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Vibrations and Acoustic Noise Analyses of Modular SPM Machines

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Abstract—This paper investigates the vibrations and acoustic noise behavior of some equal tooth width, unequal tooth width and modular surface mounted permanent magnet machines. The investigations are based on finite element analysis (ANSYS) and the performances such as radial force (and airgap magnetic pressure), vibration modes (shapes and resonant frequencies), radial displacement and acceleration of the stator, and sound pressure level have been calculated and compared amongst different machines. It has been found that due to the existence of flux gaps in stator alternate teeth, at the same operating condition (phase current and rotor speed), the modular machines can reduce the sound pressure level by up to 15dB compared to the equal tooth width permanent magnet machines. A similar reduction in sound pressure level can be achieved by adopting the unequal tooth width permanent magnet machine.

Index Terms— acoustic noise, modular machine, permanent magnet, sound pressure level, vibration.

I. INTRODUCTION

PERMANENT magnet (PM) machines have attracted increasing interest in various applications ranging from domestic appliances (air conditioning, washing machine, etc.), through renewable energy (onshore and offshore wind power) to transportation (electrical or hybrid electrical vehicles –EV or HEV, and “more electric” aircraft). In the last decades or so, many different PM machine topologies have been proposed in industry and academia. They can be roughly classified into two categories: (1) rotor mounted PM machines such as surface mounted PM (SPM) machines, interior PM (IPM) machines including I-shaped, V-shaped or ∇ -shaped IPM machines; (2) stator mounted PM machines such as flux reversal (magnets on stator tooth surface), switched flux (magnets in the middle of stator teeth) and doubly salient (magnets in stator yoke) PM machines [1]. Other unconventional PM machines such as magnetically geared, partitioned stator, or hybrid excited PM machines can also be classified into these two categories. Although some PM machines might be more suitable for certain specific applications, for example, the SPM machines are good for wind power application whilst the IPM machines are suitable for EVs and HEVs, they all exhibit inherent advantages such as high torque/power density, high efficiency over their induction or reluctance counterparts.

However, due to the existence of PM, the fault tolerant capability of PM machines could be jeopardized. For example, if a short-circuit fault occurs in the stator windings, the short-circuit current could be a few times higher than the rated current due to high PM flux linkage. This could lead to local overheating, which can destroy the stator insulation, causing disastrous consequence to the entire machine [2]. In order to improve the fault tolerant capability of PM machines, single layer windings are often preferred compared to double layer winding. This is because the former can mitigate the mutual effect between adjacent coils (or phases) so to prevent the fault, the inter-turn short-circuit fault in particular, from propagating to the healthy coils (phases). In addition to the above magnetic isolation, there will also be physical and thermal isolations between adjacent coils, leading to significantly improved fault tolerant capability.

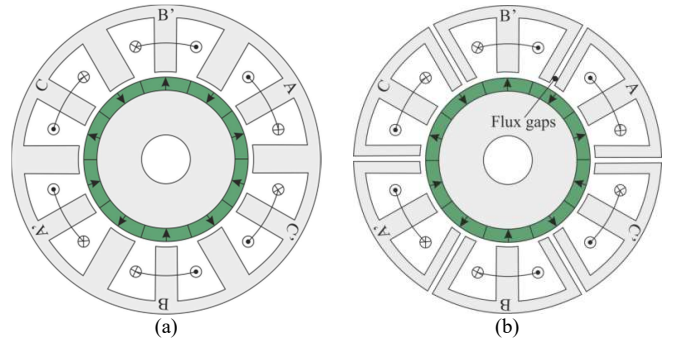


Fig. 1 Cross-sections of modular and unequal teeth (UNET) stators with 12-slot/10-pole. (a) UNET, (b) modular.

In order to further reduce the mutual coupling between stator coils (or phase windings), modular machines with segmented stator are proposed in [3-5], one example of such machines is shown in Fig. 1. There are flux gaps (FG), also called flux barriers in some literature, between adjacent stator segments, which minimize the mutual inductances between any two adjacent stator coils. It has also been found that by properly selecting the FG width and slot/pole number combination, the electromagnetic performance of modular machine can be improved, such as the average torque and efficiency can be increased whilst the torque ripple is reduced [5]. In addition, because the stator segments can be wound outside of the frame,

the winding process could be simplified, leading to potentially improved slot fill factor. However, since the stator iron core is now segmented, the mechanical integrity of the stator is destroyed. This may significantly affect the mechanical performance of the modular machines. For example, the vibration modes including shapes and resonant frequencies can be changed. Together with the changed electromagnetic performance such as radial force and airgap magnetic pressure, the vibrations and also acoustic noise of modular machines might be significantly different from their unequal tooth width (UNET) and equal tooth width (ET) counterparts. This impact of modularity (or stator segmentation) on machine vibration behaviors has not been studied before, therefore is the main novelty and contribution of this paper.

Both analytical and finite element methods can be used to calculate the vibration modes, radial displacement and acoustic noise of electrical machines. The analytical approaches can be much less time consuming and accurate enough [6]. However, they are largely constrained by the machine structures, and might not be able to handle complex structures. Therefore, the multi-physics approach based on finite element modelling becomes more and more popular in prediction of vibrations and acoustic noise [7, 8]. Such method combines the electromagnetic and structural analyses to provide a powerful insight into the vibrations and acoustic noise behaviors of electrical machines with complex structures, e.g. with different frame ribs for cooling [9]. Therefore, it will also be adopted for the vibrations and acoustic noise analyses in this paper.

II. FEATURES OF MODULAR SPM MACHINES

The cross-sections of the UNET and modular SPM machines with a 12-slot/10-pole rotor are shown in Fig. 1. Other slot/pole number combinations can be achieved by using similar stator and rotor topologies. It is worth noting that the ET machine can be obtained by simply removing the FGs in the modular machine whilst the UNET machine can be achieved by filling the FGs in modular machines using the same iron material as the stator core. In addition, to avoid the increase in saturation level, in the modular machines, the iron section widths of the teeth with and without FGs are maintained the same. This means that when the FG width is increased, the slot area needs to be reduced, leading to increase in copper loss. However, as investigated in [4, 5], the significant increase in average torque could compensate the increase in copper loss.

TABLE 1 KEY PARAMETERS OF THE MODULAR SPM MACHINE

Slot number	12	Air-gap length (mm)	1
Pole number	10	Rotor outer radius (mm)	27.5
Stator outer radius (mm)	50	Magnet thickness (mm)	3
Stator inner radius (mm)	28.5	Magnet remanence (T)	1.2
Stator yoke height (mm)	3.7	Number of turns per phase	132
Stack length (mm)	50	Filling factor k_b	0.37
Frame thickness (mm)	10		

To be consistent, the windings are always wound on the narrower teeth in the UNET machine, whilst on the teeth without FGs in the modular machine, as shown in Fig. 2, leading to single layer winding structure for both machines. The stator segments can be wound outside then inserted into the frame. The keys (6 for 6 stator segments) on the inner surface of the frame are used to fix these wound stator segments. This

makes the winding process much simpler and hence can potentially increase the slot fill factor. However, due to manufacturing tolerance, the loose contact between the keys and stator segments is often unavoidable, leading to potential radial and circumferential displacements of the stator segments. The recent studies in [10] have shown that the modular machines suffer only minor increase in unbalanced magnetic force due to segment displacement. However, other performances such as the phase back-EMF, on-load torque, etc. are largely unaffected. This proves that the modular machines are not only tolerant to electromagnetic faults but also to mechanical ones.

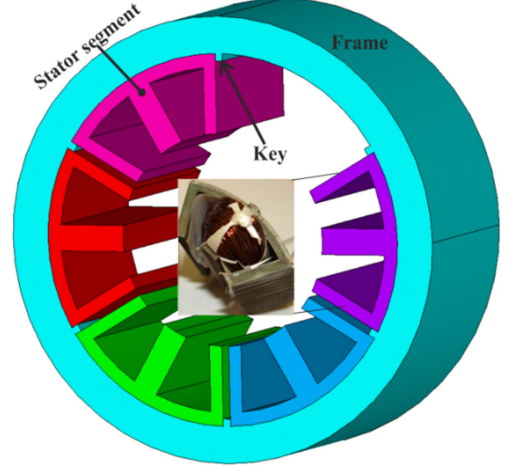


Fig. 2 3D view of modular stator with segments inserted into the frame. One segment is removed to highlight the keys on the inner surface of the frame.

Due to the presence of FGs, the main flux path within the stator magnetic circuit of the modular machine has been significantly modified compared to the ET or UNET machines, as shown in Fig. 3. This will lead to change in the airgap flux density as well as the radial magnetic force and magnetic pressure on stator segments. In addition, because the mechanical integrity of the modular stator has been destroyed, and each stator segment is largely independent of each other. These changes in electromagnetic and also mechanical performances will lead to profound change in the vibratory behavior and emitted acoustic noise, which will be investigated in-depth in the following sections.

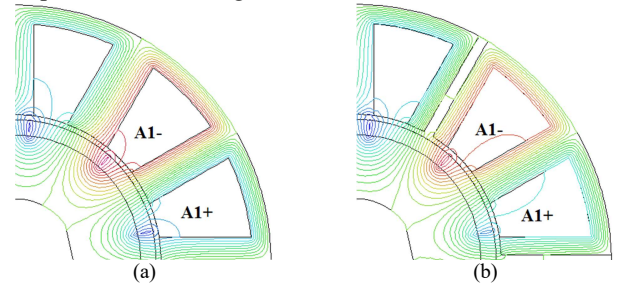


Fig. 3 Flux line distributions of investigated SPM machines, where the rotor position is for the phase A1 to have its maximum flux linkage. (a) UNET, (b) Modular. ET has similar flux line distribution as the UNET one.

III. COMPARATIVE STUDIES BETWEEN ET, UNET AND MODULAR SPM MACHINES

A. Radial Force and Magnetic Pressure in the Airgap

As the main source of vibrations and acoustic noise in electrical machines, the radial force (F_r) on each stator tooth

can be calculated based on Maxwell Stress tensor by using (1). By way of example, the stator teeth of the modular machine [see Fig. 4] have been chosen for demonstrating how the radial force has been calculated in this section.

$$F_r = \frac{R_{ag} \times L}{2\mu_0} \int_0^\tau (B_r^2 - B_t^2) d\theta \quad (1)$$

where R_{ag} is airgap radius, L is the stack length, μ_0 is the permeability of free space, τ is the span angle in the airgap, e.g. equal to one slot-pitch for teeth numbered A, B and C in Fig. 4. B_r and B_t are the radial and tangential components of airgap flux densities, respectively.

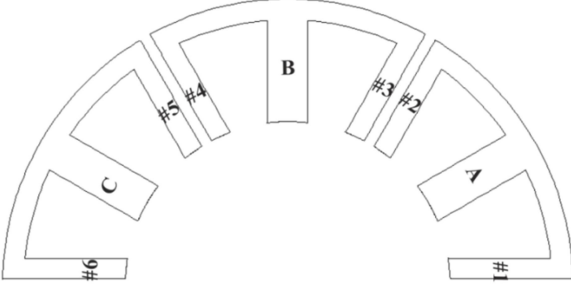


Fig. 4 Stator tooth numbers for radial force calculation.

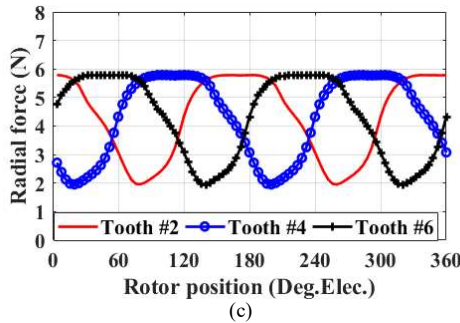
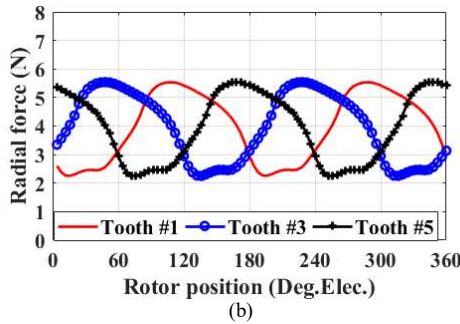
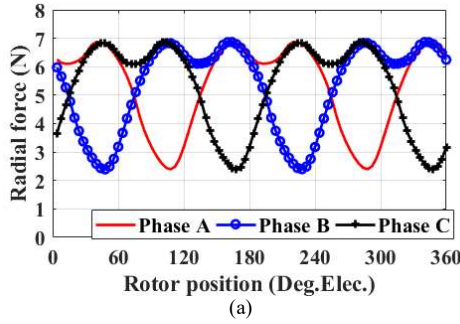


Fig. 5 Radial force on stator teeth of modular SPM supplied with 3-phase sinewave current, with a phase RMS current of 5A. The FG width is 2mm. (a) main teeth of phases A, B and C, (b) teeth #1, #3 and #5, (c) teeth #2, #4 and #6.

The stator teeth have been separated into 3 groups, i.e. group 1: main phase teeth A, B and C; teeth with FGs, group 2: #1, #3 and #5; and group 3: #2, #4 and #6. For a FG width of 2mm and a phase root-mean-square (RMS) current of 5A, the radial forces exerting on each tooth of the above 3 groups have been calculated using 2D FE software (ANSYS), as shown in Fig. 5. It is apparent that in each group, the 3 radial forces will have exactly the same amplitude but with a phase shift angle of 120 degrees due to the location of teeth in space.

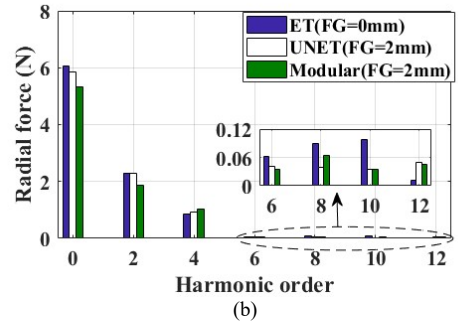
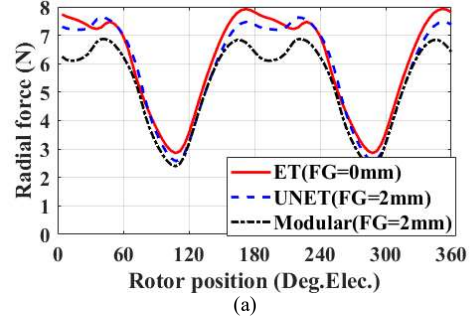


Fig. 6 Comparison between ET, UNET and modular SPM machines, in terms of radial force on one tooth of phase A. The phase current is 5Arms and the rotor speed is 2880 RPM. (a) waveforms, (b) spectra.

A comparison of radial force exerting on stator teeth has also been carried out between the ET, UNET (FG=2mm) and modular (FG=2mm) SPM machines. By way of example, only the results for tooth A have been selected and shown in Fig. 6. It can be seen that the DC component of radial force is generally reduced for UNET and modular SPM machines. However, this DC force component does not really contribute to vibrations and acoustic noise if the machine is balanced (no mode 0 vibration), which depend more on the variation in radial force. The 2nd order harmonic (dominant force component) however will contribute to vibrations and also acoustic noise and reduces in the modular machine. It is worth noting that the amplitude of stator deformation, caused by the magnetic force waves, is inversely proportional to v^4 , where v is the force harmonic order [11]. This reduction in 2nd order force harmonic could lead to significantly reduced vibrations and acoustic noise, depending on the rotor speed and also natural frequency of each vibration mode of the modular stator. The same phenomena can be observed for the 6th, 8th and 10th harmonics. However, the 4th and 12th order force harmonics can be increased if the UNET or modular machines are adopted. It is therefore important to design the modular machine carefully to avoid exciting the vibration modes which have the same natural frequencies as the relevant harmonic forces. For example, the modular machine should not be used in medium speed range because the 4th order force harmonic (higher than ET and UNET machine) could

reach the natural frequency of mode 2 (dominant vibration mode of investigated machines), therefore, leading to higher vibrations and acoustic noise level than the ET and UNET machines. However, low or high speed ranges, the vibrations and acoustic noise level could be lower, as will be investigated in section III.D.

To be complete, the radial magnetic pressure (p_r in MPa) in the airgap has also been calculated and compared between the ET, UNET and modular SPM machines. Since the stator iron core has much higher relative permeability (>1000), the flux entering the stator teeth from the airgap is assumed to be perpendicular to the tooth surface. In this case, it is generally safe to assume that the radial magnetic pressure only depends on the radial component of the airgap flux density, and can be calculated by

$$p_r = \frac{B_r^2}{2\mu_0} \quad (2)$$

As shown in Fig. 7, it is found that UNET and ET have similar maximum radial magnetic pressure in the airgap, but both are slightly higher than that of the modular machine. This means that the modular machine can potentially achieve lower vibrations and acoustic noise level. But again, this depends on the operation conditions such as rotor speed, phase current, etc. as will be investigated in the following sections.

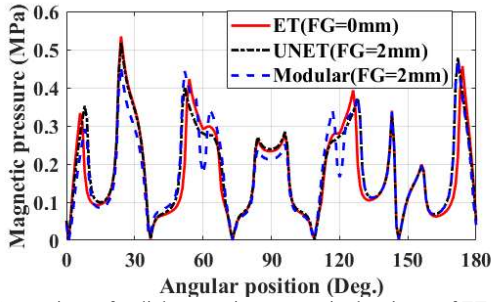


Fig. 7 Comparison of radial magnetic pressure in the airgap of ET, UNET and modular SPM machines supplied with 3-phase sinewave current, with a phase RMS current of 5A. The FG width is 2mm.

B. Modal Analyses

As mentioned previously, the change in stator structure, for example, using UNET or modular stator, may have significant impact on machine vibratory behaviors. This can be directly reflected in the change in vibration modes (shapes and also resonant frequencies), and will be investigated in this section. The modal analysis of machine stators has been carried out using 3D FEM. For simplicity, the stator windings have not been considered. The properties of materials such as stator core (FeSi) and frame (stainless steel) for the simulations are given in TABLE 2.

TABLE 2 MECHANICAL PROPERTIES OF MATERIALS

Material type	Density (kg/m ³)	Young's Modulus (GPa)	Poisson's ratio
Stator - FeSi	7700	200	0.3
Frame - Stainless steel	7870	200	0.27

The shapes and resonant frequencies of the main vibration modes are shown in Fig. 8 and TABLE 3, respectively. It is worth mentioning that for machines such as ET and UNET, the cases without considering the frame have also been

investigated. However, due to space limitation, the results have not been shown in this paper. It is found that with the frame, the stator "yoke" (real yoke + frame) becomes more robust. Therefore, the resonant frequency is increased, and the increase depends directly on the materials used for the frame and also its thickness [12]. A tight friction coupling between the laminations and frame is assumed [12], this can be considered in the FE model by gluing the stator yoke to the frame. For the modular machine, the frame is necessary to fix the stator segments as shown in Fig. 2.

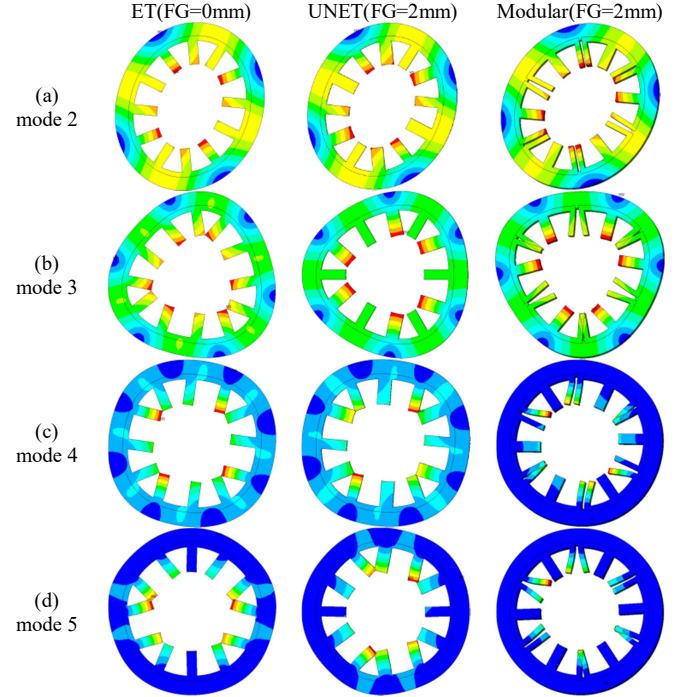


Fig. 8 Different modes of vibrations for the ET, UNET and modular SPM machines. The FG width of 2mm is chosen as example.

TABLE 3 MODE NUMBERS AND CORRESPONDING NATURAL FREQUENCIES (Hz) OF DIFFERENT SPM MACHINES

	ET (0mm)	UNET (2mm)	UNET (4mm)	Modular (2mm)	Modular (4mm)
Mode 2a	2674.7	2636.1	2608.4	2544.1	2517.4
Mode 2b	2676.8	2638.3	2609.9	2544.5	2518.4
Mode 3a	6737.1	6562.7	6402.0	6160.3	6044.3
Mode 3b	6737.8	6699.0	6700.7	6408.0	6429.0
Mode 4a	10576	10515	10445	8754.2	8761.3
Mode 4b	10587	10528	10449	8761.3	8762.2
Mode 5a	12529	12674	12695	9209.3	9264.6
Mode 5b	12532	12703	12721	9222.1	9271.9

*: 0mm, 2mm and 4mm in the table is for FG width.

From the results shown in TABLE 3, it is found that there are two natural frequencies for each vibration mode, but their difference is very small, and can be negligible. It is also apparent that using the UNET or modular stator structure, the resonant frequency for each vibration mode tends to be reduced. This is particularly the case for the modular machines, meaning that it might be easier to reach a given vibration mode for UNET or modular machines compared to the ET machine. Similar to other types of machines, it can be difficult to excite certain vibration modes. For example, the mode 3 or 5 would imply that there was an unbalance in the electromagnetic force, resulting, for example, from eccentricity due to rotor unbalance

and/or a non-uniform airgap [13]. Other higher mode numbers, e.g. mode 4 or 6, require higher fundamental frequency (or higher rotor speed) in order to be excited. Therefore, this paper will focus mainly on the influence of mode 2, which is also the most predominant mode shape in terms of vibrations and acoustic noise.

C. Radial Displacement and Vibrations

Using modular machines as example, the radial displacement and radial acceleration for different FG widths have been calculated by using 3D FEM, as shown in Fig. 9 and Fig. 10. It is assumed that an accelerometer is put at the back of the stator pole (corresponding to the tooth of phase A in Fig. 4) to measure the radial acceleration of the stator (and frame). The peaks appear at the frequency of around 2.5 kHz in the radial displacement and acceleration are corresponding to the resonant frequency of the mode 2. These peaks will determine the level of acoustic noise as will be investigated in section III.D. It is interesting to notice that if the FG width is properly selected, for example, FG = 2mm, both the radial displacement and also acceleration can be significantly reduced, leading to a potential reduction in acoustic noise as well. This is partially due to the reduction in radial force, particularly the 2nd order harmonic, as shown in Fig. 6, and also due to the change in stator mechanical structure.

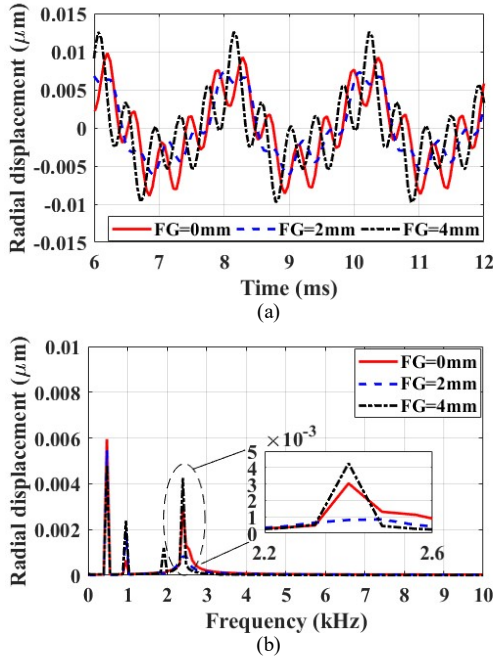


Fig. 9 Radial displacement of modular SPM machine supplied with 3-phase current. The fundamental current is 5Arms and the rotor speed is 2880 RPM. (a) waveforms, (b) spectra.

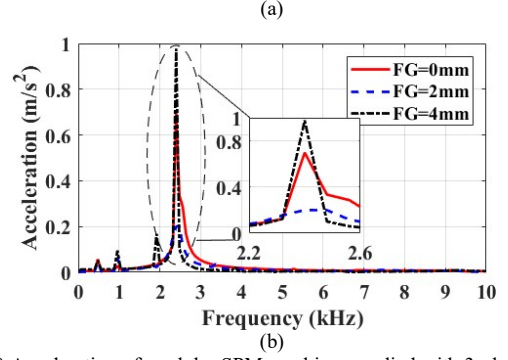
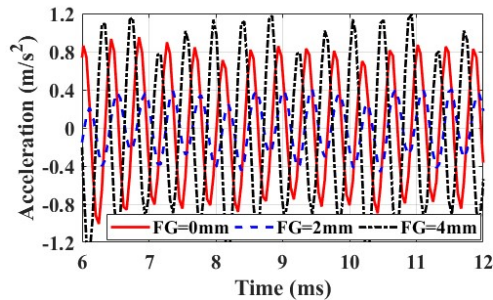


Fig. 10 Acceleration of modular SPM machine supplied with 3-phase current. The fundamental current is 5Arms and the rotor speed is 2880 RPM. (a) waveforms, (b) spectra.

A comparison in terms of radial displacement and acceleration between the ET, UNET and modular SPM machines with a FG width of 2mm has also been carried out, as shown in Fig. 11 and Fig. 12. It is apparent that both the UNET and modular stators can be effective in reducing the radial displacement and also acceleration (or vibration) provided that an appropriate FG width is selected.

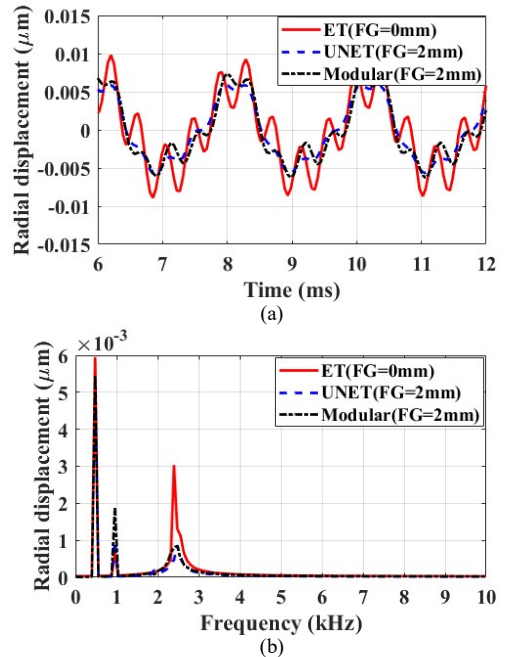
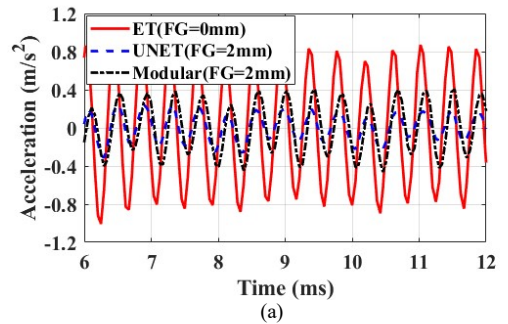


Fig. 11 Comparison between ET, UNET, and modular SPM machines, in terms of radial displacement. The fundamental current is 5Arms and the rotor speed is 2880 RPM. (a) waveforms, (b) spectra.



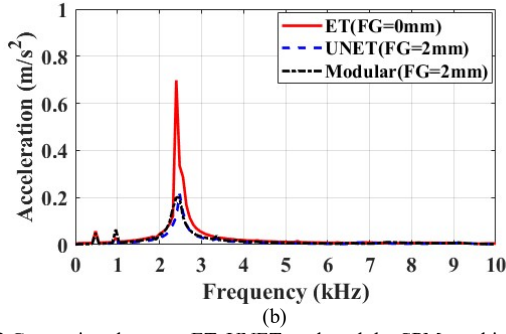


Fig. 12 Comparison between ET, UNET, and modular SPM machines, in terms of acceleration. The fundamental current is 5 Arms and the rotor speed is 2880 RPM. (a) waveforms, (b) spectra.

D. Sound Pressure and Sound Pressure Level

The sound pressure (SP in Pa) is also calculated using FEM by solving the following acoustic wave equation [8]:

$$\frac{1}{c^2} \frac{\partial^2 SP}{\partial t^2} - \nabla^2 SP = 0 \quad (3)$$

where c is the sound speed in air (344m/s).

In the FE model, it is assumed that a microphone is located at a certain distance (much larger than the stator outer radius for higher accuracy), 300mm in this paper, from machine center for measuring the sound pressure and the boundary of the air is regarded as a complete absorbing boundary. This means that a relatively large air region is needed for acoustic field analyses. In this case, to reduce the computation time for considering a large range of rotor speeds (or fundamental frequencies), a 2D model is used instead of 3D models used in previous sections. Since the machines investigated in this paper are all symmetrical ones, the results from 2D model can be deemed as satisfactory.

For a given speed, e.g. 2880 RPM (240Hz), the sound pressures for the ET, UNET and modular machines with a FG = 2mm have been calculated and compared as shown in Fig. 13. It can be seen that due to the reduction in radial displacement and also vibration, both the UNET and modular machines can achieve much lower level of sound pressure compared to the ET machine. It is also found that the UNET and modular machines achieve similar level of sound pressure due to similar level of radial displacement and vibration, as shown in Fig. 11 and Fig. 12.

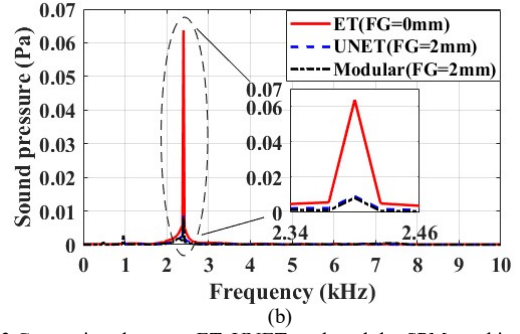
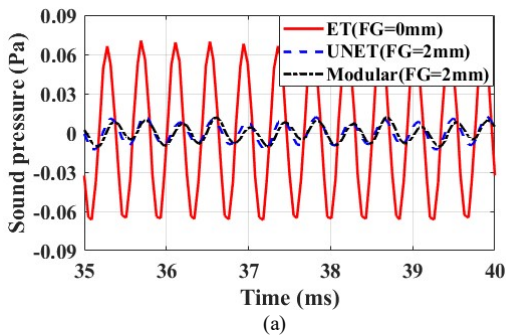


Fig. 13 Comparison between ET, UNET, and modular SPM machines, in terms of sound pressure at 300mm from machine centre (240mm from frame outer surface). The fundamental current is 5 Arms and the rotor speed is 2880 RPM (240Hz). (a) waveforms, (b) spectra.

For different rotor speeds or fundamental frequencies, a more commonly used parameter such as sound pressure level (SPL in dB) has been used for the analysis, which can be calculated by

$$SPL = 20 \log_{10} \left(\frac{SP}{SP_0} \right) \quad (4)$$

where SP_0 is the reference sound pressure (2×10^{-5} Pa). It is worth noting that the measured sound pressure in (4) will always use its RMS value.

A comparison between the ET, UNET and modular machines in terms of the total SPL for different fundamental frequencies are shown in Fig. 14 whilst different SPL harmonic components are shown in Fig. 15. It is worth mentioning that all the peaks in the SPL plot are mainly due to the excitation of the vibration mode 2. For example, at a fundamental frequency of around 1.25 kHz, the 2nd order force harmonic will generate the 2nd order SPL harmonic. And because it coincides with the resonant frequency of the mode 2 (≈ 2.5 kHz), a peak SPL will appear. However, the 4th order force harmonic will generate the 4th order SPL harmonic, and resonates with the mode 2 at a fundamental frequency of around 0.65 kHz.

Amongst all the investigated machines, it can be observed that at relatively low fundamental frequency (rotor speed) or higher frequency, the UNET and modular machines can reduce the SPL compared to the ET machine. This is particularly effective at lower fundamental frequency, e.g. 0.24 kHz, a significant reduction of about 15 dB in SPL can be observed between ET (67dB) and modular (52dB) SPM machines. The higher SPL emitted by the UNET and modular machines at medium frequency, e.g. 0.6 kHz, is mainly due to the higher level of 4th order SPL harmonic generated by the 4th order radial force harmonic. Therefore, in practical machines, the UNET or modular machines should avoid operating at this frequency in order to reduce the acoustic noise level.

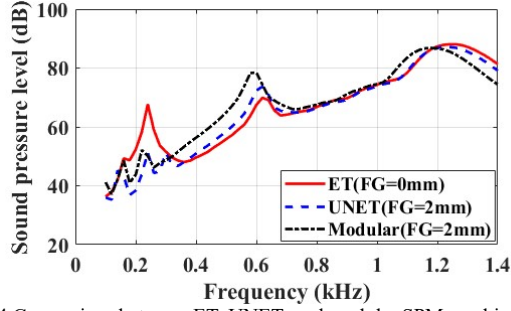


Fig. 14 Comparison between ET, UNET, and modular SPM machines, in terms SPL vs fundamental frequency of current at 300mm from machine center (240mm from frame outer surface). The fundamental current is 5Arms.

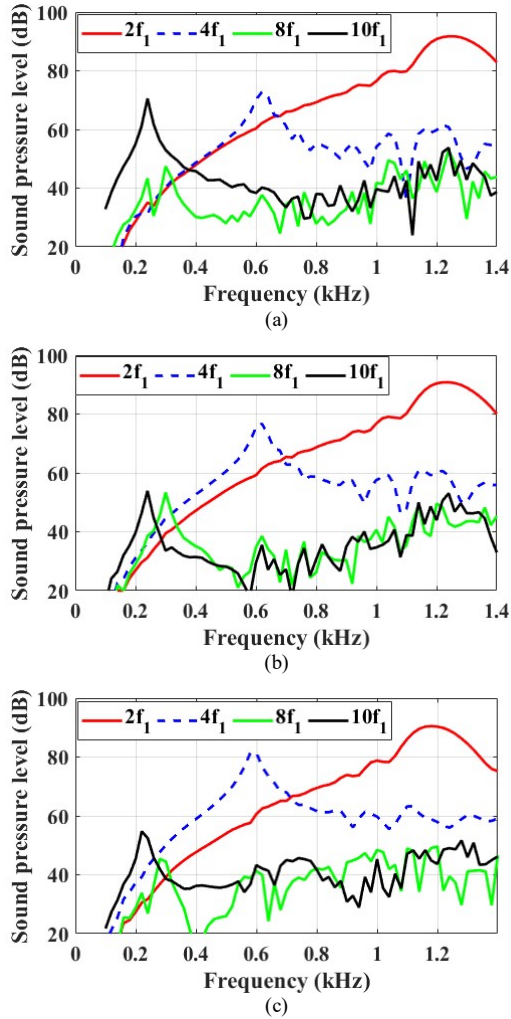


Fig. 15 SPL vs fundamental frequency of current for different dominant SPL harmonics for different SPM machines. The sound pressure is measured at 300mm from machine center (240mm from frame outer surface). The fundamental current is 5Arms and f_1 is the fundamental frequency. (a) ET (FG=0mm), (b) UNET (FG=2mm), (c) modular (FG=2mm).

IV. CONCLUSION

This paper investigates the vibratory behaviors of unequal tooth width (UNET) and modular surface mounted permanent magnet (SPM) machines. A comparison with their equal tooth width (ET) counterparts in terms of radial force, magnetic pressure, vibration modes, radial displacement, vibrations and also sound pressure level (SPL) has been carried out.

It is found that due to the change in stator structure, particularly for modular machines, the resonant frequency of each vibration mode is reduced compared to the ET machine. However, due to the reduced radial force (and magnetic pressure in the airgap), the modular and UNET machines can still achieve reduced radial displacement, vibrations and also SPL. For example, at a fundamental frequency of 0.24 kHz (equivalent to a rotor speed of 3.28×10^3 rpm), the SPL of the modular machine can be reduced by 15 dB compared to that of the ET machine.

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