Precise Vibration Measurement with Mechanical Load Isolation for Sub-Fractional Horsepower Motors

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***Abstract*--With the growing use of electric motors as the primary propulsion system in vehicles, vibrations from the main drive have decreased, making vibrations from auxiliary drives more noticeable. As a result, addressing audible noise and vibration in the design of auxiliary motors for automotive applications has become increasingly important. These compact drives, often located near the passengers, are more audible compared to the main drive system. Consequently, they can produce vibrations that may excite neighboring structures or components, leading to noise-related concerns. Accurately measuring the structure-borne noise of permanent magnet (PM) motors presents a significant challenge. This paper introduces an innovative approach to enhance vibration measurement precision and differentiate between electromagnetic and mechanical sources of vibrations, making it suitable for sub-fractional horsepower motors' vibration measurements and analysis.**

***Index Terms*— e-NVH, Permanent Magnet Motors, Sub-Fractional Horsepower, Vibration Measurement.**

I. Introduction

Electromagnetic forces are a primary source of vibration in electric motors, generating harmonics that can excite the motor's mechanical structure. The order of these harmonics is associated with factors such as synchronous speed, number of poles and slots, and the excitation method [1], [2]. In small motors, these forces are relatively small, typically in the order of a hundredth of a newton (N), requiring precise measurements [3]. The measurement process becomes more challenging when vibrations caused by the load are introduced, as they intertwine with vibration caused by electromagnetic forces, complicating the analysis. To investigate electric motor vibrations, understanding how design changes impact vibration behavior is essential. However, this task is further complicated when vibrations with electromagnetic and mechanical sources mix, making it difficult to isolate and evaluate the differences.

This article is structured as follows: Section II explains the motor structure used as the example case for investigating the proposed vibration measurement method. Section III presents both the conventional and proposed measurement methods. Section IV analyzes the measurement results in two different scenarios: first, by comparing the old measurement with the proposed method, and second, by demonstrating the effectiveness of the method through comparisons of example cases in "healthy" and "non-healthy" conditions due to manufacturing imperfections. At the end, Section V summarizes the findings.

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II. The Sample Case Motor's Structure

The example case is an axial flux permanent magnet (AFPM) motor with printed circuit board (PCB) windings and a ferrite core [4]. This motor is specifically designed to drive a small radial fan for automotive applications, with a rated output power of 1.15 Watts.

This motor was selected because, in the actual application, the blades are directly connected to the rotor, and both rotate via the same shaft and bearing. As a result, the mechanical and electromagnetic sources of vibrations combine. These combined forces are then transferred either to the structure in real applications or to force sensors for vibration measurements. This makes it an ideal example case for investigating both vibration sources together.

Fig. 1 shows the different parts of the motor, which comprises a ferrite stator core, PCB windings, and ferrite magnets. As illustrated, the stator core includes 24 slots, and the rotor has 28 magnet poles. The stator teeth feature a circular cross-section, simplifying the assembly process and reducing costs in PCB production. Table I presents the motor specifications in detail.

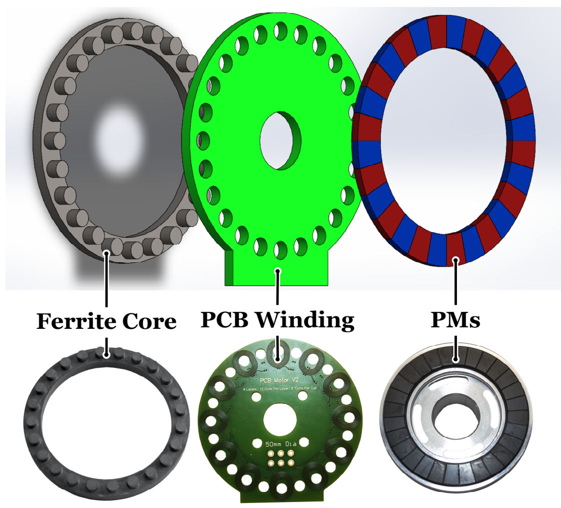

Fig. 1. Exploded view of the PCB motor with ferrite core and the prototyped parts.

TABLE I
THE MOTOR SPECIFICATIONS

Quantity	Unit	Value
Rated average output torque	[mNm]	2.2
Rated power	[mW]	1150
Air-gap length	[mm]	0.3
Pole pairs number (p)	-	14
Number of slots (Z_S)	-	24
Motor axial length	[mm]	10
Motor outer diameter	[mm]	50
Supply voltage	[V]	12.8
Input current peak	[A]	0.162
Rated speed	[rpm]	5000
Magnet thickness	[mm]	4.5
Magnet Residual flux density	[mT]	275

For the measurements, the ferrite core and PCB are placed inside an aluminum housing connected to the sensors. Two different rotor designs are used in the measurements: one is a radial fan, and the other is a rotor without blades, designed to connect to an external eddy current load. These designs will be explained in detail in Section III.

III. MEASUREMENT METHODS AND SETUPS

A. Conventional Vibration Measurements Method

The conventional vibration measurement setup consists of three-axis force sensors and follows the VW 82469 standard [5]. The force sensors are mounted on a stainless steel cylinder, which is decoupled from the bottom support. Due to the cylinder's mass significantly exceeding that of the system, it is considered a rigid abutment according to the standard. The sensors' data are collected via the 3-channel sound and vibration measurement modules (NI-9232) from National Instruments. As specified by the standard, the measured forces from all attachment points are summed and presented in a one-third octave band analysis. Fig. 2 shows the test bench with the connected fan and sensors.

Fig. 2. Conventional vibration measurement setup.

In this measurement method, vibrations arising from mechanical factors such as unbalancing or bearing defects can transfer through the motor structure and be detected by the sensors. While it is possible to differentiate these vibrations from electromagnetic ones during post-processing, challenges arise when they interact with non-linear materials and combine with electromagnetic forces, complicating electromagnetic force analysis. This is particularly pronounced in small motors, where the amplitude of magnetic forces is relatively low.

B. Proposed Vibration Measurements Method

To investigate the structure-borne noise behavior of electric motors effectively, it is important to understand how electromagnetic design impacts measurement results to gain valuable feedback for design improvements. However, this understanding becomes challenging when electromagnetic vibrations are mixed with mechanical vibration sources. The proposed measurement method addresses this issue by mechanically isolating the load from the sensors, ensuring that mechanical forces do not interfere with the sensor measurements.

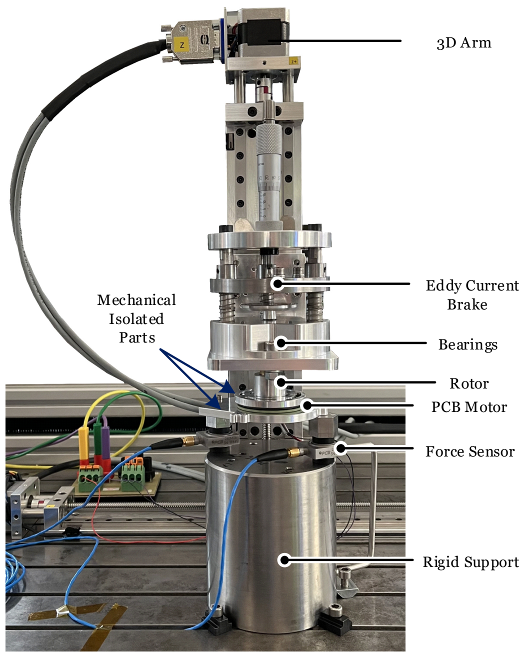

Fig. 3. Proposed vibration measurement setup.

Fig. 3 illustrates the modified measurement setup. In this setup, the rotor is integrated with an eddy current load and both components are mounted on a three-dimensional arm, allowing precise movement in three directions with a resolution of one-hundredth of a millimeter. The rotor, aligned with the stator's center, is suspended from the top through its connection to the eddy current brake. The stator remains fixed to the sensors and the stainless steel cylinder, maintaining the same arrangement as in the previous setup.

The eddy current brake was selected for its minimal torque ripple, which can be considered negligible, and its torque-speed characteristics closely resemble those of a

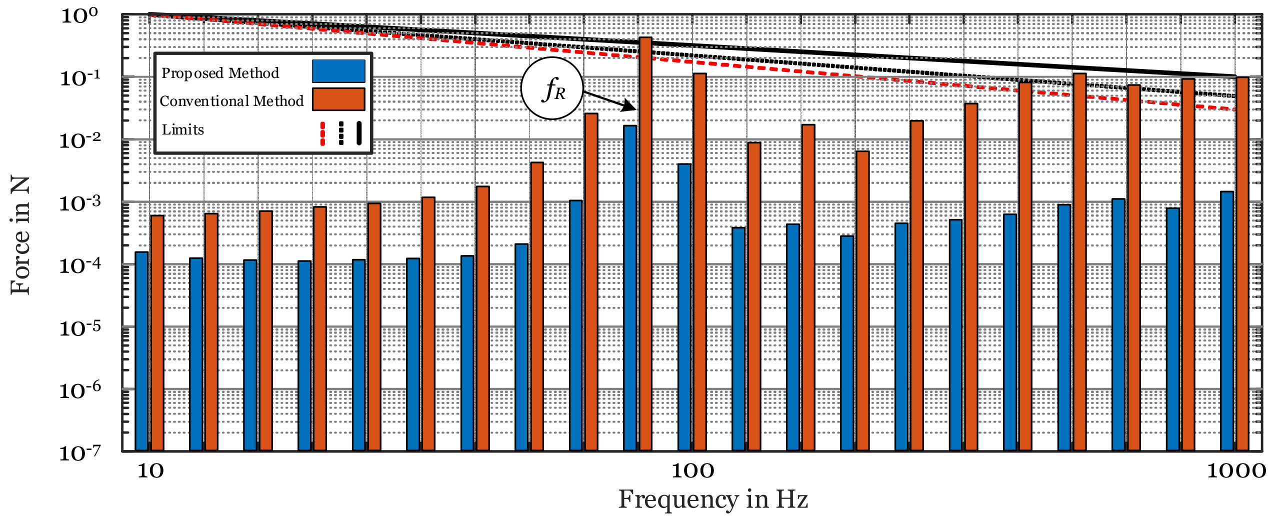

Fig. 4. One-third octave band analysis of structure-borne noise measured using both the conventional and the proposed method.

fan load. This makes it an ideal choice for the measurement setup. Additionally, the eddy current brake provides the flexibility to adjust the load magnitude, allowing for testing under varying load conditions.

IV. Measurement Results and Analyses

Magnetic forces are characterized by amplitude and frequency. Frequency is an important factor for resonance prediction and is vital for noise, vibration, and harshness (NVH) analysis [6], [7]. This research primarily focuses on force frequency, as they can significantly excite the components connected to the drive. The force sensors used in the measurement method are capable of detecting the forces in a wide range of frequencies.

Pulsating forces are, by definition, in phase across both the stator and the rotor. These forces are observed at the same frequency by both the rotor and the stator, similar to torque and counter-torque interactions. A rotor pole will inevitably experience variations in magnetic forces at multiples of the stator slot passing frequency, $Z_S f_R$, where Z_S is the number of slots and f_R is the rotor's mechanical rotational frequency. Conversely, a stator tooth will experience variations in magnetic forces at multiples of the pole passing frequency, $2pf_R$, where $2p$ is the number of poles.

As a result, pulsating forces occur at multiples of the least common multiple (LCM) between $Z_S f_R$ and $2pf_R$ [6]. Therefore, the frequency at which these forces occur is given by:

$$f = \mathrm{LCM}(Z_S, 2p) f_R \tag{1}$$

It should be noted that if there is any asymmetry in the rotor poles and slots, pulsating forces with frequencies of $Z_S f_R$ and $2pf_R$ will appear in addition to the LCM between $Z_S f_R$ and $2pf_R$.

In the following subsections, two different scenarios are analyzed to show the accuracy of the proposed measurement method.

A. *Impact of Load Isolation on Vibration Measurements*

Fig. 4 illustrates the measured structure-borne noise in the one-third octave band for the PCB motor using both the conventional and the proposed vibration measurement methods, respectively, as described in Section III. The motor is excited by a three-phase sinusoidal voltage and operates at 5000 rpm, with a consistent load of 2.2 mNm applied for both measurement methods. According to the standard, forces from all attachment points are summed and presented as a one-third octave-band spectrum [4].

The primary distinction between these two measurements lies in the type of load and its connection to the measurement points. In the conventional method, the load is a fan that is mechanically connected to the measurement points, allowing both mechanical and electromagnetic forces generated by the rotating parts to influence the measurements. In contrast, the proposed method utilizes an eddy current brake as the load, which has no mechanical connection to the measurement points. This isolation ensures that only electromagnetic forces are transmitted and recorded during measurements, effectively eliminating any interference from mechanical forces caused by rotating components.

The results are plotted on a logarithmic scale for both force and frequency, with the limits represented as three distinct lines. The frequency range is selected up to 1000 Hz, which is typically the most critical range for vibration analysis [5]. The comparison reveals that, across all frequencies, the amplitude of the measured force using the non-isolated method is consistently higher than that of the proposed method. In certain frequencies, the amplitude is more than 100 times greater, exceeding the specified limits at six points.

Considering f_R, which is the frequency corresponding to the rotational speed of 5000 rpm, and comparing the forces at this frequency, it becomes evident that the fan experiences mechanical unbalance. While this mechanical problem can be disregarded during analysis as a non-electromagnetic source, it is important to note that the amplitude of all other forces at different frequencies is influenced by this unbalance. Moreover, if there is a bearing problem or a fan with varying levels of unbalance, it can alter the force signatures. These problems are particularly pronounced in sub-fractional horsepower motors, where the absolute force values are very small and can be easily affected.

All of these uncertainties complicate the replication of measurement results and make it challenging for motor designers to concentrate on structure-borne noise caused by electromagnetic forces. In contrast, with the proposed method, the sensors exclusively measure electromagnetic forces, resulting in considerably more accurate and repeatable outcomes.

B. Validation of Measurement Precision Using Defective Components

In this subsection, the vibration behavior of the example case PCB motor with a healthy core and a defective one is compared using the proposed measurement method to demonstrate its capability to detect and distinguish small changes.

Fig. 5 shows a microscopic view of one of the core's teeth, which was damaged during the prototyping process. The tooth has a diameter of 3 mm, and the broken section is marked. Although this defect is minor and does not impact the motor's overall performance, it introduces asymmetry in the core. According to the analytical expression at the beginning of Section IV, force at the $2pf_R$ frequency is expected to appear in the measurements.

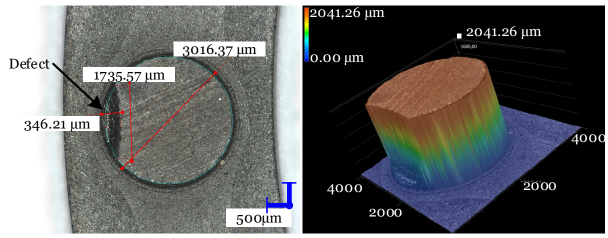

Fig. 5. Microscopic view of the defective core tooth.

Furthermore, during the prototyping process, segmented rotor magnets were used. Due to manufacturing tolerances, any asymmetry in the pole pairs should result in a force with the frequency of $Z_S f_R$ appearing in the measurement results.

To investigate the effect of the mentioned asymmetry on vibration behavior, two test were conducted under the same conditions, with the defective core used in one of the tests. The forces were recorded, and after applying a fast Fourier transform (FFT), the results are presented.

Fig. 6 shows the forces along all three axes for the healthy core. The dominant force occurs at the $Z_S f_R$ frequency, with sidebands also appearing, which results from an unbalanced electromagnetic force. The presence of the force at $Z_S f_R$ frequency indicates that the rotor poles are not perfectly symmetrical. Although the asymmetry is minimal, it can be detected using the proposed measurement method. Fig. 7 presents the forces along all three axes for the defective core. In addition to the forces observed in the measurements with the healthy core, the force at the $2pf_R$ frequency increases, as indicated in the figure. The defect also influences the amplitude of other

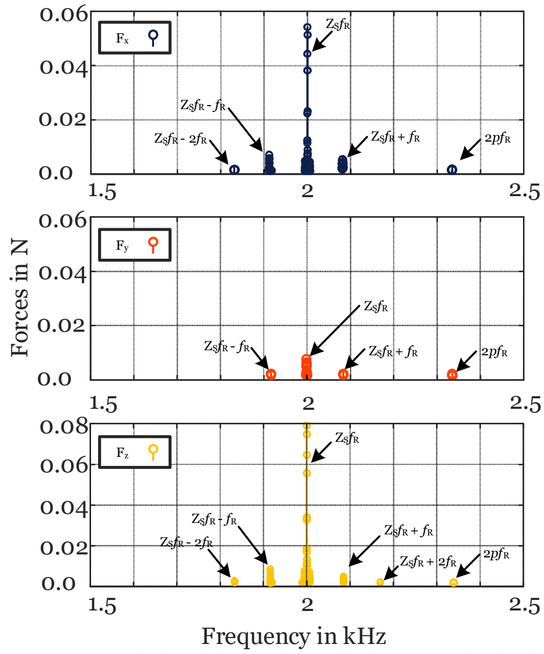

Fig. 6 FFT analysis of forces along all three axes for the healthy core.

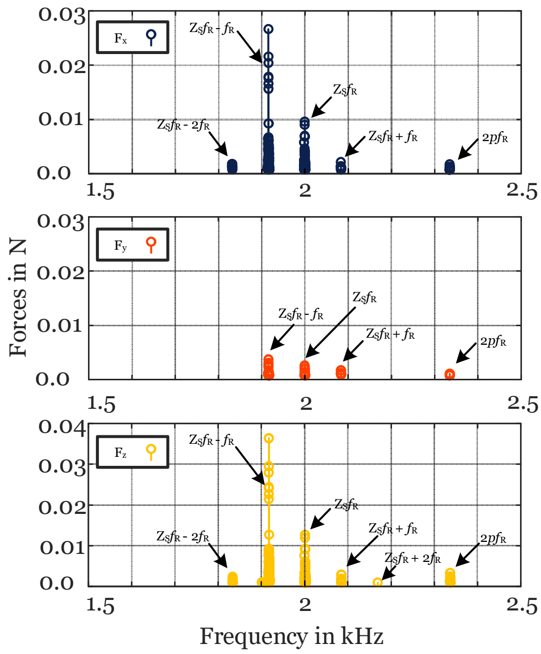

Fig. 7 FFT analysis of forces along all three axes for the defective core.

forces. Consequently, the comparison between Fig. 6 and Fig. 7 demonstrates the accuracy of the measurement method and its capability to reveal the effects of small changes on motor design.

V. Conclusions

This study presents a new vibration measurement method that significantly enhances accuracy in sub-fractional horsepower motors vibration measurement. The proposed approach effectively isolates mechanical vibrations originating from the connected load, enabling more reliable and precise detection of electromagnetic forces. Its robustness against mechanical interference makes it a valuable tool for motor designers seeking to assess vibration characteristics with greater clarity. The method's effectiveness was validated through a series of measurements, followed by comprehensive comparison and analysis. Future work will involve finite element analyses and their comparison with the measured results.

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