

Hybrid Random Carrier-Based Noise Suppression for Automotive Electronic Water Pumps: Theoretical and Experimental Study

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1. Introduction

As a core component of the automotive thermal management system, the performance of the automotive electronic water pump (AEPW) directly impacts the cooling efficiency and reliability of the entire vehicle. The Permanent Magnet Synchronous Motor (PMSM) is widely employed in the drive unit of electronic water pumps owing to its high efficiency, compact size, and superior control performance. However, the problem of electromagnetic noise (EN) has grown increasingly prominent. Specifically, when variable frequency speed regulation is adopted, Pulse Width Modulation (PWM) operates at a high switching frequency, giving rise to high-frequency EN. This type of noise is sharp, harsh, and highly penetrative, which not only undermines driving comfort but also may deteriorate the motor's performance and shorten its service life [1-2]. Consequently, investigating effective EN suppression strategies is of great significance for enhancing the overall performance of automotive electronic water pumps.

Harmonic noise refers to motor vibration and noise caused by high-frequency components generated during PWM modulation. To suppress such harmonic noise, a variety of electromagnetic noise suppression methods can be utilized, including optimizing motor design [3-4], adjusting the frequency and amplitude of the injected signal [5-6], and optimizing magnetic circuit design [7-8]. All these methods aim to reduce the high-frequency components generated during PWM modulation, thereby mitigating the occurrence of electromagnetic noise. PWM modulation technology has emerged as a research hotspot in suppressing electromagnetic noise in permanent magnet synchronous motors due to its high energy conversion efficiency, excellent speed regulation performance, reduced electromagnetic interference, elimination of the need for motor structure modification, and ease of implementation.

Random PWM and periodic PWM are the two primary modulation strategies. The key advantage of random PWM technology [9-10] lies in its ability to uniformly distribute high-order harmonics, thereby effectively reducing motor electromagnetic noise; however, it suffers from poor stability. Zhang et al. [11] evaluated the voltage, current, and acoustic noise characteristics of five random switching frequency strategies [12-15] through theoretical power spectrum analysis. They verified the noise reduction effect of random pulse width modulation (RPWM) on servo motor drive systems, while comprehensively considering costs and feasibility, which holds certain reference value for noise reduction in permanent magnet synchronous motors. Xu et al. [16] described the electromagnetic vibration frequency and

investigated the influence of PWM voltage harmonic modulation depth and DC voltage fluctuations on harmonic content, yet they did not explore the impact caused by vibration. Periodic carrier frequency PWM (PCFPWM) can stably suppress high-frequency harmonics [17-18], but its drawback is that the suppression effect is insignificant. Ji et al. [19] proposed an innovative method to determine the optimal period for reducing current harmonics using a genetic algorithm. The optimized PCFPWM reduced the total vibration level; however, this method may require long calculation time and involves high computational complexity.

Space Vector Pulse Width Modulation (SVPWM) technology [20-22] has been widely adopted due to its remarkable effectiveness in harmonic suppression; however, it still has limitations. Specifically, it tends to result in large harmonic amplitudes around integer multiples of the carrier frequency in the stator current [23]. Song et al. [24] introduced an advanced hybrid SVPWM technique designed for medium-voltage drives, which employs multiple active vector time-varying sequences. The proposed method outperforms other approaches within specific intervals but exhibits insignificant suppression effects in other intervals. Wang et al. [25] proposed a random asymmetric SVPWM method based on Markov chains, which alters the switching state by adjusting the vector sequence to modify harmonic coefficients. This method is straightforward and innovative, yet it fails to consider the impact of different modulation coefficients. A hybrid strategy based on the SVPWM strategy has been proposed. Das focused on investigating a novel PWM technology--Random Space Vector Pulse Width Modulation (RSVPWM)--to reduce noise in induction motors (IMs) powered by two-level three-phase voltage source inverters (VSIs). This technology integrates Random Pulse Width Modulation (RPWM) and Space Vector Modulation (SVM) technologies, achieving noise reduction by creating gaps in the line voltage spectrum at selected frequencies within the human audible range, with excellent performance. Deng et al. proposed a new strategy based on random pulse position modulation to eliminate current harmonics and electromagnetic noise at specific frequencies. This strategy utilizes a constant switching frequency and eliminates current harmonics and noise at the selected frequency by uniquely designing the pulse position and duty cycle. Experimental results demonstrate that this method not only reduces electromagnetic noise but also avoids potential motor resonance issues. Although these hybrid strategies enhance the stability of random strategies, they increase algorithmic complexity.

Building on the SVPWM strategy, this paper integrates the advantages of random carrier technology and pe-

riodic modulation technology, and proposes a Hybrid Random Carrier Space Vector Pulse Width Modulation (HRCSVPWM) technology. This technology aims to effectively disperse high-order harmonics while reducing the computational complexity of the motor control system. Finally, simulation verification and experimental validation were conducted, with noise and vibration experiments performed specifically for the proposed HRCSVPWM technology.

In summary, unlike conventional random PWM strategies that suffer from poor stability due to uncontrolled frequency variation, and unlike existing hybrid SVPWM approaches [20-22] that primarily focus on either harmonic spreading or spectral flatness in isolation, the proposed HRCSVPWM uniquely combines a Xorshift-based random carrier with a sawtooth wave spread-spectrum modulation function. This integration provides both the harmonic dis-

person advantage of random carrier strategies and the frequency-spread stability of periodic modulation, without requiring additional hardware modifications to the existing AEWP control system.

2. Correlation Analysis Between Electromagnetic Noise and Harmonics

The extreme operating environment of electronic water pumps makes sensors prone to damage. To enhance reliability and reduce costs, sensorless control technology is adopted. Sensorless control primarily achieves precise rotor control by generating a circular magnetic field, thereby ensuring smoother operation of the pump motor. As illustrated in Fig. 1, a typical vector control system comprises several components, including speed loop feedback, current loop feedback, and an SVPWM control block, to realize precise control of the automotive electronic water pump (AEWP).

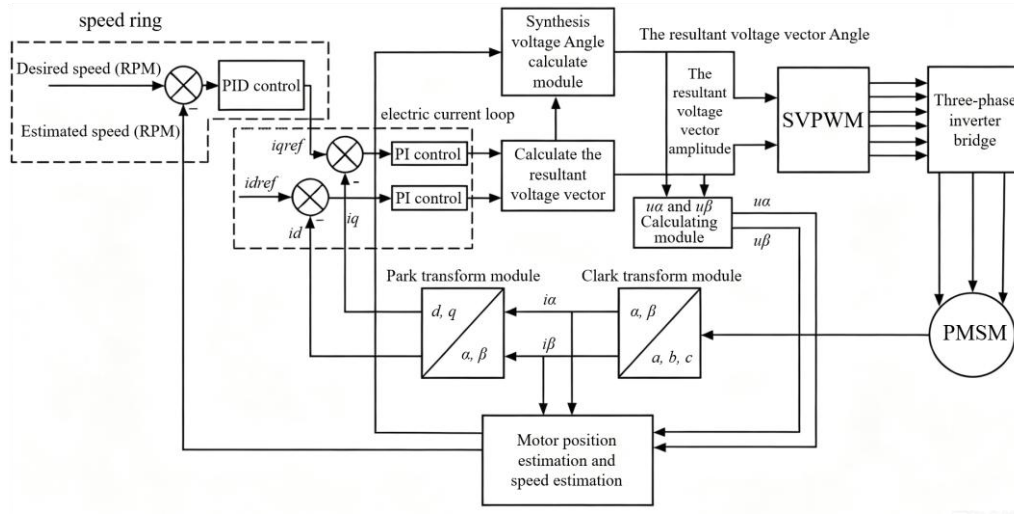


Fig. 1 Block diagram of the vector control system

$$U_{ao}(\theta) = \begin{cases} \frac{1}{2}MU_{dc} \cos \theta & \left(-\frac{\pi}{6} \leq \theta \leq \frac{\pi}{6}, \frac{5\pi}{6} \leq \theta \leq \pi, -\pi \leq \theta \leq -\frac{5\pi}{6} \right) \\ \frac{\sqrt{3}}{2}MU_{dc} \cos\left(\theta + \frac{\pi}{6}\right) & \left(\frac{\pi}{6} \leq \theta \leq \frac{\pi}{2}, -\frac{5\pi}{6} \leq \theta \leq -\frac{\pi}{2} \right) \\ \frac{1}{2}MU_{dc} \cos\left(\theta + \frac{\pi}{3}\right) & \left(\frac{\pi}{2} \leq \theta \leq \frac{5\pi}{6}, -\frac{\pi}{2} \leq \theta \leq -\frac{\pi}{6} \right) \end{cases} \quad (1)$$

PWM harmonics are consistently concentrated at the carrier frequency and its integer multiple frequencies. When the carrier frequency is denoted as f_c , clustered distributions of carrier harmonics and their sideband harmonics emerge around integer multiples such as $2f_c$ and $3f_c$. These constitute the primary components of PWM harmonics, and those appearing in the vicinity of such integer multiples are termed carrier frequency-multiple PWM harmonics.

The input voltage and current contain high-order harmonics, particularly at the carrier frequency and its integer multiples, which exert a significant influence on the generation of electromagnetic noise. The stator current can be expressed as follows:

$$i_h(t) = \sum_{h=1}^{\infty} I_h \cos(\omega_h t - \phi_h), \quad (2)$$

where, I_h is the peak of harmonic current; h is the harmonic order; ω_h is the angular frequency of the harmonic current.

The harmonic voltage components at carrier-frequency multiples drive corresponding high-order harmonic currents in the stator windings, as expressed in Eq. (2). These harmonic currents, in turn, generate additional magneto-motive force (MMF) components in the air gap, as formulated in Eq. (3). The interaction between these harmonic MMF components and the rotor permanent-magnet field produces radial electromagnetic force waves (Eq. (4)), whose frequency components coincide with the dominant PWM harmonic frequencies. These time-varying radial force waves are the primary excitation source of stator structural vibration, which subsequently radiates as electromagnetic noise. Therefore, reducing the amplitude of harmonic voltage components--particularly at carrier-frequency multiples--directly attenuates the radial electromagnetic force

peaks, thereby suppressing vibration and acoustic emission.

When high-order harmonic currents are injected into the stator windings, the air-gap magnetomotive force generated by the magnetic field of the stator windings can be expressed as:

$$f_2(\theta, t) = \sum_v f_v(\theta, t) + \sum_h f_h(\theta, t) = \sum_v F_v \cos(\omega_v t - v\theta - \phi) + \sum_h F_h \cos(\omega_h t - \phi_h). \quad (3)$$

When high-order harmonic currents are present in the input current, the expression for the air-gap synthetic magnetomotive force must account for the influence of high-order harmonic magnetomotive forces:

$$f_c = \sum_\mu f_\mu(\theta, t) + \sum_v f_v(\theta, t) + \sum_h f_h(\theta, t). \quad (4)$$

This expression describes the magnetomotive force in a PMSM; the superposition of these magnetomotive forces enables the motor to realize energy conversion between the rotor and stator.

The magnetic flux density of the synthetic air-gap magnetic field can be obtained by superimposing the fundamental flux density and the higher harmonic flux density, as follows:

$$b_c(\theta, t) = b_1(\theta, t) + b_2(\theta, t) + b_h(\theta, t). \quad (5)$$

At this time, the radial electromagnetic force of the pump motor is:

$$p_r(\theta, t) = \frac{1}{2\mu_0} b_c^2(\theta, t) = \frac{b_1^2(\theta, t) + 2b_1(\theta, t)b_2(\theta, t) + b_2^2(\theta, t)}{2\mu_0} + \frac{2b_1(\theta, t)b_h(\theta, t) + 2b_2(\theta, t)b_h(\theta, t) + b_h^2(\theta, t)}{2\mu_0}. \quad (6)$$

The electromagnetic force is generated by the interaction between the high-order harmonic current magnetic field, the permanent magnet main magnetic field, the fundamental wave of the armature current and its harmonic magnetic field, and their own harmonics.

In summary, the chain from harmonic voltage → harmonic current → air-gap MMF → radial electromagnetic force → structural vibration → acoustic noise establishes the theoretical basis for noise reduction through PWM harmonic control. The following section presents the HRCSVPWM strategy specifically designed to suppress the harmonic voltage components identified in this analysis.

3. Hybrid Random Carrier Rejection Strategy

The Random Carrier Space Vector Pulse Width Modulation (RCSVPWM) strategy is a widely adopted harmonic suppression technology. Its principle is to randomly vary the carrier frequency to realize the randomization of the switching frequency based on the SVPWM control strategy, thereby dispersing the harmonics concentrated around integer multiples of the carrier frequency and weakening the

harmonic peaks. The carrier frequency is formulated as follows:

$$f_c = f_{c0} + R_i \Delta f, \quad (7)$$

where f_c is the carrier frequency, f_{c0} is the fixed carrier center frequency, R_i is a random number varying within $[-1, 1]$, Δf is a bandwidth. The randomness of the random number exerts a significant influence on the modulation results. A random number with poor uniformity will cause harmonics to concentrate more in certain frequency bands, leading to increased noise and reduced system stability. Common random number generation methods include the look-up table method, mathematical formula method, and logic method. In this paper, the Xorshift algorithm is employed to generate random sequences, which essentially consists of a series of feedback shift registers. Based on CPU XOR and shift operations, it offers faster computing speed than general logic operations.

As shown in Eq. (7), L and R are order matrices over the binary field.

$$L = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 1 & 0 \end{pmatrix}, R = \begin{pmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \cdots & 0 \\ 0 & 0 & \ddots & 1 \\ 0 & 0 & \cdots & 0 \end{pmatrix}. \quad (8)$$

A vector x of order m over a binary field with a 1-bit left and right shift of x can be denoted as xL and xR , respectively. At this point, variables a and b are introduced, such that L^a and R_b represent an a -bit left shift and b -bit right shift, respectively.

$$x(I + L^a), x(I + R_b), \quad (9)$$

where, I is the identity matrix; the above two equations represent the 10OR operation on the result of shifting vector x by a bits to the left or b bits to the right, i.e., Eq. (10)

$$x^\wedge = x \ll a, x^\wedge = x \gg b. \quad (10)$$

A small number of multiplications of $(I + L^a)$ and $(I + R_b)$ are used to construct a random sequence generator, as shown in Eq. (11)

$$x(I + L^a)(I + R_b). \quad (11)$$

Considering that the main controller of the automotive electronic water pump is mostly a 32-bit processor, a 32-bit random sequence generator should be designed, which can be described as follows:

$$x^\wedge = x \ll 13, x^\wedge = x \gg 17, x^\wedge = x \ll 5. \quad (12)$$

The coefficients 13, 17, and 15 of the trinomial in the formula are selected based on references to meet the randomness requirements of the generated random sequence. The carrier frequency distribution generated by the Xorshift algorithm is uniform, with good randomness.

To more effectively suppress PWM harmonics and reduce computational burden within the same random

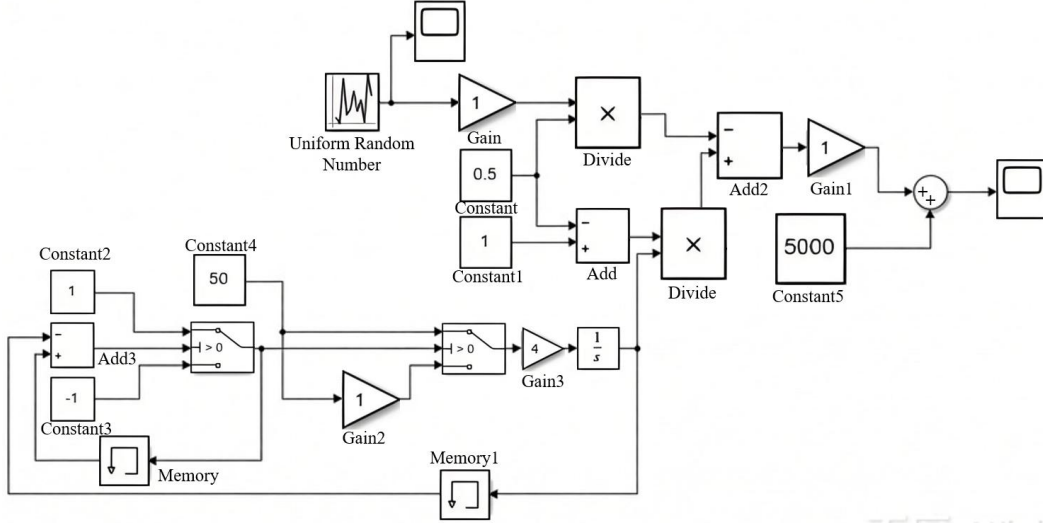


Fig. 2 Hybrid random number generator

range, this paper proposes the HRCSVPWM algorithm, which combines the sawtooth wave function spread spectrum modulation strategy. The hybrid random number generator, as shown in Fig. 2, generates a random number that, together with the carrier frequency, forms a new carrier frequency. The mixing of random carrier frequencies and periodic carrier frequencies is achieved by modifying the value of Constant. Using this hybrid random carrier frequency modulation method, the output triangular wave and its spectrum can be obtained; the goal of frequency spread noise reduction is achieved by adjusting parameters. The random carrier formula after introducing the sawtooth wave spread spectrum modulation strategy is given by

$$f_c = f_{c0} + [(1-k)S(t) + kR_{\text{Xorshift}}] \Delta f. \quad (13)$$

In the formula, f_c denotes the carrier frequency, f_{c0} denotes the fixed carrier center frequency, Δf denotes the fixed bandwidth, $S(t)$ denotes the sawtooth wave function with an amplitude varying within $[-1, 1]$, x denotes the coefficient of random carrier frequency modulation, R_{Xorshift} denotes a random number varying within $[-1, 1]$, generated by the random sequence generator based on the Xorshift algorithm.

This hybrid random carrier suppression strategy adjusts the proportional parameter k_0 according to different operating conditions of the motor. After the hybrid random carrier, the output voltage of the pump motor control system is expressed as:

Parameter selection guidelines for the HRCSVPWM formulation are as follows.

1. Proportional coefficient k : this parameter controls the weight ratio between the periodic spread-spectrum component and the random modulation component. A larger k shifts more weight toward the sawtooth-wave periodic component, improving carrier frequency regularity at the cost of reduced randomness. In this study, k was tuned through simulation parametric sweeps across the range $[0, 1]$, and the value that minimized peak harmonic amplitude while maintaining stable current waveform quality was selected.

2. Sawtooth wave function $S(t)$: a sawtooth wave is adopted in preference to sinusoidal or triangular waveforms

because its linear ramp profile provides superior frequency-spread flatness across the switching-frequency deviation band, as analysed in Section 3.1. The modulation frequency of $S(t)$ is set to remain well below the carrier frequency to avoid beating artefacts.

3. Bandwidth Δf : the bandwidth defines the half-range of carrier frequency variation ($f_c \pm \Delta f$). It is constrained from below by the minimum spread required to effectively disperse harmonic energy below the psychoacoustic annoyance threshold, and from above by the maximum permissible switching-frequency deviation that preserves acceptable current THD and motor thermal performance.

4. Random term R : the Xorshift algorithm generates R uniformly distributed over $[-1, 1]$ with a very long period ($2^{32}-1$ for the 32-bit implementation), offering better uniformity than linear congruential generators and faster computation than hardware-based true-random sources, making it well-suited for real-time embedded control.

$$\frac{u_a}{E_d/2} = \frac{a_0^*}{2} + \sum_{n=1}^{\infty} a_n^* \cos n(\omega_s t + \Delta f \sin(\omega_m t)). \quad (14)$$

The angular frequency ω_m is used to modulate the signal. Further simplification yields the harmonic components around the carrier frequency, which can be obtained as follows:

$$H_1 = \sum_{n=0}^M J_n(k\Delta f) \cdot C_2 \cos(\omega_s + n\omega_m)t. \quad (15)$$

The term $J_n(k\Delta f)$ represents the n -th order Bessel function of the first kind, which is used to simplify the trigonometric functions in the formula. The radial electromagnetic force under the hybrid random carrier modulation strategy is expressed as:

$$A_{me_\mu}^{...*} = J_n(k\Delta f \times (1 + \Delta\omega)) \times \frac{\pi D_i L_{ef} P_{m_ \omega_\mu}}{m_c \sqrt{(\omega_m^2 - \omega_\mu^2)^2 + 4\varepsilon^2 \omega_\mu^2 \omega_m^2}}. \quad (16)$$

It can be seen from the formula that the vibration suppression rate under this suppression strategy is significantly higher than that under a single modulation strategy.

By using a triangular wave function with an amplitude periodically varying within $[-1, 1]$ as the modulation signal, and adjusting the center frequency and bandwidth to change the range of switching frequency variation, frequency spread noise reduction can be achieved. Compared to sine waves, triangular waves offer superior frequency spread noise reduction performance. Randomizing the cyclic frequency of the modulation signal can further enhance the frequency spread effect.

The HRCSVPWM algorithm, which combines the RCSVPWM algorithm based on the Xorshift function with the sawtooth wave periodic function, exhibits both the PWM harmonic suppression effect of the RCSVPWM control strategy and the frequency spread effect of the periodic function on PWM harmonics. Therefore, the HRCSVPWM control strategy proposed in this paper can be applied to active noise and sound quality control of automotive electronic water pumps. By adjusting the proportion parameter k_0 of periodic frequency modulation and random frequency modulation, frequency spread noise reduction can be realized.

4. Simulation Verification

In the simulation model of this paper, the motor-related parameters are shown in Table 1, which are consistent with those of the vehicle-mounted pump motor and the experimental test pump motor to ensure consistency between the simulation and the experiment.

In Fig. 3, the ordinate denotes the ratio of the amplitude at each frequency to the fundamental wave amplitude, expressed as a percentage. As observed in Fig. 3, under the SVPWM control scheme, the PWM waveform presents prominent amplitude components near 6000 Hz, 12000 Hz and 18000 Hz, which correspond to the first, second and third multiples of the carrier frequency. The maximum PWM harmonic peaks in these three frequency bands are 88.04%, 76.58%, and 59.39% of the fundamental amplitude, respectively.

It can be seen from Fig. 4 that for the harmonic distribution of the phase voltage PWM under the HRCSVPWM control strategy, the harmonics originally appearing at 6000 Hz, 12000 Hz, and 18000 Hz have been fully dispersed and suppressed. Part of the harmonic energy is shifted to the low-frequency band, with a small number of harmonics emerging in this range. The maximum amplitude of these harmonics is 21.84% of the fundamental amplitude, and the PWM harmonics around 1x the carrier frequency has been attenuated to 0.43% of the fundamental amplitude.

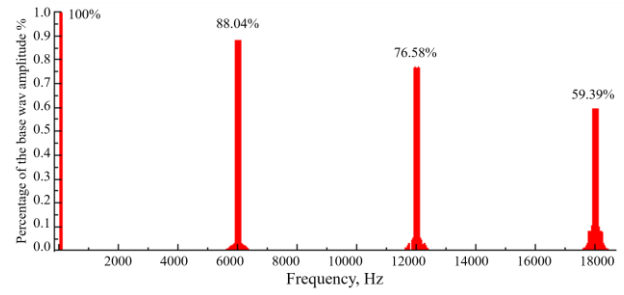


Fig. 3 SVPWM phase voltage spectrum analysis plot

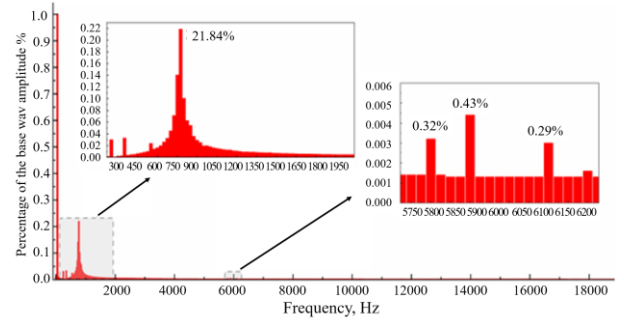


Fig. 4 HRCSVPWM phase voltage spectrum analysis plot

This indicates that the HRCSVPWM control strategy can fully disperse and suppress PWM harmonics in the frequency bands near the carrier frequency and its integer multiples. For PWM harmonics in the low-frequency band, it also exerts a certain inhibitory effect and significantly suppresses harmonic peaks.

According to the above simulation results, applying the HRCSVPWM control strategy can effectively reduce the generation of carrier-frequency harmonics during the SVPWM modulation process and disperse harmonic energy into the surrounding frequency bands.

5. Experimental Verification

The vibration and noise test system for the electronic water pump mainly comprises sensors, acquisition devices, and analysis devices. This system is designed in accordance with the noise test method for electronic water pumps in a semi-anechoic chamber, with its schematic diagram. In the experiment, a 378B02 capacitive acoustic sensor manufactured by PCB Company and an HT356B21 tri-axial acceleration sensor are used, along with a Siemens LMS SCADAS mobile data acquisition system. The acoustic sensor and vibration sensor transmit data to the LMS data acquisition system via BNC cables, and the processed data is then transmitted to a computer through twisted-pair cables. The LMS Test. Lab software is installed on the computer to display and process the experimental result.

The vibration and noise data acquisition settings are as follows: bandwidth of 25600 Hz, sampling frequency of 51200 Hz, resolution of 1 Hz, amplitude set to root mean square, and sound pressure level calculated using the A-weighting method. Fig. 5 shows the general layout of the high-frequency electromagnetic noise characteristic experiment for the electronic water pump.

An experimental test was conducted on the phase voltage of the electronic water pump. In this experiment, the

Table 1

Electrical pump motor parameters

Electric Machine Parameter	Parameter Index
Rated Power, W	60
Rated Speed, rpm	5000
Number of Poles	2
Stator Winding Phase Resistance, Ω	0.146
Stator Winding Phase Inductance, mH	0.49
Load Moment of Inertia, $\text{kg} \cdot \text{m}^2$	4.7×10^{-6}
Motor Flux Linkage, Wb	0.001

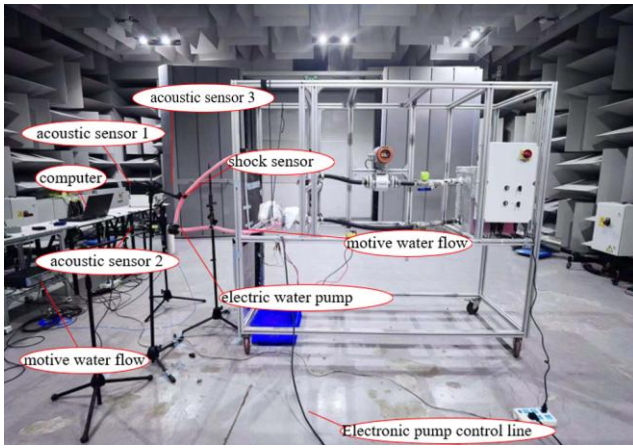


Fig. 5 General layout of electronic water pump test

electronic water pump test bench was used, and an oscilloscope was employed to collect the voltage waveform input to the pump motor. After fast Fourier transform, the frequency spectrum distribution of the input voltage waveform of the electronic water pump was obtained, as shown in Fig. 6.

From the test results of the electronic water pump presented in Fig. 6, it can be observed that significant harmonics appear near the 1x and 2x carrier frequencies. This is attributed to potential errors in the SVPWM modulation process, which cause fundamental wave distortion and subsequent surges in harmonic components.

To ensure result reliability, each test condition was measured five consecutive times following a thermal stabilisation period of no less than 10 minutes. The measurement equipment complied with IEC 61672-1 Class 1 for acoustic sensors (accuracy ± 0.5 dB) and ISO 16063-21 for

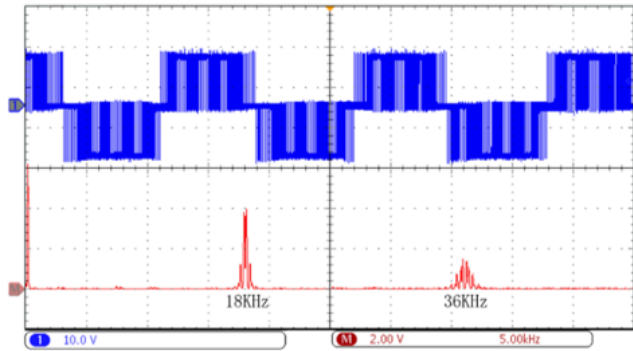


Fig. 6 Measured phase voltage waveform and frequency spectrum

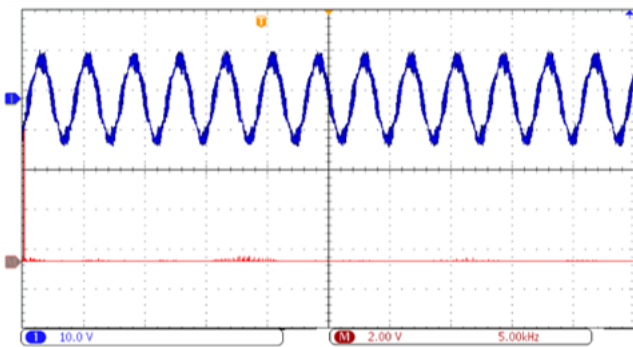


Fig. 7 Phase current waveform and frequency spectrum diagram of the electronic water pump

vibration accelerometers. The background noise level in the semi-anechoic test room was below 25 dB(A), providing a signal-to-noise ratio exceeding 10 dB for all reported measurements. All numerical results are presented as the mean of five repeated measurements; the maximum standard deviation across all reported SPL values did not exceed ± 0.4 dB(A), confirming adequate test repeatability. Measurement uncertainty was estimated in accordance with ISO/IEC Guide 98-3 (GUM) and found to be within ± 0.6 dB(A) at a 95% confidence level.

The input phase voltage waveform and spectrogram of the electronic water pump using the HRCSVPWM control strategy are shown in Fig. 7. After phase voltage and spectrum analysis, the phase current waveform of the electronic water pump, following PWM signal conversion, is close to a sine wave. Harmonics are significantly reduced and distributed within a specific frequency band, particularly near the 1x and 2x carrier frequencies. Compared with the SVPWM experimental results, the harmonic amplitude is significantly decreased, and the total harmonic distortion (THD) is also significantly improved.

A dynamic experiment on the high-frequency electromagnetic noise of the electronic water pump was conducted under constant external environmental conditions, with the duty cycle uniformly accelerated from 20% to 95% within 20 s. Noise data of the electronic water pump under the two control strategies were collected, and the changes before and after were visualized using a colormap. The results are shown in Figs. 8 and 9.

It can be seen from Figs. 8 and 9 that during the accelerated operation of the electronic water pump, the high-frequency electromagnetic noise remains concentrated in the frequency bands around 6 kHz, 12 kHz, and 18 kHz.

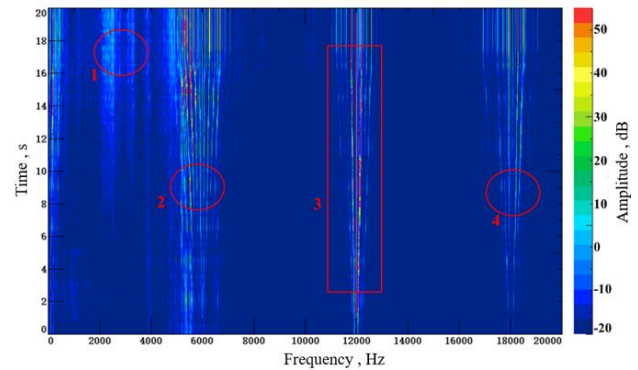


Fig. 8 Noise colormap plot for the SVPWM control strategy

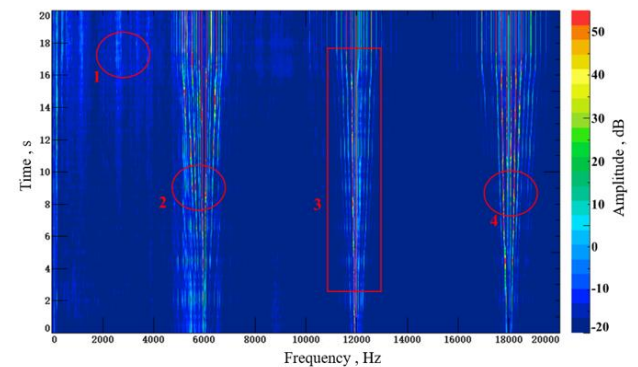


Fig. 9 Noise colormap plot for the HRCSVPWM control strategy

The SVPWM control strategy exhibits obvious order-related characteristics with an umbrella-shaped distribution. In Fig. 8, the areas marked 1, 2, 3, and 4 indicate that the high-frequency band noise under the SVPWM control strategy is sharp and harsh, causing discomfort. The proposed HRCSVPWM high-frequency electromagnetic noise suppression strategy in this paper achieves significant noise reduction at 2x and 3x the carrier frequency, as shown in the circled areas 3 and 4 of Fig. 9. The sound pressure level in the frequency band near 1x the carrier frequency is attenuated, and the umbrella-shaped order distribution is transformed into a bundled order distribution, as shown in the circled areas 1 and 2 of Fig. 9. Additionally, the HRCSVPWM control strategy outperforms the SVPWM control strategy in suppressing sound pressure levels: the original narrowband noise is converted into broadband

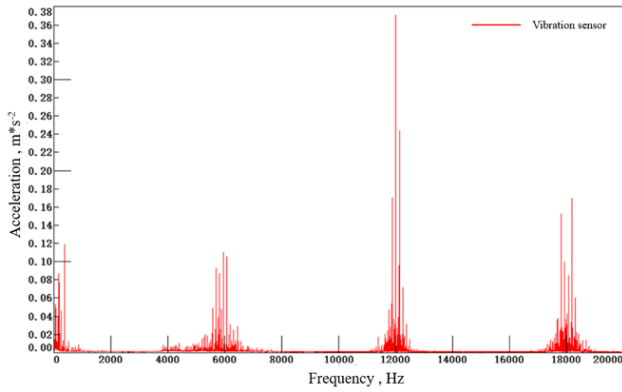


Fig. 10 Vibration frequency spectrogram of the electronic water pump (80% duty cycle)

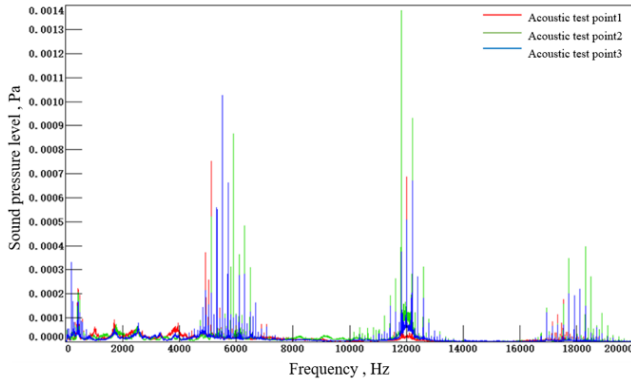


Fig. 11 Frequency spectrogram of electronic pump noise (80% duty cycle)

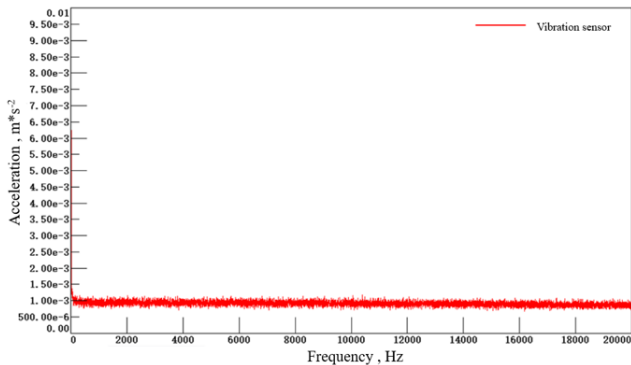


Fig. 12 Vibration frequency spectrograms of the electronic water pump (reverse trailing condition)

noise, such that experimenters are hardly affected by the noise generated by the electronic water pump.

To better observe the spectral characteristics of vibration and noise, a Hanning window function is used to perform a Fourier transform on the collected time-domain signals, yielding the vibration and noise spectra of the electronic water pump under steady-speed conditions, as shown in Figs. 10 and 11. It can be seen from Figs. 10 and 11 that the vibration and noise of the electronic water pump are concentrated in the frequency bands around 6 kHz, 12 kHz, and 18 kHz, corresponding to 1x, 2x, and 3x the carrier frequency, respectively. Vibration and noise exhibit a strong correlation with identical distribution patterns. Meanwhile, a small amount of vibration and noise appear in the 0-1000 Hz low-frequency band. Their distribution patterns are consistent with those of PWM harmonics in the harmonic suppression experiment, which experimentally confirms the correlation between PWM harmonics and high-frequency electromagnetic noise--consistent with the aforementioned theoretical and simulation results.

Similarly, a back-dragging experiment was conducted to obtain the vibration and noise spectra of the back-dragged electronic water pump under steady-speed conditions, as shown in Figs. 12 and 13.

It can be seen from Figs. 12 and 13 that the vibration and noise of the electronic water pump occur in the 0-4000 Hz low-frequency band, with almost no vibration or noise present in the frequency bands near the carrier frequency and its integer multiples. This indicates that most of the high-frequency electromagnetic noise in the automotive electronic water pump originates from the PWM harmonics driving the pump's operation, exhibiting a strong correlation with the electronic water pump's control strategy.

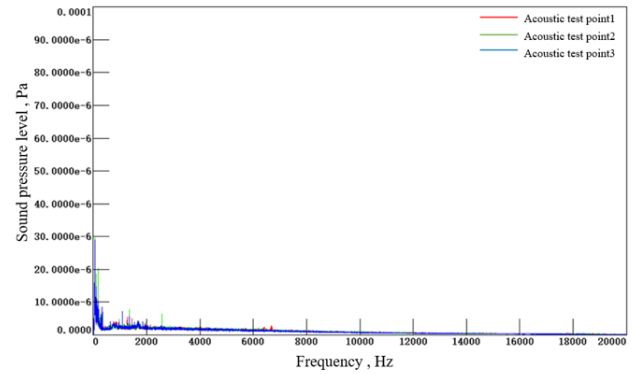


Fig. 13 Frequency spectrogram of electronic pump noise (reverse trailing condition)

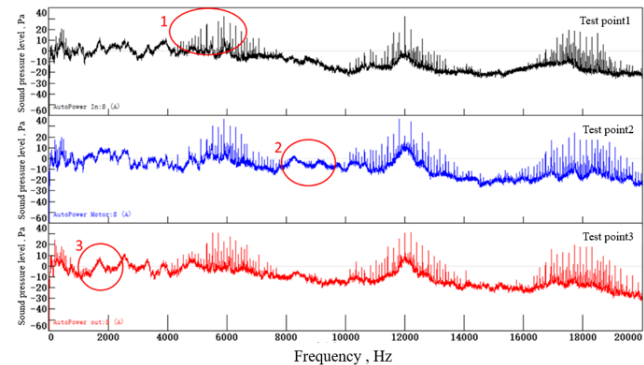


Fig. 14 Noise sound pressure level (SPL) frequency spectrum of the SVPWM control strategy

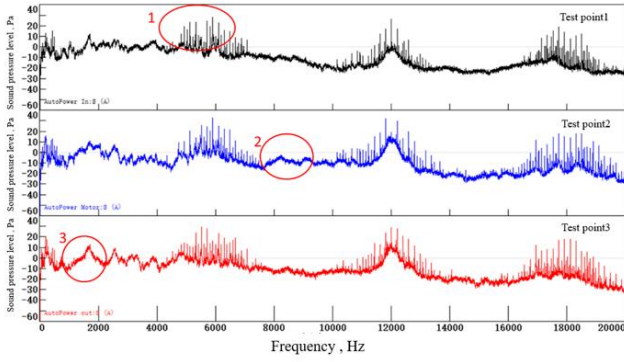


Fig. 15 Noise sound pressure level (SPL) frequency spectrum of the HRCSVPWM control strategy

The distribution patterns of noise sound pressure levels (SPL) before and after high-frequency electromagnetic noise suppression were further compared, with data from the three test points processed as shown in Figs. 14 and 15.

As can be seen from Figs. 14 and 15, the main distribution characteristics of the noise boost stage waveforms under the two control strategies are consistent, concentrated in the frequency bands near the carrier frequency and its integer multiples. However, there are differences in the distribution patterns at the fine-grained level. By comparing the curve segments circled by ellipse 1 in Figs. 14 and 15, the noise of the electronic water pump under the SVPWM control strategy at 6 kHz exhibits central symmetry, with higher levels in the middle and lower levels on both sides. The HRCSVPWM control strategy, leveraging the advantages of random switching frequency modulation, disperses concentrated noise, resulting in a slight increase in noise near the carrier frequency and a rising trend on both sides. Comparing the curve segments circled by ellipse 2 in Figs. 14 and 15, the sound pressure level of the SVPWM control strategy exceeds 0 dB here, while the HRCSVPWM control strategy reduces it to below 0 dB by dispersing the energy concentrated in this frequency band. Comparing the curve segments circled by ellipse 3 in Figs. 14 and 15, the sound pressure level of the electronic water pump under the HRCSVPWM control strategy shows a slight increase in the low-frequency band. These distribution patterns are consistent with the simulation results in the previous section, confirming the effectiveness of the proposed strategy for high-frequency electromagnetic (HF EM) noise suppression.

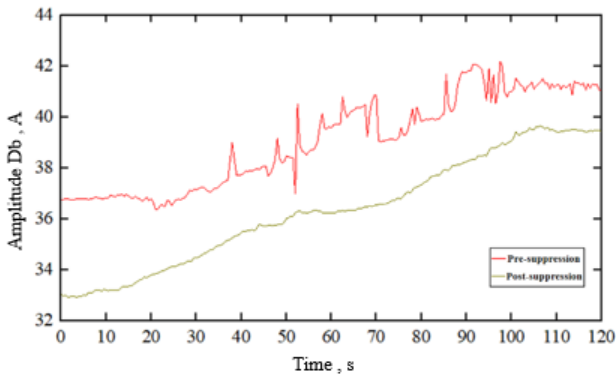


Fig. 16 Comparison of sound pressure levels in the electronic water pump experiment

The sound pressure levels before and after applying the electromagnetic noise suppression method for the electronic water pump using the hybrid random carrier modulation strategy were compared and analyzed, with the results shown in Fig. 16.

The effect on sound pressure levels was tested by comparing noise characteristics before and after the application of the hybrid random carrier modulation strategy. Experimental results indicate that using this method can significantly reduce the sound pressure level of the electronic water pump under various operating conditions, with an average reduction of approximately 3 dB(A).

To assess whether the proposed HRCSVPWM strategy introduces any negative side-effects, additional measurements were carried out. In terms of control stability, the rotor speed response and phase current waveforms were monitored during the transition between SVPWM and HRCSVPWM operation; no discernible increase in speed ripple or current distortion was observed, confirming that the proposed strategy does not impair closed-loop stability. Regarding pump efficiency, the input power was recorded at each operating point; the measured efficiency variation between the two strategies remained within $\pm 0.3\%$, which is within the instrument resolution and can be considered negligible. The randomised switching frequency modifies the instantaneous distribution of switching losses across the power devices; however, thermal imaging indicated that the maximum device junction temperature rose by less than 2 degC compared with conventional SVPWM, which is well within the rated thermal margin of the inverter module. While these short-term experimental results demonstrate stable and efficient operation under HRCSVPWM, a systematic evaluation of long-term reliability under sustained varying loads and thermal cycling conditions warrants further investigation, which is identified as future work.

6. Conclusions

To address the electromagnetic noise issue in automotive electronic water pumps, this paper presents an improved hybrid random carrier technology building upon existing random carrier technology. This method integrates the advantages of periodic PWM modulation and random PWM modulation technologies, achieves integration through their correlation, and employs a Xorshift-algorithm-based random sequence generator to generate high-quality uniform random numbers. Through simulation and experimental verification, the following conclusions are drawn:

1. The SVPWM control strategy adopted by automotive electronic water pumps produces stator currents rich in high-order harmonics at the carrier frequency and its integer multiples. Following the analytical chain established in Section 2, these harmonic currents generate additional MMF components in the air gap, which interact with the rotor permanent-magnet field to produce radial electromagnetic force waves at corresponding frequencies. These time-varying force waves excite stator structural vibration that radiates as electromagnetic noise. The present analysis thus establishes a rigorous physical basis linking harmonic voltage suppression to the reduction of electromagnetic noise in AEWPs.

2. Compared with the conventional SVPWM strategy, the proposed HRCSVPWM technology significantly suppresses the sound pressure response of the AEWP across

all tested operating conditions, achieving an average reduction of approximately 3 dB(A) (from 36.68 dB(A) to 33.45 dB(A), mean of five repeated measurements per condition, standard deviation $\leq \pm 0.4$ dB(A)). No measurable degradation in pump efficiency ($\leq \pm 0.3\%$), closed-loop stability, or device thermal performance (junction temperature rise < 2 degC) was observed, confirming that the noise reduction is achieved without adverse impact on system operation.

3. The HRCSVPM strategy proposed in this paper integrates a Xorshift-based random carrier generator with a sawtooth wave spread-spectrum modulation function, yielding both the harmonic dispersion advantage of random PWM and the frequency-spread stability of periodic modulation. This combination effectively disperses concentrated high-order harmonics while maintaining low computational complexity, rendering the method readily implementable on existing 32-bit motor control processors without hardware modification. The strategy therefore offers a practical and cost-effective means of improving the acoustic quality of AEWP in automotive thermal management systems.

4. The experimental validation was conducted under specific steady-state operating conditions of the AEWP. The influence of the proposed strategy on long-term component reliability under sustained thermal cycling and dynamic load transients requires further experimental investigation. Future work will also explore the integration of HRCSVPM with active noise cancellation approaches and its applicability to other PMSM-driven automotive auxiliary components to broaden the practical impact of the findings.

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HYBRID RANDOM CARRIER-BASED NOISE SUPPRESSION FOR AUTOMOTIVE ELECTRONIC WATER PUMPS: THEORETICAL AND EXPERIMENTAL STUDY

Summary

To effectively mitigate the electromagnetic noise (EN) from automotive electronic water pump (AEWP), this paper proposes and validates an EN suppression method based on hybrid random carrier technology. Drawing on the control model of AEWP and Space Vector Pulse Width Modulation (SVPWM) harmonic theory, the relationship between harmonics and EN in the control system is analyzed, and the mechanism of random signals is explored. Based on the control model and theory of AEWP, randomized carrier wave mixing is introduced, and a harmonic method of Hybrid Random Carrier Space Vector Pulse Width Modulation (HRC SVPWM) is proposed. Simulation results are spectrally analyzed using the power spectrum transform method to verify the suppression capability of the carrier randomization technique on higher harmonics. Additionally, experimental verification is conducted via a noise characteristics test platform, confirming the method's correctness and effectiveness. This approach significantly reduces the high-frequency vibration and noise of AEWP without compromising the original control system or requiring additional hardware inputs. Thus, the research findings provide a novel solution for reducing EN in AEWP, with substantial practical value for electronic water pumps development.

Keywords: automotive electronic water pump (AEWP), electromagnetic noise (EN), harmonic suppression, hybrid random carrier space vector pulse width modulation (HRC SVPWM).

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