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Review Article

A Review of the Research Progress of Motor Vibration and Noise

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Motor vibration and noise is an important index to measure motor performance. How to reduce vibration and noise is one of the important topics in the field of motor design. Analysis, calculation, and reduction of motor vibration and noise have attracted more and more attention from motor designers. Based on the three main types of noise sources of motors, this paper firstly analyzes their causes and mechanisms and secondly introduces their main research methods. Although there are many summary articles on the research of motor vibration and noise, most of the theories and research methods on the causes of various kinds of noise are not comprehensive enough, lacking theoretical calculation and analysis, especially for mechanical noise and aerodynamic noise. This paper summarizes the research in the recent ten years, especially in the recent five years, with a view to providing a reference for the future development of this field.

1. Introduction

The development of new high-performance motors and their drive systems is an important part of the country's economic, industrial, and technological development, involving civil, aerospace, military, and other fields. According to the development spirit of the country's "14th Five-Year Plan," green development is an inevitable trend in the future development of all walks of life, especially in fields sensitive to vibration and noise, such as ship power and electric vehicles. In addition to the strong driving performance of the motor, low vibration and noise is also another important indicator to measure the motor and its driving system, which is one of the goals of green development.

It should be pointed out that the violent vibration of the motor caused by the electromagnetic force will not only affect the driving performance of the motor but also cause serious pollution to people's living and working environment and affect people's mental and physical health. How to properly handle the high drive and low noise of the motor is currently a research hotspot of well-known universities and research institutions at home and abroad.

Motor noise is mainly divided into three categories: mechanical noise, aerodynamic noise, and electromagnetic noise. Figure 1 shows the main noise sources of motors and their main causes. The first thing to be clear is that the vibration of the motor is not a single type of noise but a complex superposition of three noise sources. In general research, one or two types of main noise sources will be identified first, and then, the main noise sources will be analyzed separately on this basis. In this paper, for the convenience of discussion, the research progress of three kinds of noise will be discussed separately, focusing on the research progress of electromagnetic noise, in order to provide a reference for future research in this field.

2. Mechanical Noise of the Motor

2.1. Overview of Mechanical Noise. When the motor is running, the noise generated due to friction, the collision between various components, and the imbalance of the rotor and structural resonance are called mechanical noise [1]. Therefore, the study of motor structure noise is also the study of the above parts.

2.1.1. Rotor Unbalanced Noise. During the manufacturing process, assembly, and working process of the motor, the

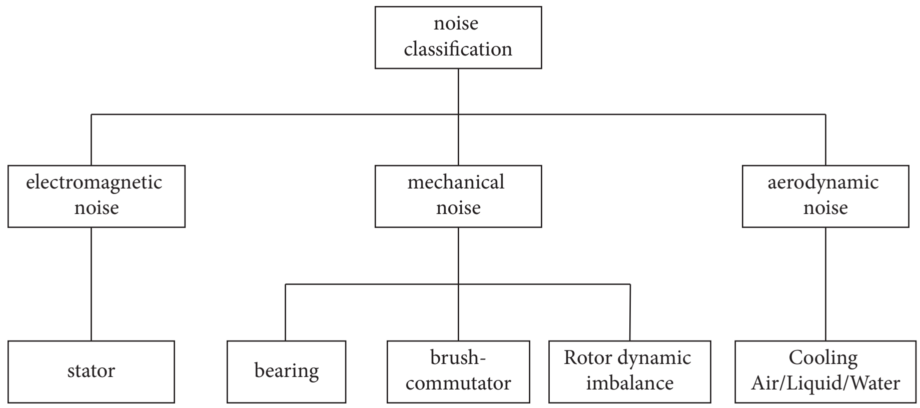

Figure 1: Motor noise source.

rotor is worn or asymmetrical due to various reasons. These problems will lead to the imbalance of the rotor and cause noise. The rotor unbalanced noise frequency is as follows:

$$f_0 = \frac{60}{n}, \tag{1}$$

where n is the motor speed.

2.1.2. Bearing Noise. Bearings are the key components that support the stator and rotor in the motor. During the working process of the motor, on the one hand, the bearing is subjected to various forces in the motor to generate vibration noise. On the other hand, the rolling elements of the rolling bearing move relative to the inner and outer rings of the bearing when the motor is running, and the friction and collision with the contact surface produce vibration noise [2]. Table 1 lists the possible peak frequencies and causes of bearing noise.

In the table, d represents the diameter of the bearing ball (mm); D represents the diameter of the bearing pitch circle (mm); α represents the contact angle; n represents the speed of the motor shaft (r/min); f_r indicates frequency; Z represents the number of bearing balls.

When the identification accuracy of the noise source is not high, the frequency characteristics of the bearing noise can also be estimated by the number of bearing balls. Table 2 gives the empirical formulas for the characteristic frequencies of different noises of the bearing:

2.2. Research Progress. Zhang et al. used the piezoelectric module in the ANSYS simulation software and used EMI (piezoelectric impedance) technology to determine the resonance frequency bands of the stator and rotor of the small motor at three frequency points and found that by changing the thickness and material of the motor stator. The natural frequency and resonance frequency band, which can be changed by parameters such as EMI, have laid the foundation for EMI technology in the treatment of motor vibration and noise reduction [3]. Song and Lu Lianyong put forward measures and methods to control mechanical noise through the research and analysis of the bearing noise of explosion-proof motors, but they mainly start from the aspects of production, maintenance, and use, without in-depth theoretical analysis [4]. He of Kunming University of Science and Technology, through the test of the vibration and noise of the propulsion motor under the test bench, based on the idea of modal hybrid parameter adjustment and modeling, the experimental modal analysis and finite element modeling of each subcomponent of the motor were carried out. The dynamic model of the connecting bearing of each subcomponent is simplified, and finally, the dynamic equivalent finite element model of the whole machine is obtained [1]. Wang et al. from Southwest Jiaotong University proposed a noise source identification method based on EEMD-FastICA-STFT, analyzed three kinds of automobile starter motors, and concluded that the main mechanical noise of the starter motor is the first order, and the main noise source is the rotor unbalanced noise [5]. Zhang et al. used the power spectrum method to analyze and process the vibration and noise of the motor and identified the mechanical noise of the motor [6]. Generally speaking, the suppression of the mechanical noise of the motor mainly focuses on the machining accuracy of the motor and the degree of lubrication of the bearings, so as to reduce the modal resonance of the motor [7].

3. Aerodynamic Noise of the Motor

3.1. Overview of Aerodynamic Noise. The root cause of the aerodynamic noise of the motor is the sharp pulsation of the airflow pressure in the motor ventilation system and the friction between the airflow and the duct. This type of noise mainly includes the following: the rotation noise generated by the high-speed rotation of the air fan; the eddy current noise generated by the protrusion on the rotor surface of the motor during the rotation process that affects the airflow; the whistle sound generated by the airflow encountering obstacles.

3.1.1. Rotational Noise. When the fan rotates at a high speed, the air particles will be affected by the periodic force of the fan blades, resulting in pressure pulsation and in rotating noise. The frequency of the rotational noise is related to the number of times the blades hit the air particles per second:

Table 1: Possible peak frequencies and causes of bearing noise.

Reasons	Frequencies
Inner ring rotation frequency	$f_i = (60/n)$
The frequency at which the rolling elements pass through a point on the inner ring	$f_{ic} = (1/2)z(1 + d/D\cos\alpha)f_r$
The frequency at which the rolling elements pass through a point on the outer ring	$f_{oc} = (1/2)z(1 - d/D\cos\alpha)f_r$
The revolution frequency of the rolling elements	$f_b = (1/2)(1 - d/D\cos\alpha)f_r$
Cage rotation frequency	$f_c = (1/2)(1 - d/D\cos\alpha)f_r$

Table 2: Bearing noise empirical formula.

Reasons	Frequencies
The frequency at which the rolling elements pass through a point on the inner ring	$f_{ic} = 0.6 * z * f_r$
The frequency at which the rolling elements pass a point on the outer ring	$f_{oc} = 0.4 * z * f_r$
The revolution frequency of the rolling elements	$f_b = 0.23 * z * f_r (z < 10)$ $f_b = 0.18 * z * f_r (z > 10)$
The revolution frequency of the rolling elements	$f_c = 0.381 \sim 0.4 * f_r$

$$f_b = \frac{60Z_b n}{60}, \tag{2}$$

where k is 1, 2, 3, . . .; Z_b is the number of leaves; n is the fan speed (r/min).

3.1.2. Eddy Current Noise. During the rotation of the fan, any small protrusion on the fan blade will affect the airflow. Due to the action of the viscous force, a series of small eddies will be split, and the splitting of the vortices and the vortices will disturb the air, resulting in noise. The frequency is

$$f_\Lambda = Sh\frac{\nu}{D}i, \tag{3}$$

where $i = 1, 2, 3, \ldots$; Sh is the Stohalide number, between 0.14 and 0.20, generally 0.185; υ is the relative velocity of the gas and the object; D is the projection of the front surface width of the object on the plane perpendicular to the velocity.

3.1.3. Flute. When the airflow encounters an obstruction, a single-frequency whistle will be issued. Common ones are as follows:

(1) *Interference between Stator and Rotor Air Ducts*. Radial ventilation channels are often arranged in the stator and rotor iron cores of large and medium-sized motors, and they are aligned in the axial direction. Because the spacer is installed in the ventilation duct, when the motor is running, the rotation of the rotor will drive the spacer to vibrate, so that it is sometimes aligned and sometimes staggered, resulting in pressure fluctuations. Its frequency mainly depends on the number of rotor slots and the speed:

$$f_D = k\frac{Z_2 n}{60}, \tag{4}$$

where $k = 1, 2, 3, \ldots$; Z_2 is the number of rotor slots; n is the rotor speed (r/min).

(2) Interference between Rotor Bars and Stator Windings. The gap between the rotor bars of the induction motor and the ends of the stator windings also creates interference and whistles. Medium-sized two-pole asynchronous motors generally do not have rotor ventilation slots in view of mechanical strength. Cooling air enters between the air gap and the rotor wedges from both ends and then flows into the stator radial ventilation slots, which produce a whistle sound.

(3) Interference between the Fan Blades and the Cooling Ribs of the Base. In a closed external fan-cooled motor, if the blades of the fan are relatively close to the cooling ribs of the base, pressure pulsations will be generated at the entrance of the air duct of the cooling ribs, resulting in a whistle sound. Its frequency is

$$f = M\frac{n}{60}, \tag{5}$$

where M is the least common multiple of the blades and the cooling ribs.

3.2. Main Research Methods. There are two main methods for the study of aerodynamic noise, one is the finite element method based on the Lighthill equation, which is mainly suitable for the calculation of low-frequency noise; the other is the statistical energy method, which is suitable for the calculation of high-frequency noise [8].

3.2.1. Lighthill's Aeroacoustic Theory. Lighthill composed the fluid equation and the momentum equation into the form of an inhomogeneous wave equation and compared the flow field equation with the sound wave equation, and different parts were regarded as sound sources. The fluid motion equations and momentum equations expressed in the form of Cartesian tensors are as follows:

$$\frac{\delta\rho}{\delta t} + \frac{\delta\rho u_i}{\delta y_i} = 0, \tag{6}$$

$$\frac{\delta(\rho u_i)}{\delta t} + \frac{\delta\left(\rho u_i u_j + p\delta_{ij} + \tau_{ij}\right)}{\delta y_j} = 0, \tag{7}$$

where u_i, p, ρ are the velocity, pressure, and density of the fluid, respectively, t refers to time, δ_{ij} for the Kronecker symbol. τ_{ij} refers to the fluid viscous stress tensor, which for Stokes fluids is

$$\tau_{ij} = \mu\left(-\frac{\delta u_i}{\delta y_j} - \frac{\delta u_j}{\delta y_i} + \frac{2}{3}\frac{\delta u_k}{\delta y_k}\delta_{ij}\right), \quad (8)$$

where μ is the hydrodynamic viscosity.

Equation (6) takes the partial derivative with respect to time, and subtracting equation (7) from the space divergence, we get

$$\frac{\delta^2 \rho}{\delta t^2} = \frac{\delta^2\left(\rho u_i u_j + p\delta_{ij} + \tau_{ij}\right)}{\delta y_i \delta y_j}. \quad (9)$$

Subtracting $c_0^2\nabla^2\rho$ both sides at the same time becomes the inhomogeneous wave equation; that is, the Lighthill equation is as follows:

$$\frac{\delta^2 \rho}{\delta t^2} - c_0^2\nabla^2\rho = \frac{\delta^2 T_{ij}}{\delta y_i \delta y_j}, \quad (10)$$

where T_{ij} is the Lighthill tensor:

$$T_{ij} = \rho u_i u_j + p\delta_{ij} + \tau_{ij} - c_0^2\rho\delta_{ij}. \quad (11)$$

The advantage of the Lighthill equation is that the flow field and the sound field are artificially separated; that is, the turbulent flow field is obtained first, and then, the sound radiation prediction is performed by obtaining the equivalent sound source according to (10).

3.2.2. Basic Principles of Statistical Energy Method. Figure 2 shows the energy flow model of the statistical energy method of the two systems, P_i represents the input power of the ith system, $P_{i\,d}$ represents the dissipated power of the ith system, and P_{ij} represents the average power delivered by system i to system j.

According to energy conservation law, there is the following energy relationship between the two subsystems:

$$\begin{cases} P_1 = P_{1\,d} + P_{12} - P_{21}, \\ P_2 = P_{2\,d} + P_{21} - P_{12}. \end{cases} \quad (12)$$

Due to radiation and other reasons, the power loss of each subsystem is

$$P_{\mathrm{id}} = \omega\eta_i E_i, \quad (13)$$

where ω is the angular frequency (rad/s), E_i is the average vibrational energy of space-time energy of subsystem i, η_i is the internal loss factor of system i, η_{ij} is the coupling loss factor between subsystems i and j, so the energy delivered by subsystem i to subsystem j is

$$P_{ij} = \omega\eta_{ij}E_i - \omega\eta_{ji}E_j. \quad (14)$$

Therefore, the energy conservation equation shown in equation (12) can also be written as follows:

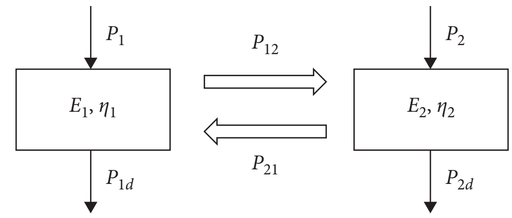

Figure 2: SEA model of two subsystems.

$$\begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = \omega\begin{pmatrix} \eta_{s1} & -\eta_{21} \\ -\eta_{12} & \eta_{s2} \end{pmatrix}\begin{pmatrix} E_1 \\ E_2 \end{pmatrix}, \quad (15)$$

where η_{si} is the total loss factor of system I and is the internal loss factor of system i and the sum of all coupling loss factors.

Extending equation (15) to a system with N subsystems, if the input power P_i, internal loss factor η_i, and coupling loss factor of all subsystems η_{ij} are known, then the vibration energy of each subsystem can be predicted by the SEA balance equation.

3.3. Research Progress. Many researchers at home and abroad have also carried out a lot of research work on the aerodynamic noise characteristics of motors. ZuoShuguang et al. used the boundary element method to calculate the aerodynamic noise of the claw-pole motor and found that this method can describe the noise generation mechanism more accurately than the FW-H model and has more engineering application value [8]. In order to reduce the ventilation noise of the motor, Ma et al. measured the ventilation noise of different electric fans and determined whether the fan meets the cooling requirements of the motor through the temperature rise test of the motor, providing a new solution for improving the aerodynamic noise of the motor [9]. Wang and SuGuoxia control the aerodynamic noise from the two aspects of the noise source and propagation direction and propose a method to reduce the aerodynamic noise of the high-voltage square box asynchronous motor by optimizing the diameter of the fan and the structure of the fan blade [10]. Qin et al. used the steady SSTk-ω turbulence model to analyze the aerodynamic noise characteristics of PMSM based on the FW-H coupled unsteady flow field, carried out sound field experiments, and found that the main noise source of PMSM is the surface sound of the centrifugal fan. The power can reach 166 dB peak [11]. Jianhua converted the traditional Lighthill equation into the weak integral form of Helmholtz and also used the FW-H equation coupling to calculate the noise radiation of the centrifugal fan [12]. On the basis of the calculation and experimental analysis of the cooling fan of the automobile generator, Wang et al. proposed a set of rotating noise prediction methods for the first time [13]. Zhang and Dong Dawei established a three-dimensional nonconstant numerical simulation method to study the aerodynamic noise optimization design of the front-end cover of the generator [14]. Zhu and Wang established a simulation calculation model of the internal flow field of the traction motor and used the calculation result of the unsteady internal flow field as the sound source to calculate and analyze the aerodynamic noise characteristics of the motor [15]. Chen et al. used the separation eddy simulation method and Lighthill acoustic analogy theory to simulate the sound field and flow field of the traction motor. The results show that the aerodynamic noise source is mainly concentrated in the fan area, which is caused by the periodic rotation of the fan [16]. Gill et al. proposed one-, two-, and three-component integrated turbulent disturbance models for the first time and performed noise calculations [17]. Fenini et al. calculated the aerodynamic noise emitted by the subsonic dry air flow through the orifice plate from the two aspects of the external sound pressure level and the internal sound power level and established a new CFD calculation model for solving the Reynolds number average equation. The problem of sound power generated by the orifice plate [18]. Ding conducted a noise test for an air-cooled permanent magnet motor. When measuring the noise spectrum of the motor, he found that the permanent magnet motor with 2000 rpm/min is mainly aerodynamic noise, and the motor with 1600 rpm/min is mainly electromagnetic noise. Through comparative analysis, he found that unequal-pitch blades are more effective in reducing the aerodynamic noise of the motor [19]. In 2019, Fan et al. used the CFD method to conduct numerical analysis on the steady-state and transient flow and sound field of an air-cooled motor and verified it through experiments [20]. In 2021, Zheng et al. studied the self-fan-cooled traction motor and analyzed the motor's external flow field based on the principle of computational fluid dynamics. Through fan structure optimization, the fan performance was improved [21]. Weiping Li and Taiming Huang put forward a numerical simulation method to predict the aerodynamic noise of claw-pole motor for vehicles and verified its effectiveness through experiments [22]. Shen et al. established a finite element acoustic calculation model based on the calculation results of the unsteady flow field of the self-ventilated motor, simulated and calculated the aerodynamic noise of the motor at the highest speed, obtained the amplitude and spectrum characteristics of the aerodynamic noise generated by the cooling fan, and compared them with the test results. The results show that the calculation method described in this paper is suitable for predicting the noise in the motor technical design stage [23].

4. Electromagnetic Noise of the Motor

4.1. Overview of Electromagnetic Noise. In the motor, the electromagnetic noise is the main component of the motor noise, which mainly propagates outward through the magnetic yoke. The air-gap magnetic wave acts on the stator core teeth to generate two electromagnetic force components, radial and tangential. The radial component causes the stator core to vibrate and deform, which is the main source of the electromagnetic noise of the motor. The tangential component causes the tooth root to bend and produce local deformation, which is the secondary source of the electromagnetic noise of the motor. When the radial electromagnetic force wave is close to the stator frequency, resonance will occur, which greatly enhances the motor noise. Moreover, most of the motors are driven by inverter source systems. When the drive voltages contain rich harmonic components, especially when these harmonics are large enough and close to the stator frequencies, obvious electromagnetic vibration will also be generated. From Maxwell's equations, the radial electromagnetic force per unit area in the air-gap magnetic field can be calculated as follows:

$$P_r = B^2 \frac{(\theta, t)}{(2\mu_0)}, \tag{16}$$

where B is the air-gap magnetic density, θ is the mechanical angular displacement, and is the vacuum permeability.

There are main wave magnetic potentials and various harmonic magnetic potentials in the stator and rotor windings of the motor, and they superimpose each other to generate various force waves. The radial electromagnetic force wave generated by the main wave magnetic field is

$$P_{r1} = P_0 + P_1. \tag{17}$$

In the formula, $P_0 = (B^2/(4\mu_0)) \approx (B_\delta^2/(4\mu_0))$, and it is an invariant part of the radial force wave, which acts on the stator core evenly without vibration and noise.

$$P_1 = P_0 \cos(2p\theta - 2\omega_1 t - 2\theta_0). \tag{18}$$

Among them, p is the number of pole pairs of the dominant wave, ω_1 is the angular velocity of the dominant wave, and θ_0 is the initial phase angle. P_1 is the alternating part of the radial force wave. The angular frequency of this force wave is twice the power frequency, which makes the stator and rotor generate vibration noise twice the power frequency.

Due to the influence of the stator and rotor cogging, the permeance will change periodically, which will cause the periodic change of the air gap magnetic density, which will also generate electromagnetic noise, called tooth harmonic noise. The tooth harmonic noise frequency is

$$f = \frac{iQn}{60}. \tag{19}$$

Among them, i is the harmonic order, Q is the cogging number, and n is the rotational speed.

Due to the asymmetry of the magnetic flux distribution caused by the eccentricity of the stator and the rotor or the asymmetry of the magnetic circuit, there will be a unilateral magnetic pull force on one side with a large force and a small force on the other side, which will also generate vibration noise. Figure 3 is the basic flow of research and analysis on electromagnetic vibration.

4.2. Research Progress of Electromagnetic Force Analysis. The radial electromagnetic force wave of the motor is the main reason for the electromagnetic vibration of the motor. After the continuous research on the electromagnetic force characteristics of the motor by domestic and foreign

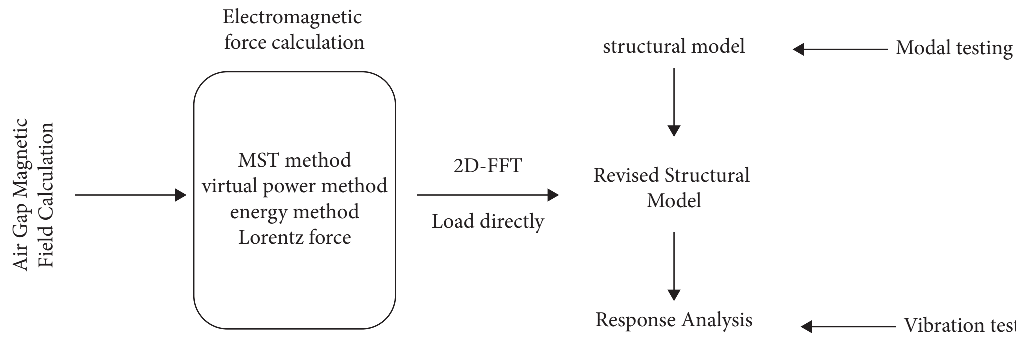

Figure 3: Basic flow of electromagnetic vibration analysis.

scholars, there are mainly two methods: the analytical method and the finite element method.

The analytical method obtains the distribution of the magnetic field by multiplying the magnetic potential by the magnetic permeability and then obtains the magnitude of the electromagnetic force according to the Maxwell stress tensor method [24]. Professor Hu and Zuo Shuguang proposed an analytical model method for predicting the nonlinear radial electromagnetic force caused by the saturated magnetic field, which can be used to calculate the radial electromagnetic force at any pole-to-pole and any rotor position [25]. Professor Han et al. proposed a quasianalytical calculation method that can analyze the impact of different rotor topologies on vibration and noise, which saves calculation time and resources and improves accuracy [26]. Zhang used the analytical method to deduce the analytic expression of the excitation force wave of the permanent magnet motor under load and pointed out that the asymmetry of the design or installation of the permanent magnet will generate low-order spatial excitation force waves, resulting in larger vibration noise [27]. The exact subdomain method proposed by Wu et al. takes into account the effect of the slot in the stator core of the motor and is currently the most accurate method for solving the surface-mounted permanent magnet motor analytically [28]. Islam and Husain used the Maxwell stress tensor method combined with the air gap radial and tangential magnetic field distributions obtained by the two-dimensional analytical method to study the radial and tangential electromagnetic force distribution of the surface mount permanent magnet motor along the circumference. Analytical model of radial and tangential electromagnetic forces for permanent magnet motors [29]. Liao et al. proposed a novel harmonic current suppression algorithm, which can not only accurately analyze the harmonic voltage, harmonic current, and their effects on the permanent magnet synchronous motor and its drive system but also suppress the harmonic current of the motor due to the distortion of the motor air gap magnetic field [30]. When Xiao et al. studied the variable frequency motor, they calculated and analyzed the electromagnetic excitation force characteristics of the motor air gap under the variable frequency excitation according to Maxwell's law and found that the high-frequency harmonic introduced by the converter would make the motor radiate a lot of noise near the switching frequency [31]. Huiying studies the soft switching technology to reduce the impact of harmonic input from the drive system on motor vibration [32].

The finite element method discretizes the motor into finite units through the principle of difference, which improves the accuracy of the electromagnetic calculation of the motor, and can deal with nonlinear and local saturation effects through the finite element method. Professor Xing et al. proposed a fast calculation method for electromagnetic force density in 2021 and verified the effectiveness of the method through finite element analysis [33]. Professor Feng et al. established an electromagnetic finite element model for the IPMSM with different air gap states and believed that the air gap deformation would affect the vibration calculation results [34]. Wang and Wu believed that the influence of low-frequency harmonic current on radial electromagnetic force depends on the amplitude and phase of the harmonic current [35]. Professor Wang Dong from the Naval University of Engineering calculated the radial electromagnetic force wave of the motor through the three-dimensional finite element method and summarized the variation law of the electromagnetic force wave along the axial direction of the motor [36]. Sun et al. of Hanyang University in South Korea used the finite element method and the Maxwell stress tensor method to calculate the radial electromagnetic force of two permanent magnet motors with 8 poles, 9 slots and 8 poles and 12 slots, respectively. The results show that the former has a larger lower order than the latter. Radial force [37]. Taking a 32 kW motor as an example, Zhou et al. analyzed the variation characteristics of harmonic magnetic field density and radial electromagnetic force when the power supply contains low-order harmonics by using the time-stepping finite element method and designed a low harmonic winding scheme to reduce the low-frequency vibration of the motor when the power supply contains low-order harmonics [38]. Zechen et al. calculated the magnetic potential and electromagnetic exciting force of single- and double-layer low harmonic winding by analytical method and compared the ordinary double layer short distance winding by 2D finite element analysis simulation. It was found that the single- and double-layer low harmonic winding improved its air gap magnetic density distribution and motor stability due to the reduction of magnetic potential harmonics of its stator winding. At the same time, due to the reduction of its radial magnetic density harmonic amplitude, the electromagnetic excitation force of the motor is reduced, which can effectively weaken the vibration and noise of the motor [39]. Liang et al. established the TMPS-HESM model of magnetic pole eccentricity when studying the vibration and noise of TMPS-HESM and established the vibration and noise model through ANSYS finite element simulation software, which effectively demonstrated that magnetic pole eccentricity can effectively reduce the harmonic content of air gap magnetic flux density, especially the third harmonic [40]. Liu et al. deduced the analytical expression of the electromagnetic force wave of DSR-PMSM by introducing the offset factor. Then, the vibration displacement response spectrum and noise sound pressure characteristics of DSR-PMSM before and after the internal and external armature teeth offset are analyzed and compared with the help of the finite element platform, which has certain theoretical value and engineering significance for improving the NVH performance of the motor [41]. Ai and Lan calculated the static characteristics and electromagnetic force of the motor by the finite element method, and the results verified the feasibility of the magnetic suspension operation of the motor [42].

4.3. Research Progress of Motor Structure Modal. The vibration of the motor is not only related to the electromagnetic excitation force but also to the structural mode of the motor. Common motor modal analysis methods include the analytical method, numerical method, and experimental method. The analytical method is mainly based on equivalent parameters (equivalent mass, equivalent stiffness, etc.), the numerical method is mainly based on the finite element method, and the experimental method is mainly based on the hammer method and the vibration exciter method [43].

The modal analysis of modern motor structures is a combination of the main finite element method and the experimental method. Wang and Wang analyzed the low-order natural frequencies of the large induction motor stator modal with windings and without windings and found that the finite element calculation results were lower than the experimental values when the windings were not considered. The conclusion is that the windings are not negligible and the end windings are negligible [43]. Xie Ying et al. studied the stator modes of small induction motors. She conducted experimental measurements and comparisons of the stator modes with end windings and the end windings removed and came to the conclusion that the end windings have little influence on the stator modes [44]. Dai and Cui Shumei also proposed a method to directly distinguish the natural frequencies of the various orders of the modal under the installed and working conditions of the motor according to the noise spectrum and electromagnetic excitation force characteristics [45]. Professor Hong et al. from Tsinghua University proposed a modal analysis method based on electromagnetic vibration exciter, which can well reflect the running state of the motor [46]. Li et al. studied the effects of windings and dipping paint on the natural frequency of the motor stator structure by a combination of finite element and experimental methods [47]. Jin et al. calculated the vibration characteristics and noise amplitude of the motor with or without stator core magnetostrictive effect and determined the influence of magnetostrictive effect on the harmonic distribution of motor vibration noise [48]. Wang and Wu provided a finite element core parameter prediction method for modal analysis of the motor stator core, which improved the simulation prediction accuracy [49]. Zhang et al. carried out a modal analysis on the stator of the permanent magnet synchronous motor through finite element analysis and hammering method. The results show that the modal frequency of the stator structure of the motor is greatly different from the frequency of the radial electromagnetic force wave, and resonance will not occur due to the radial electromagnetic force of the motor [50]. Professor Liu et al. established an equivalent digital physical three-dimensional model for the motor end cover, obtained the calculation mode and modal vibration mode of the end cover through modal analysis, and used a lightweight design method to optimize the structural topology of the motor end cover [51]. Huo and Hu proposed a dome topology, which is different from the traditional motor controller cover, to reduce motor vibration [52].

4.4. Research Progress of Electromagnetic Vibration of Motors. The natural extension of the electromagnetic force analysis and structural modal analysis of the motor electromagnetic vibration research analysis type is because the electromagnetic force analysis depends on the analysis of the electromagnetic field of the motor, and the characteristics of the electromagnetic field are greatly affected by the nonlinear characteristics of the ferromagnetic material of the motor, so the analytical method is based on the analysis method. The electromagnetic force analysis of the electromagnetic force can only analyze the frequency characteristics of the electromagnetic force but not the amplitude characteristics of the electromagnetic force. Therefore, the frequency characteristics of motor vibration are generally analyzed by analytical method, and the amplitude characteristics of motor vibration are analyzed by numerical method [53].

In the analysis of electromagnetic vibration by analytical method, Fiedler et al. combined the electromagnetic force obtained by the one-dimensional magnetic field and the cylindrical shell model and applied the modal superposition method to deduce the analytical model of electromagnetic vibration of the switched reluctance motor. The salient pole stator of the motor is quite different, and the model does not consider the actual end cover and installation constraints of the motor [54]. He studied the electromagnetic vibration and noise of the brushed DC permanent magnet motor, and his research showed that the thickness of the epoxy resin adhesive between the stator permanent magnet and the casing has a great influence on the stator structural mode and vibration noise [55]. Guo studied the electromagnetic vibration of the disc motor and established an analytical model of the electromagnetic vibration response of the disc motor [56]. Huang studied the electromagnetic vibration characteristics of induction motors with variable frequency power supply, pointed out that the electromagnetic force harmonic content is rich in variable frequency power supply, and suggested that the selection of carrier frequency should avoid the slot frequency of induction motors as much as possible [57]. Xie et al. studied the vibration characteristics of the induction motor when the end ring is broken and found that the side frequency vibration near the fundamental frequency changes significantly after the end ring is broken, and the motor can be diagnosed by analyzing the signal [58]. Yang proposed the method of using harmonic current injection to suppress motor vibration from the perspective of motor control. The effectiveness of this method is verified [59]. Through finite element simulation and prototype tests, Wang and Wang compared and evaluated the performance of two commonly used torque ripple and electromagnetic vibration suppression schemes in electric vehicle drive motor engineering. The results show that the rotor pole segmented motor can achieve the same force and energy quality as the skewed slot motor under the working condition of large load and inertia and has a good suppression effect on electromagnetic vibration [60]. Ren used the finite element method to simulate and analyze the vibration response of the motor for the harmonic current introduced by the inverter and established a multifield coupling vibration response prediction model of the permanent magnet synchronous motor [61].

5. Conclusion

The research on motor noise is very complex, it involves many disciplines, such as electromagnetism, acoustics, mathematics, mechanical structure, fluid mechanics, and the structure of the motor itself is also very complex, which brings more research difficulty. Here, this paper only briefly introduces the causes and research methods of various motor noises and briefly reviews the research progress in this field in recent years. The conclusions are as follows:

(1) The mechanical noise of the motor is mainly generated by the interaction between the various components in the operation of the motor. The earliest research on the vibration and noise of the motor in the world is the mechanical noise. Because it is mainly related to the structure and manufacturing materials of the motor, the current research is mainly aimed at this.

(2) The aerodynamic noise of the motor is mainly related to the airflow in the motor ventilation pipe, which mainly involves aerodynamics, fluid mechanics, and other disciplines. At present, the main research methods are still based on Lighthill's aeroacoustic theory and statistical energy method, and numerical simulation of the airflow in the motor is carried out through computer simulation software.

(3) The electromagnetic noise of the motor is mainly generated by the radial electromagnetic force, which is also a hot spot in the research field of motor vibration and noise. In recent years, the research mainly focuses on the analysis and calculation of electromagnetic force wave and its vibration principle, as well as the main parameters affecting vibration. The calculation method of electromagnetic force wave and electromagnetic vibration is extended from the simplified analytical method to the finite element method. Because the finite element method has high solution accuracy and fast convergence speed, the numerical simulation is better.

With the progress of society and the development of technology, especially the development of some new special motors, further research is needed on the vibration and noise of motors.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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