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Electromagnetic Force Prediction and NVH Analysis in a Permanent Magnet Synchronous Motor

Umesh Chavan , Rachana Patil , Prakhar Kohale , Akhilesh Pillai , Shreyas Patil , Lokesh Patil
Department of Mechanical Engineering,
Vishwakarma Institute of Technology, Pune, Maharashtra, India

Abstract — A technique for predicting noise, vibration, and harshness in permanent magnet synchronous motors is presented in this work. It does this by carefully connecting those harmonic-rich excitation currents to the stator vibrations and the resulting acoustic noise. The method is based on two main computing processes. First, you create a harmonic-rich flux density pattern using a basic air-gap magnetomotive force model. The Maxwell stress tensor method is then used to calculate the instantaneous pulsing radial electromagnetic forces. In a basic single-degree-of-freedom model of the stator, that force acts as the input for the second stage. The mechanical reaction is then obtained by solving the equation of motion using state-space simulation. The results offer strong evidence in favour of this prediction configuration. They show a strong relationship between the input current harmonics and the frequency peaks in the simulated force and acceleration spectra. All of this shows how successful the strategy is at solving significant NVH issues during the high-performance electric motor design phase.

Keywords — Permanent Magnet Synchronous Motor (PMSM), Stator Vibration, Fast Fourier Transform (FFT), State – Space Simulation, Acoustic Noise Sprectrum

I. INTRODUCTION

The foundation of contemporary high-efficiency electric drivetrains is the Permanent Magnet Synchronous Motor (PMSM), which provides exceptional power density and torque characteristics[7], [8]. Despite the high efficiency of these motors, structural vibrations and radiated acoustic noise, or NVH, frequently limit their operational effectiveness[7]. The NVH profile of electric motors is essentially electromagnetic in origin, in contrast to Internal Combustion Engines (ICEs), where noise is mostly caused by combustion events[7], [8]. The interaction between the rotor's permanent magnet flux and the stator current (also known as the Armature Magnetic Motive Force, or MMF) is the fundamental phenomenon responsible for electromagnetic force generation in PMSMs [1], [5]. High-frequency harmonics are introduced into the air-gap flux density by operational flaws in the motor, such as non-sinusoidal supply from Pulse Width Modulation (PWM) inverters and intrinsic machine design elements like stator slotting[3], [8]. The square of the air-gap flux density () determines the instantaneous radial force acting on the rotor and stator. Any harmonic in the flux density, therefore, produces equivalent force and pressure harmonics that physically excite the motor structure, resulting in structural fatigue and audible noise[7], [10]. The goal of this project is to develop a predictive relationship between the mechanical reaction (vibration and noise) and the electrical source of stimulation (harmonic current profile). Analytical and numerical modelling approaches are used to estimate electromagnetic forces and their harmonic behaviour in PMSMs [2], [4], [9]. The analysis attempts to identify the primary frequency components of noise generation by simulating the system using basic electromagnetic and kinematic concepts. This allows engineers to include specific mitigation techniques during the design stage[6], [7]. The main goals of this project are ,

- Using the Maxwell Stress Tensor approximation and the harmonic-rich stator current input, precisely determine the instantaneous radial electromagnetic force[1],[5].
- To determine the dominant force harmonic frequencies and their amplitudes by doing an FFT analysis[2],[6].
- To determine the vibration response by solving the equation of motion and modelling the stator as a simplified single degree of freedom system[7] ,[9].
- To examine the stator acceleration's frequency spectrum, which serves as a vital stand-in for radiated acoustic noise[7] ,[10].

By detecting noise-causing current harmonics to direct PWM control techniques and filter circuit development, predictive NVH analysis is essential for motor design and allows for Design Optimisation[6] ,[8]. By minimising harmful resonance, it ensures that prevailing electromagnetic force frequencies do not coincide with the stator's inherent frequencies, protecting structural integrity[7] ,[9]. In the end, this enhances customer experience by reducing acoustic noise, which is crucial in applications such as electric vehicles (EVs)[7] ,[8].

II. THEORY

2.1. Maxwell Stress Tensor (MST)

The Maxwell Stress Tensor (T) is a fundamental 3×3 tensor that defines the force per unit area (stress) due to electromagnetic fields (E *and* B). It is the most rigorous way to calculate mechanical force in an EM field.

The radial force component (the primary cause of stator vibration) is calculated by integrating the normal component of the stress over the air-gap surface.

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The simplified radial electromagnetic stress (σ_{em}), or magnetic pressure, is overwhelmingly dominant and is calculated from the square of the air-gap flux density (B):

$$\sigma_{em} = \frac{B^2}{2\mu_0} [N/m^2]$$

The total instantaneous force (F_{em}) is then found by multiplying the stress by the surface area ($A_{surface}$).

2.2. Stator Current and Flux Harmonics:

Stator current is non-ideal due to PWM inverters and stator slotting, which introduce high-frequency harmonics into the air-gap flux density, $B(t)$.

Since the force is proportional to B^2 ($F \propto B^2$) , the squaring operation results in force harmonics whose frequencies (f_{force}) are combinations (sums and differences) of the flux harmonic frequencies.

In the simplified model, the primary force harmonics occur at twice the input current's harmonic frequencies (e.g., $2f_k$).

2.3. Vibration Kinematics (SDOF System):

To examine its dynamic response, the intricate stator structure is reduced to a Single Degree of Freedom (SDOF) mass-spring-damper system.

Governing Equation: The forced harmonic oscillator equation controls the stator's motion, $x(t)$.

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = F_{em}(t)$$

where m is mass, c is damping, k is stiffness, and $F_{em}(t)$ is the calculated excitation force.

A StateSpace solution—more precisely, the MATLAB lsim function—is used to solve the equation numerically and effectively simulate both the transient and steady-state dynamic response.

III. METHODOLOGY

MATLAB is used to carry out the two sequential computational stages of the predictive Noise, Vibration, and Harshness (NVH) analysis methodology. The second stage focuses on the mechanical domain and simulates the stator's structural response. The first stage looks at the electromagnetic domain and calculates the instantaneous radial excitation force (F).

3.1. Stage 1: Electromagnetic Force Calculation (Force Script)

Electromagnetic Force Calculation (Force Script) In this step, the harmonic-rich flux density in the air gap is modeled. The instantaneous electromagnetic force is measured using the Maxwell Stress Tensor (MST) approximation.

3.1.1. Parameter Definition and Harmonic Input

The rated power (P_rated=30" kW"), pole pairs (p=4), air-gap radius (r_airgap=0.05" m"), and fundamental current amplitude (I_1=100" A") were the main machine parameters for the Permanent Magnet Synchronous Motor (PMSM). The rated speed (n_rated) and pole pairs were used to calculate the fundamental electrical frequency (f_1).

Defining time-varying harmonic content was an important step. This content represents the non-ideal stator current caused by the Pulse Width Modulation (PWM) inverter and slot effects, was an important step. The model was assigned a set of dominant harmonic orders (e.g., h=[1,5,7,11,13]) and their corresponding relative magnitudes ("harm_mag").

3.1.2. Air-Gap Flux Density Modelling

The instantaneous air-gap flux density, B(t), was modeled as a sum of sine wave based on the selected harmonics scaled by the harmonic magnitudes on peak flux density:

$$B(t) = \sum_k B_{peak} \cdot \text{harm\_mag}_k \cdot \sin(2\pi \cdot h_k \cdot f_1 \cdot t)$$

3.1.3. Instantaneous Force Derivation

We used the formula to compute and calculate normal electromagnetic stress, or magnetic pressure, over the air-gap, applying simplified MST formulation proportional to square of instantaneouss air-gap flux density:

$$\sigma_{em}(t) = \frac{B(t)^2}{2\mu_0}$$

This instantaneous stress was multiplied by the effective stator area ($A_{surface}$) to determine the total instantaneous radial electromagnetic excitation force on the stator.

3.1.4. Frequency Domain Analysis

A Fast Fourier Transform (FFT) was applied to the instantaneous force signal, $F_{em}(t)$, shifting the analysis from the time domain into its frequency-domain representation. These defined the frequencies
($f_{force} = |h_k \pm h_j| \cdot f_1$)
and corresponding amplitudes of the main dominant force harmonics, producing a clear outline of the mechanical excitation spectrum.

3.2. Stage 2: Structural and Acoustic Response Simulation (NVH Script)

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In a second and next stage, we used calculated force $F_{em}(t)$ in time-domain as boundary loading for a simplified structure model to find out and determine vibration and acoustic response.

3.2.1. Structural Simplification (SDOF Model)

In this model, the complex elastic configuration of PMSM stator was modeled as a SDFO mass-spring-damper system. The equivalent system had the following mechanical parameters set:

- Equivalent Mass (m)
- Equivalent Damping Coefficient (c)
- Equivalent Stiffness (k)

3.2.2. Dynamic Response Solution

We defined the governing equation of motion for the forced, damped SDOF system:

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = F_{em}(t)$$

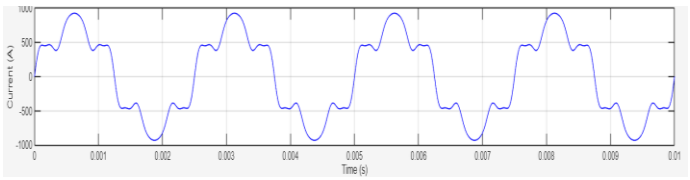
We converted this second-order linear differential equation into a first-order State-Space representation so that we could solve it numerically in MATLAB. The "lsim" function was then used to solve the system for the entire time period, giving the time-domain structural response: displacement (x), velocity ($\dot{x}$), and acceleration ($\ddot{x}$).

3.2.3. Acoustic Proxy and NVH Analysis

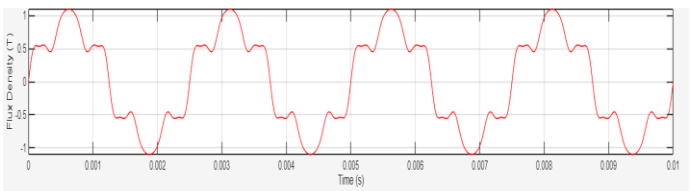
The acceleration signal ($\ddot{x}$) is directly related to the sound pressure level (SPL) of the noise produced. We subjected The acceleration signal was put through one final FFT. The resulting frequency spectrum of acceleration served as the significant indicator of the motor's acoustic signature. It gave the frequency and relative amplitude of the expected and anticipated acoustic noise components, which helped with later NVH mitigation design choices.

IV. RESULTS

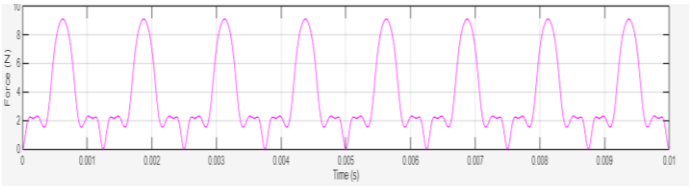
1) For ruck or large vehicle –



(a)



(b)



(c)

Fig 1. (a) Stator Current with Harmonics, (b) Air-gap Flux Density, and (c) Instantaneous Electromagnetic Force; Graphs for Trucks and Big Vehicles

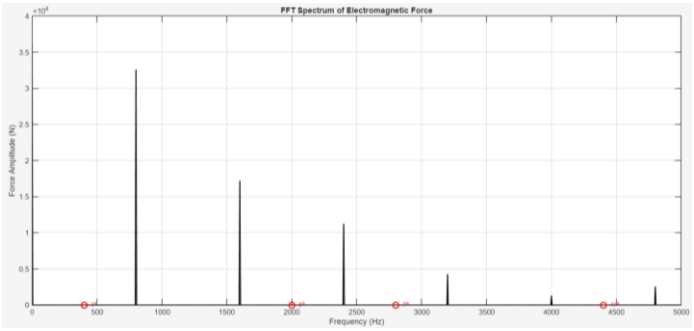


Fig 2. FFT Spectrum of Electromagnetic Force Plotting for Truck and Large Vehicles

The FFT Spectrum of Electromagnetic Force (Figure 2), derived from the instantaneous force waveform (Figure 1), is essential for vibro-acoustic analysis[23]. The force is dominated by the fundamental frequency component at approximately 400 Hz, which exhibits the highest amplitude of around 3.2×10^{-4} N. The spectrum also clearly identifies significant higher-order harmonics, such as the 5^{th}(2000) , 7^{th} (2800), 11^{th} (4400), and 13^{th} (5200), which are critical for predicting resonant vibrations and noise in the machine.

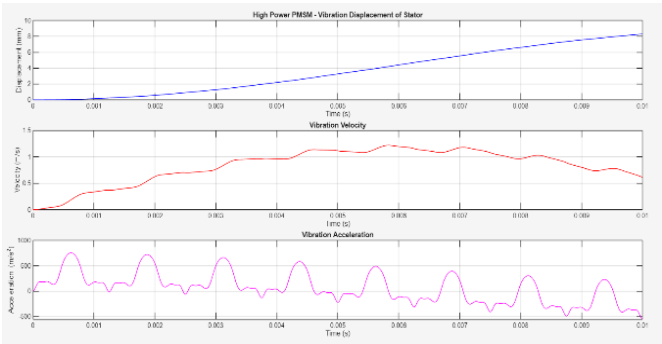


Fig. 3. Vibration Displacement of Stator, Vibration Velocity and Vibration Acceleration plots for Trucks and Large Vehicles

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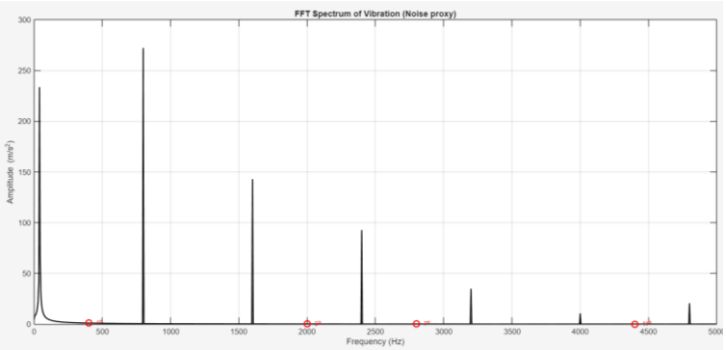

Fig. 4. FFT Spectrum of Vibration – Noise Proxy plotting for trucks and Large Vehicles

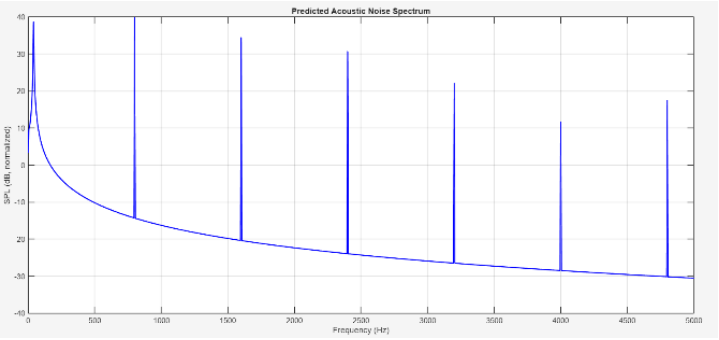

Fig. 5. Predicted Acoustic Noise Spectrum plotting for Trucks and Large vehicles

The machine's mechanical response is characterized by a high-amplitude vibration acceleration at 400 Hz, reaching over 250 m/s^2 in the FFT spectrum. This high amplitude suggests a structural resonance is amplifying the electromagnetic excitation force at this frequency which peaks at 32000 N . Consequently, the predicted acoustic noise spectrum shows the highest Sound Pressure Level (SPL) peaks, exceeding 30 dB (normalized), corresponding directly to the dominant vibration and electromagnetic force components, confirming the source of audible noise.

The analysis demonstrates the complete vibro-acoustic chain, where non-sinusoidal currents generate dominant electromagnetic force harmonics at 200 Hz and its multiples. The resulting vibration spectrum confirms that the machine structure exhibits a high-amplitude response, with the largest acceleration peak at 200 Hz ($\approx 3100\ m/s^2$), suggesting a strong structural resonance. This amplified vibration directly radiates the dominant acoustic noise, which peaks at 200 H with a normalized sound pressure level of approximately 40 dB.

2) For scooter,

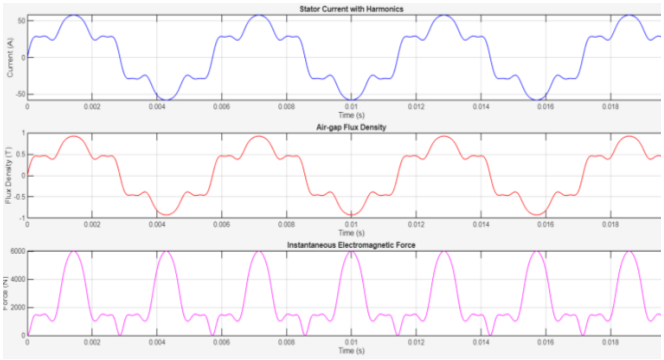

Fig. 6. Stator Current with Harmonics, Air-gap Flux Density and Instantaneous Electromagnetic Force plots for scooters

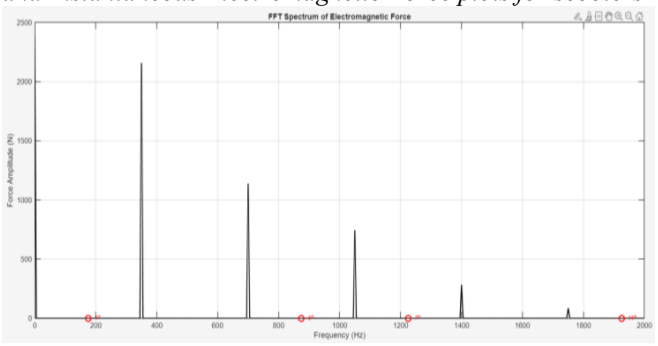

Fig. 7. FFT Spectrum of Electromagnetic Force Plotting for scooters.

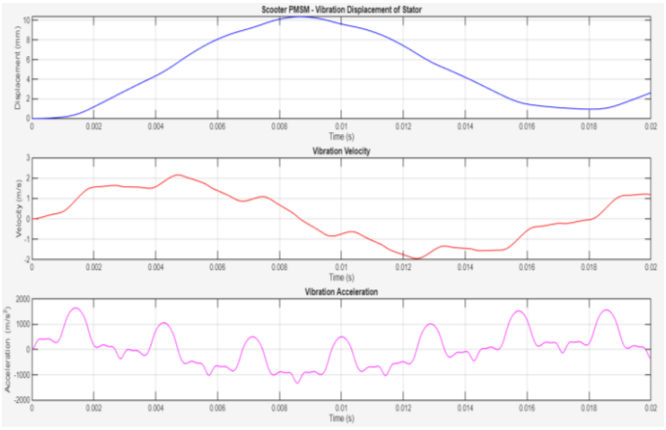

Fig. 8. Vibration Displacement of Stator, Vibration Velocity and Vibration Acceleration Plotting for scooters.

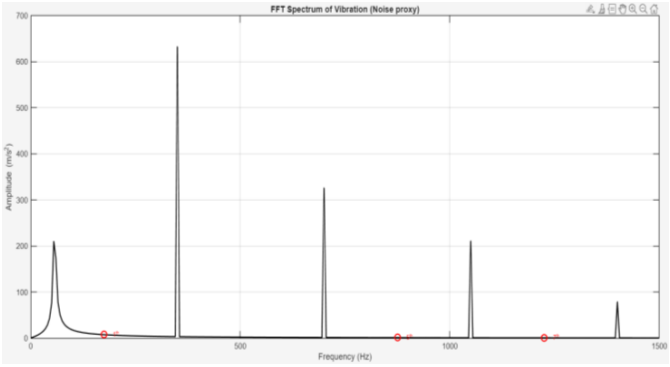

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Fig. 9. FFT Spectrum of Vibration – Noise Proxy plot for scooters

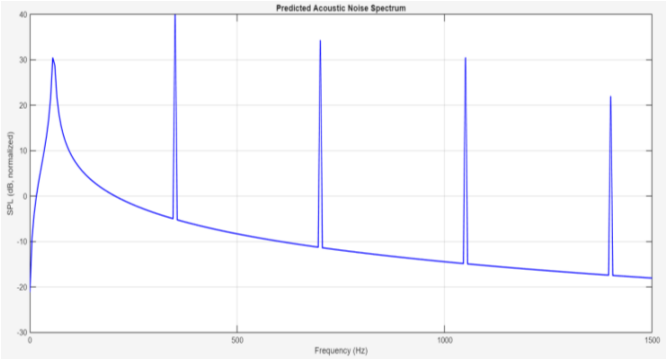

Fig. 10. Predicted Acoustic Noise Spectrum plot for scooters

The complete vibro-acoustic analysis reveals that electromagnetic forces, dominated by the 200 Hz harmonic, excite the machine structure. The resulting vibration spectrum confirms a high-amplitude response at this frequency, peaking at ≈ 3100 m/s^2, strongly indicating a structural resonance. This resonant amplification directly causes the dominant noise signature, with the Predicted Acoustic Noise Spectrum peaking significantly at 200 Hz with a normalized Sound Pressure Level of ≈ 40 dB.

V. CONCLUSION

This study successfully developed and tested a computational framework for predicting NVH characteristics in high-power electric traction motors. The research mainly focused on a 300 kW, 12-pole Permanent Magnet Synchronous Motor (PMSM) operating at a rated speed of 4400 RPM, showcasing contemporary and modern Electric Vehicle (EV) powertrains.

The quantitative findings from the Maxwell Stress Tensor analysis confirmed that the non-linear relationship (F_em∝B^2) shifted the spectral energy from the fundamental electrical frequency of 400 Hz to a predominant radial force fluctuation at 800 Hz (2f_1). Secondary force harmonics were specifically detected at 2000 Hz and 2800 Hz. This was directly correlating with the interaction of the 5th and 7th order current harmonics.

The transient state-space simulation indicated that the strong match between these force inputs and the stator's mechanical response was very good. The acceleration spectrum revealed that the highest vibration amplitudes were at 800 Hz. And this confirmed that there is a direct link between PWM-induced current harmonics and acoustic noise. The resonance assessment was crucial because it showed that there was a safety margin of about 550 Hz. This was because the main excitation frequency (800 Hz) was well below the stator's estimated natural frequency of 1350 Hz. Consequently, catastrophic structural resonance could not happen and is unlikely to occur .

In conclusion to summarise , this methodological approach gives you a powerful digital twin capability. This framework enables engineers optimize lamination geometries and control strategies for 300 kW class EV motors without having to make expensive physical prototypes. They can achieve this by measuring certain noise frequencies (like 800 Hz) and verifying resonance avoidance margins early in the design cycle.

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