The Influence of the Load Condition upon the Radial Distribution of Electromagnetic Vibration and Noise in a Three-Phase Squirrel-Cage Induction Motor

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ABSTRACT

The reduction of electromagnetic vibration and noise in three-phase squirrel-cage induction motors (IMs) has become very important from an environmental standpoint. However, the relationship between the radial distribution of the electromagnetic vibration and noise and the force wave that causes them has yet to be analyzed in sufficient detail. In this paper, we present the results of several experimental trials and show the analysis of an IM under various load conditions to study the causes of the vibration and noise components by examining of their radial distributions.

Keywords: Electromagnetic vibration, Electromagnetic noise, Radial distribution, Harmonic flux, Slot combination

1. INTRODUCTION

In recent years, enhanced environmental considerations have led to an increased demand for low-noise induction motors (IMs). Although the basic theory of IMs has been clarified in numerous studies [1], the relationship between the radial distribution of electromagnetic vibration and noise and the force wave that causes them has yet to be analyzed in sufficient detail.

In this study, we experimentally examine the radial distributions of electromagnetic vibration and noise in an IM under various load conditions. Because the occurrence frequency (f_v) of the vibration and noise components changes according to the load condition, the mechanical resonance effects on these components also changes. Therefore, to eliminate the mechanical resonance effects, f_v can be held constant as the load condition varies by adjusting the frequency and amplitude, (f and V, respectively) of the source voltage used to maintain the gap flux [2].

In this paper, we first discuss the occurrence frequencies and modes associated with various types of dominant electromagnetic forces generated by the interaction of harmonic fluxes within the IM gap. We then describe our experimental methods, and finally, we show that the radial distributions of the dominant electromagnetic vibration and noise components in an IM under load conditions match the mode shapes of the corresponding dominant electromagnetic forces on the basis of the results of several trials.

2. DOMINANT ELECTROMAGNETIC FORCES

Figure 1 shows a summary of the causes of electromagnetic vibration and noise in an IM. The electromagnetic noise is caused by electromagnetic vibration, which in turn is caused by the electromagnetic force. The electromagnetic force is generated by the interaction among the air-gap fluxes in an IM toward the radial direction. This flux is expressed as the product of the magnetomotive force and air-gap permeance whose main component is the slot permeance. Furthermore, Figure 1 shows that many harmonic components affect the electromagnetic vibration and noise. The electromagnetic noise is also affected by the mechanical resonance of the IM. Therefore, clarifying the complex relationship among the electromagnetic vibration, noise,

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electromagnetic radial force, and mechanical resonance is important to design an IM with lesser vibration and noise.

The general equations for the primary causative electromagnetic forces of the dominant electromagnetic vibration and noise components in an IM were derived in [2]. Table I lists the summary of the occurrence frequencies f_M (Hz) and modes M for three dominant electromagnetic force types in an IM driven by a sinusoidal power supply. Where, n_s and n are the number of stator and rotor slots, p' is the pole pair, s is the slip, and L and K are integers that indicate the orders of the stator and rotor slot permeance, respectively. For convenience, each dominant electromagnetic force is allocated a classification number. This table also lists two types of electromagnetic Forces -[I] and [II]- that are produced depending on the load conditions. Force [I] results from the interaction between the stator fundamental flux and the rotor harmonic flux at no-load, whereas Force [II] is produced by the interaction between these two fluxes under loaded conditions. Table I clearly shows that f_M is proportional to f; therefore, f_M can be maintained as constant by adjusting f to avoid the effects of the IM mechanical resonance.

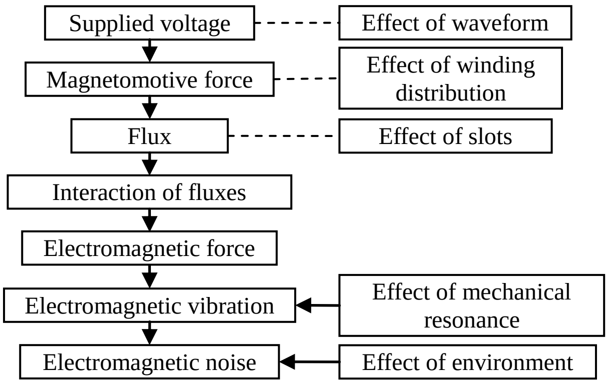

Fig. 1. Causes of electromagnetic noise.

Table I.
Occurrence frequencies and modes of
various dominant electromagnetic forces.

No.	Frequency: f_M	Mode: M
①	$\lvert(1-s)Kn/p'-2\rvert f$	[I] $\lvert(p')+(p'+Ln_s-Kn)\rvert$ [II] $\lvert(p'+Ln_s-Kn)+(p')\rvert$
②	$\lvert(1-s)Kn/p'\rvert f$	[I] $\lvert(p')-(p'\pm Ln_s\mp Kn)\rvert$ [II] $\lvert(p'\pm Ln_s\mp Kn)-(p')\rvert$
③	$\lvert(1-s)Kn/p'+2\rvert f$	[I] $\lvert(p')+(p'-Ln_s+Kn)\rvert$ [II] $\lvert(p'-Ln_s+Kn)+(p')\rvert$

3. TEST MOTOR AND MEASUREMENT

Table II lists the specifications of the test motor used in this study. The four-pole motor is rated at 200 V/60 Hz, has a power output of 1.5 kW, and has 36 and 33 stator and rotor slots, respectively. Although this slot combination is not commercially used, it is employed in the test motor because it produces appropriate dominant electromagnetic vibration and noise components. The natural frequencies were measured using an impact hammer, and we confirmed that they remain approximately constant even if the rotors were exchanged.

Figure 2 shows the arrangement of the experimental apparatus, and Figure 3 shows a photograph of the motor noise laboratory. To minimize the external vibration effects, the test motor was set on a damper rubber. A room with special acoustic properties was constructed to keep the reflected sound and background noise below 40 dB. To avoid abnormal starting phenomena and to allow control of the supplied frequency f, a sine-wave variable-frequency supply was used. Two acceleration pickups -one movable and other fixed to the top of the IM- were used to detect radial vibrations and to feed the resulting signals via charge amplifiers into a fast Fourier transform (FFT) analyzer.

Movable and fixed microphones mounted at the upper center position of the IM stator were used to detect the electromagnetic noise, and the sound pressure levels (in decibels) were measured by the FFT analyzer through sound level meters. To estimate the electromagnetic noise in more details, the distance between the center of the test motor and each microphone was fixed at 0.5 m, which was shorter than the distance stipulated in Japanese Industrial Standards (JIS) C 4210 [3]. Measurements of the vibration and noise were performed both at no-load and rated-load conditions. When the load condition changed, the electromagnetic vibration and noise occurrence frequency f_v were altered by varying the slip. As a result, the mechanical resonance effect on the electromagnetic vibration and noise changed. The vibration and noise components were measured under ten conditions: at a constant supply voltage of 200 V/60 Hz and at a condition where f_v was kept constant by adjusting the supplied voltage while the ratio of the voltage to the frequency was maintained at 200 V:60 Hz.

Table II. Specification of the test motor.

Rated output	1.5 kW	Number of poles: $2p'$	4
Rated voltage	200 V	Rated frequency	60 Hz
Number of stator slots: n_s	36	Number of rotor slots: n	33
Skew of rotor slot	No skew	Main natural frequencies	625, 990, 1110, 1980, 2100, and 3090 Hz

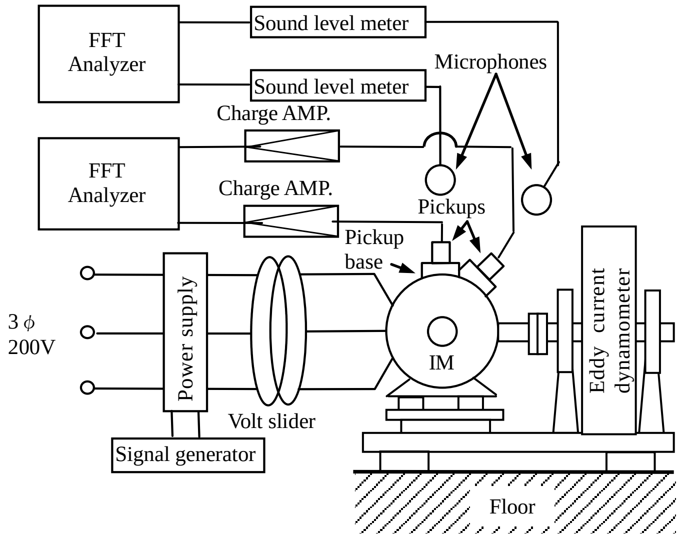

Fig. 2. Arrangement of the experimental apparatus.

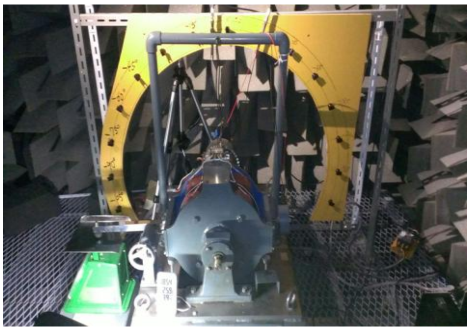

Fig. 3. Motor noise laboratory.

4. EXPERIMENTAL RESULT

Figure 4 shows the dominant electromagnetic vibration and noise of the test motor under various load conditions. When the load condition is changed, no change was observed in the occurrence frequencies of the dominant components. However, the acceleration level of the vibration and the sound pressure level of the noise changed. We also confirmed that the frequency of the dominant electromagnetic noise component was the same as that of the dominant electromagnetic vibration component. The three components shown in Figure 4 were assessed to determine their respective causes (from Table I). The results listed in Table III.

The occurrence frequencies of the 990, 1980, and 2970 Hz vibration components were caused by the electromagnetic force waves of modes M = 3, 6, and 9, respectively.

Figure 5 shows the time-continuous graphs of the radial distributions of the vibration and noise components where the occurrence frequency is kept constant at f_v = 990 Hz by adjusting the supplied voltage at 0 % load condition. Figure 6 shows the radial distributions when the dominant electromagnetic vibration is kept constant at 990 Hz by adjusting the supplied voltage under 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 % load conditions.

The distribution of the 990 Hz component appears to have M = 3 at no-load [1]. However, we found that the mode changed from 40 % of the load factor from this measurement even though the force was at Mode 3 at this frequency. Existing theory suggests that a double-mode distribution such as this would result when strong mechanical resonance effects occur; our results confirmed this effect.

Table III. Dominant electromagnetic vibration and noise components.

f_v constant under various load conditions (Hz)	No.	M	K	L
990	②	3	1	1
1980	②	6	2	2
2970	②	9	3	3

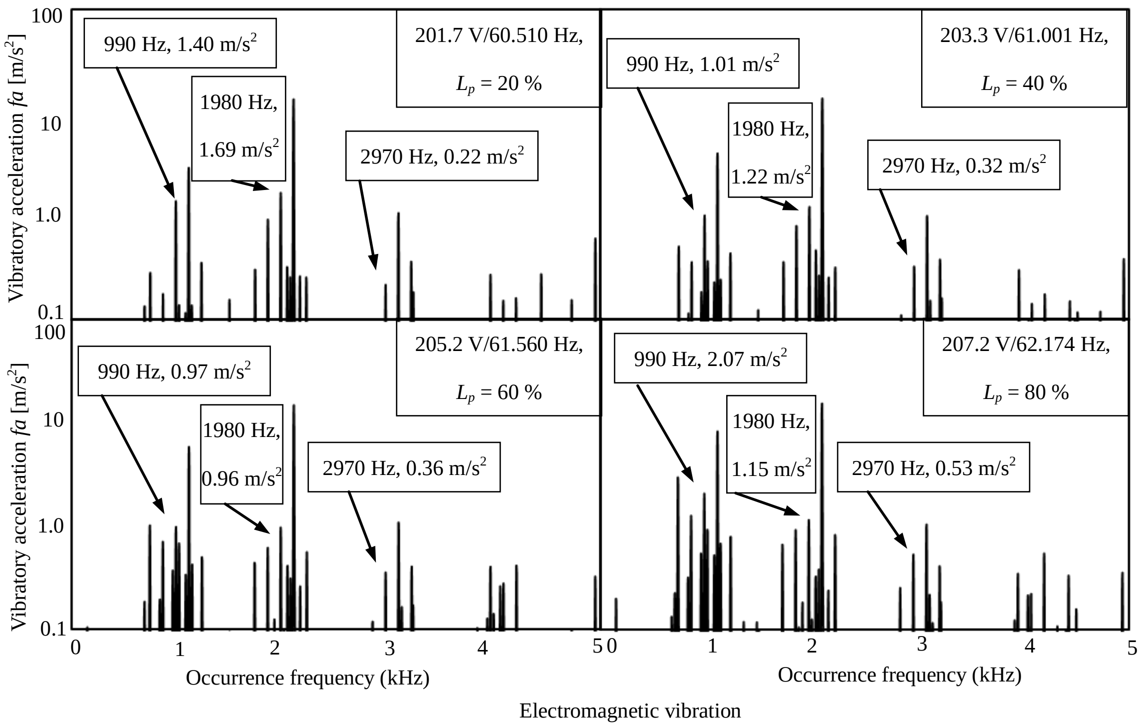

Fig. 4. Dominant electromagnetic vibration at 0°

Therefore, the distributions of the dominant electromagnetic vibration have the same mode structure as that of the electromagnetic force in some cases, as listed in Table III.

5. CONCLUSIONS

In this study, an IM under various load conditions was analyzed to determine the causes of the vibration and noise components by examining their radial distributions. The radial distributions of these components were quantitatively analyzed in detail over a variety of driving frequencies and load conditions. We believe that the results of this study will be useful in developing vibration and noise reduction methods for IMs.

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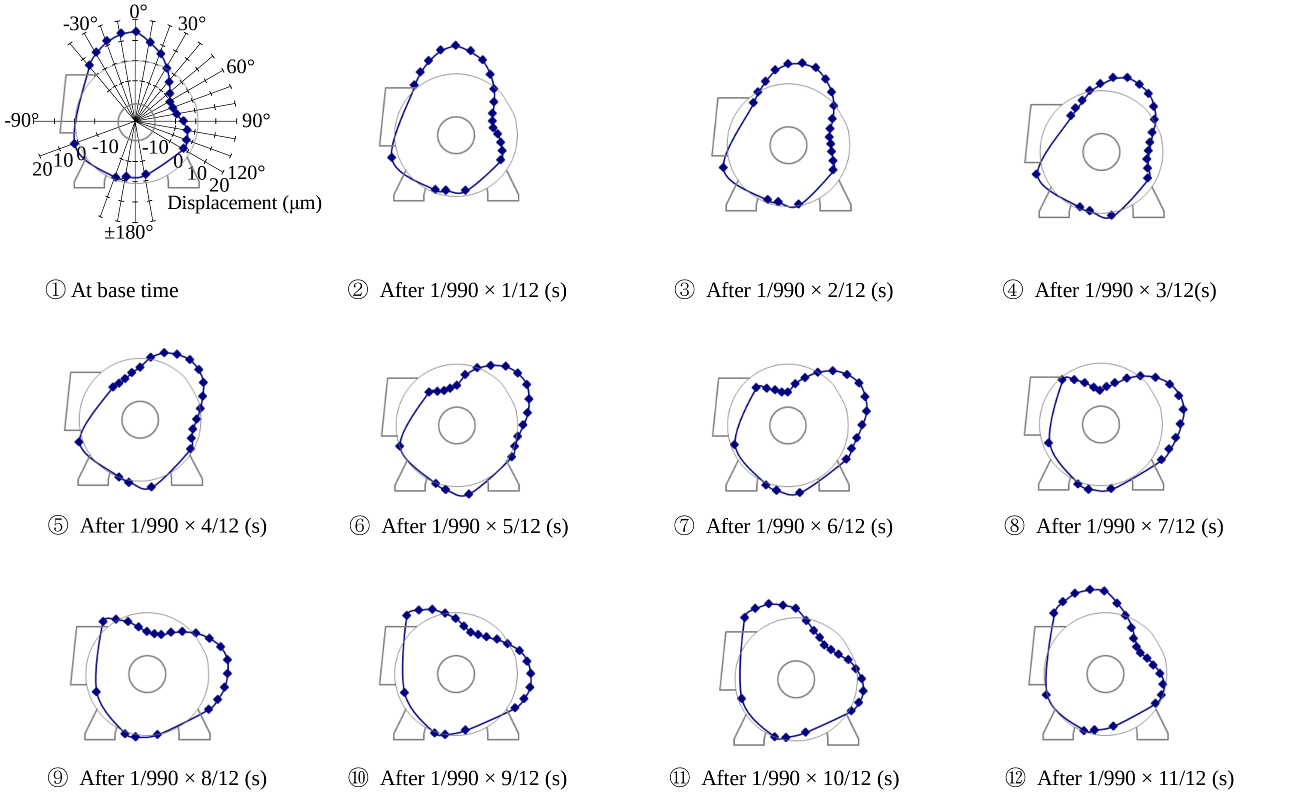
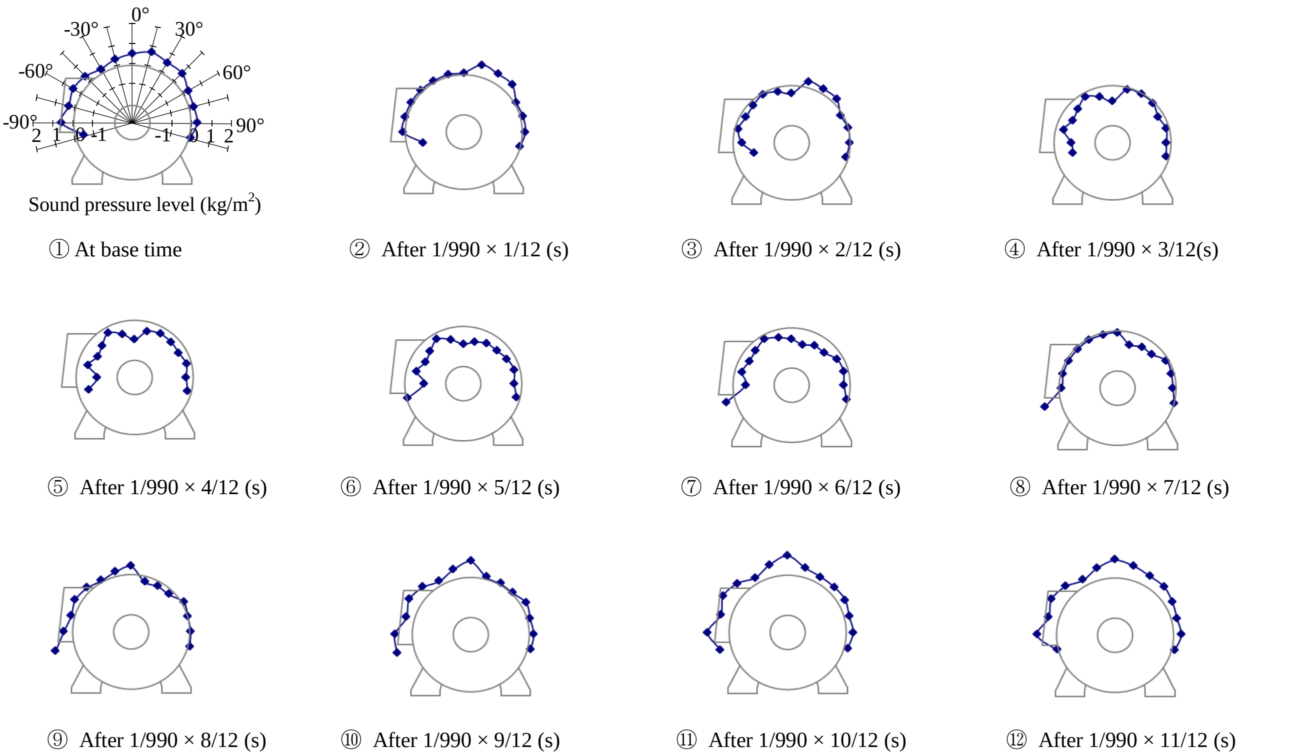


(a) Electromagnetic vibration.



(b) Electromagnetic noise.

Fig. 5. Radial distribution when the 990 Hz component is kept constant by adjusting the supplied voltage at 0 %.

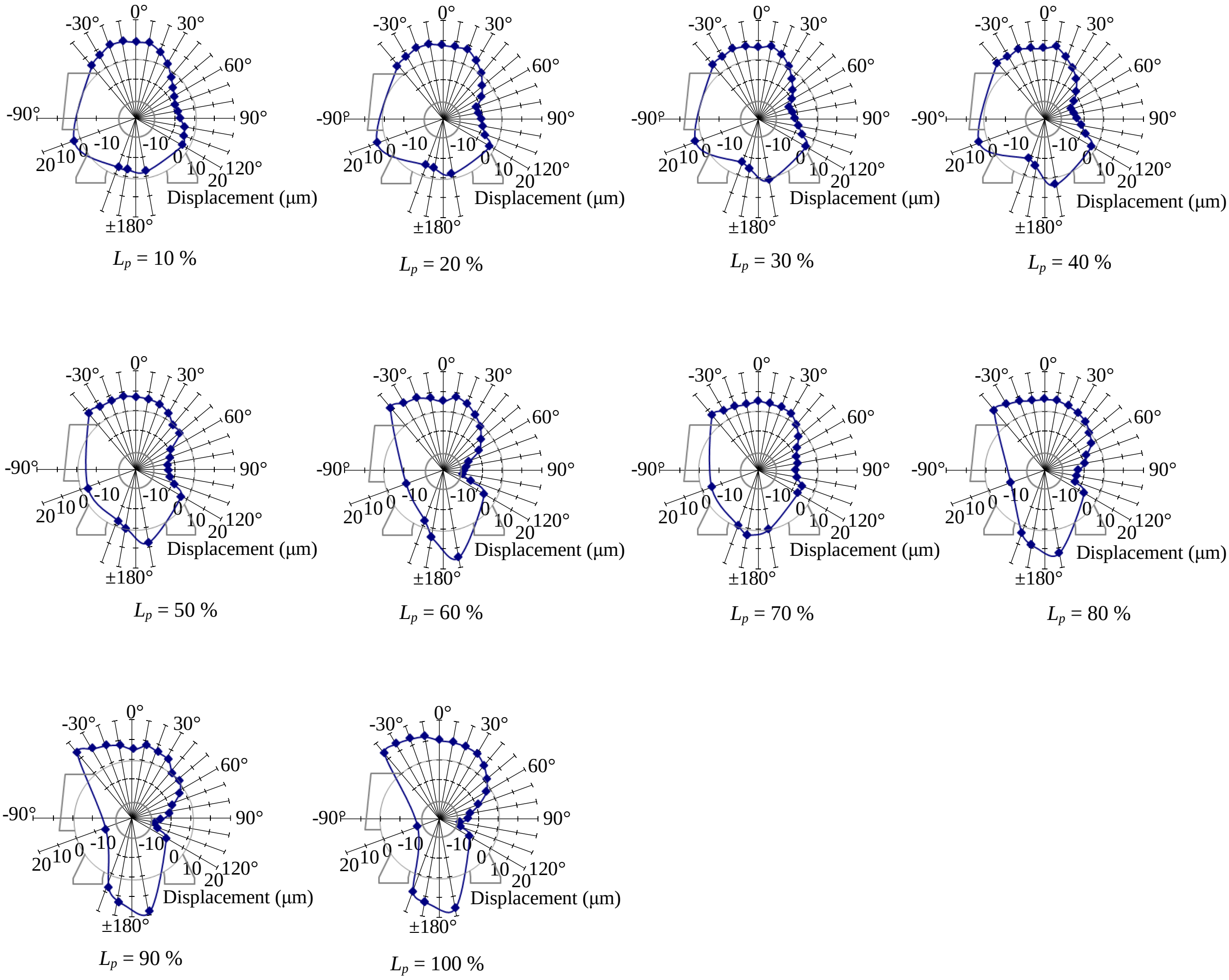


Fig. 6. Radial distribution when the 990 Hz component is kept constant

by adjusting the supplied voltage under 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 %.