As for the transmission, the difference between spur and helical gears is analyzed from the perspective of TE excitation harmonics, and the benefits brought by microgeometry gear tooth corrections are discussed. The Romax acoustic analysis, applied to a well-designed electric powertrain, highlights that both the mechanical and electromagnetic sources contribute to a quantitatively comparable acoustic response. Waterfall and operational deflection shapes analysis helped to identify the cause of some resonances excited by the different vibrational sources.
More generally, this study highlights the need to supplement classical tools for the

design of electrified propulsion systems with advanced simulation tools capable of predicting the behavior of the entire system, in order to be aware of and take early action to solve any NVH problems.

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