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Digital Twin of Permanent Magnet Synchronous Motor Based on Finite Element Analysis and UNITY

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ABSTRACT

Permanent magnet synchronous motor is the key equipment in modern industry and intelligent manufacturing, at the same time, the environment for permanent magnet synchronous motor work is also diverse. Through digital twin technology to solve the problem of understanding the working conditions of permanent magnet synchronous motor, not only greatly improves the work efficiency but also can improve the utilization degree of permanent magnet synchronous motor. Aiming at the problem of digital twin realization of permanent magnet synchronous motor, a method combining finite element analysis and Unity3D dynamic display technology is proposed. In order to realize the purpose of the digital twin and the function of data driving and data mapping, the motor running data is obtained by analyzing the state of a motor with finite element analysis technology. The radial basis function (RBF) interpolation is used to calculate the speed condition without finite element analysis, thus realizing the finite element data of the full speed condition of the permanent magnet synchronous motor. The digital twin platform of the permanent magnet synchronous motor is established by Unity3D software, which can realize the functions of virtual and real mutual control, real-time connection, and state monitoring.

1. Introduction

A permanent magnet synchronous motor is the key equipment in modern industry and intelligent manufacturing. With the continuous development of high-speed processing technology, precision manufacturing technology numerical control technology, and other advanced manufacturing technologies in today's society, permanent magnet synchronous motors are gradually evolving into the current development trend of numerical control equipment. In 2022, sales of new energy vehicles in China reached 6.887 million units[1], a year-on-year increase of 93.4%, PMSM[2] is widely used in the fields of new energy, equipment manufacturing, aerospace and smart home[3], and occupies a crucial position in modern industry and intelligent manufacturing.

Permanent magnet synchronous motor has obvious advantages.

(1) High efficiency. The excitation source of PMSM is a permanent magnet, which saves part of the electric energy required for exciting the magnetic field.

(2) Small size, high power density, and lightweight.

(3) Wide speed range. The excitation field generated by PMSM's permanent magnet is used to adjust the motor current and frequency, so as to achieve the adjustment range of motor power and speed.

(4) High reliability and safety.

In industrial production, the reliability and stability of permanent magnet synchronous motors are of great significance to the safe operation of the whole system. If the motor fails, it may lead to system shutdown, bring economic losses, and even endanger the life safety of the staff in serious cases[4].

With the development of various emerging information technologies and the proposal of Industry 4.0 and intelligent manufacturing, digital twin technology has been proposed as an effective means to realize intelligent manufacturing. Faced with a problem that can not be effectively monitored, digital twin technology provides an effective method for real-time perception, accurate prediction, and fault diagnosis by establishing the digital twin model of the object and realizing intelligent decision-making through twin data analysis and simulation verification.

Digital twin technology, as the name suggests, is to build a "twin" that corresponds to a physical entity in the digital world. It makes full use of physical models, sensor data, operation history, and other data, and completes mapping in virtual space by integrating multi-discipline, multi-physical quantity, multi-scale, and multi-probability simulation process, so as to realize real-time

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monitoring and simulation analysis of the whole life cycle of physical equipment[5]. The digital twin combines the design parameters of the physical prototype with the historical operation data, integrates the multi-disciplinary and multi-physical modeling and simulation process, maps the physical prototype to the virtual space in an all-around way, and simulates the whole life cycle process of the physical prototype[6].

First, digital twin technology enables digital modeling, that is, the construction of digital models corresponding to physical entities. This model can accurately reflect the geometry, physical properties, operation logic, and other information of the physical entity. Secondly, data integration and processing are also a major feature of digital twins. According to the information of sensors and data sources, digital twin technology can carry out efficient data processing and analysis, mining massive data and extracting valuable information. in addition, based on digital models and data integration, digital twin technology can realize real-time simulation and monitoring of physical entities. By simulating the operating state of physical entities, the performance changes are predicted to provide real-time support for decision-making.

Since the digital twin technology was put forward, the concept has caused an upsurge in various professions[7-8]. The rapid development of information technology and digital technology has further promoted the research and application of digital twins in many industries such as manufacturing, urban management, medical care, agriculture, and electricity. In manufacturing, digital twins are expected to solve the problem of how the physical world and the information world interact and integrate in advanced manufacturing [9].

Therefore, the author boldly innovates the combination of a digital twin and a permanent magnet synchronous motor to find a way to realize the digital twin of a permanent magnet synchronous motor. It provides a new way of thinking not only for motor design and manufacture but also for state detection and state prediction of the permanent magnet synchronous motor running process.

2. Experimental platform

Tao Fei's team from Beijing University of Aeronautics and Astronautics proposed the concept of "digital twin workshop" and the five-dimensional model of digital twin [8-9], and expounded the architecture of digital twin system construction.

$$\mathrm{M_{DT}} = (\mathrm{PE}, \mathrm{VE}, \mathrm{Ss}, \mathrm{DD}, \mathrm{CN}) \qquad (2\text{-}1)$$

(2-1) In the formula, PE represents the physical entity, VE represents the virtual entity, Ss represents the service, DD represents the twin data, and CN represents the connection between the components.

According to this five-dimensional model theory, the author uses ANSYS finite element analysis and UNITY 3D animation display function to propose a method to realize the digital twin and build a platform.

The main components of the permanent magnet synchronous motor digital twin experiment platform are:

(1) A Lenovo Legion Y7000 2020 laptop as the host computer.

(2) The invention relates to an 80-permanent magnet synchronous motor and driving system thereof.

(3) A planetary reducer.

(4) A magnetic particle brake, a torque sensor.

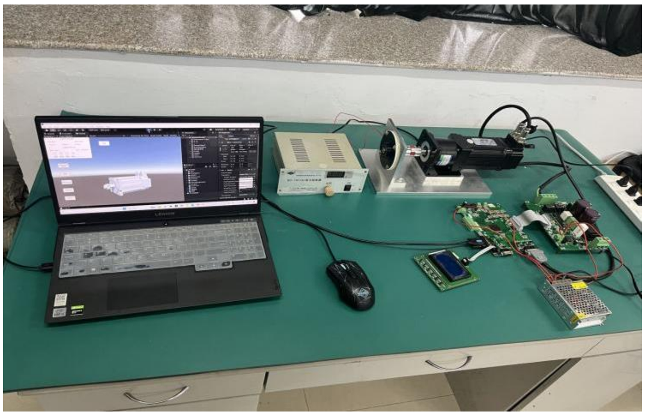

Fig. 1. Experimental platform of digital twin system of permanent magnet synchronous motor

Taking a permanent magnet synchronous servo motor as the center, an experimental platform of a digital twin system of permanent magnet synchronous motor is built. The driving device and magnetic powder brake are used to realize the performance change of the motor under different loads at different speeds. The motor drive device is composed of a motor control board with DSP2812 as the core and a 3KW drive board. This DSP2812 control board ADC acquisition has 8-channel synchronous sampling and 16-bit high-precision off-chip ADC. With DAC conversion, incremental with Hall photoelectric encoder and DB9FM communication interface, voltage and current acquisition and serial communication can be realized. On the other hand, the DSP2812 control board can be controlled by an external keyboard and LCD screen display. In order to realize the virtual and real interaction of the digital twin system, the author adds RS232 serial communication, so that the client can upload the data collected by the sensor through serial communication and realize the control of the drive system by the host computer.

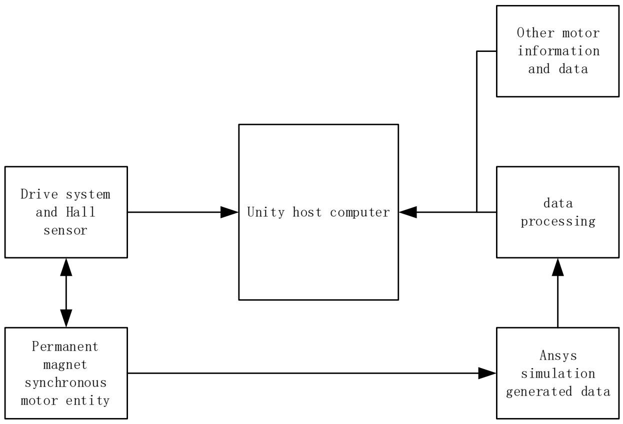

Fig. 2. Digital twin system architecture model

This system is also divided into five parts:

(1) Physical entity: consists of a permanent magnet synchronous servo motor, driver and sensor, and other physical components.

(2) Virtual model: It is modeled by SolidWorks, rendered by 3DMAX, and finally imported into the unity3D platform to build.

(3) Connection: Serial communication is used to achieve communication between physical entities and computers. Using Python to realize the communication between data and Unity3D host computer platform.

(4) Data: The 1:1 model of the motor was simulated by Ansys

software. Through the analysis of the electromagnetic field and stress field, all the data of the permanent magnet synchronous motor under the specified working conditions at each speed are obtained and stored.

(5) Services: Use the unity3D platform to build an upper computer interface to realize virtual and real mutual control of the solid motor. The data in finite element analysis of the motor is obtained and the harmonic response field is calculated by radial basis function interpolation. In the upper computer platform, the finite element working conditions of all motor speeds are displayed in real-time.

3. Finite element analysis of permanent magnet synchronous motor with 1:1 model

Finite Element Method (FEM) is an effective numerical method for solving initial boundary value problems of partial differential equations. From the point of view of applied mathematics, the basic idea of the finite element method can be traced back to the work of Courant in 1943, who first tried to apply the pieced continuous function defined on a series of triangular regions in combination with the principle of minimum potential energy. To solve St. Venant's twist problem. Since then, many applied mathematicians, physicists, and engineers have studied the discrete theory, method, and application of finite element method from different angles. With the rapid development of computer science and technology, the finite element method, as an effective method of engineering analysis, has been extended from the initial application in solving two-dimensional problems of planar structures to three-dimensional problems. The problem of statics is extended to the problem of dynamics and stability. From linear problems to nonlinear problems; From structural mechanics to fluid mechanics, electromagnetism, heat transfer, and other disciplines; From aviation technology to aerospace, civil construction, machinery manufacturing, water conservancy engineering, shipbuilding, electronic technology, and atomic energy technology, and other fields; From the solution of a single physical field to the coupled calculation of multiple physical fields, its application has been greatly expanded in depth and breadth and has become an important part of computer-aided engineering (CAE).

The basic idea of the finite element method is to discretize the continuous solution domain of a complex model into a set of finite elements that are connected in a certain way. By assuming a reasonable approximate solution for each small unit, the condition of solving the whole domain is deduced, and then the approximate solution of the model is obtained. The connecting points of the elements are called "nodes", the collection of elements is called the finite element structure, and the specific arrangement of elements is called the "grid". Compared with other numerical methods, the finite element method has many advantages and characteristics: Finite element analysis (FEA) can be used for any field problem, such as heat conduction, stress analysis, magnetic field problems; There are no geometric constraints, and the object or area being analyzed can have any shape; Boundary conditions and loads are not limited; Material properties are not limited to isotropy and can vary from one unit to another or even within a unit; Components with different behaviors and different mathematical descriptions can be combined; The finite element structure is similar to the object or region being analyzed; The approximation of the solution can be easily improved by grid subdivision so that more units will appear where the field gradient is large and more equations need to be solved.

ANSYS software is a large general finite element analysis software developed by the American ANSYS company. It is the fastest-growing computer-aided engineering (CAE) software worldwide. It can be connected with most CAD software interfaces to realize data sharing and exchange. It is a large general finite element analysis software integrating structure, fluid, electric field, magnetic field, and sound field analysis. It is widely used in the nuclear industry, railway, petrochemical, aerospace, machinery manufacturing, energy, automobile transportation, national defense, electronics, civil engineering, shipbuilding, biomedicine, light industry, mining, water conservancy, household appliances, and other fields. ANSYS is powerful, simple, and convenient to operate, and has become an internationally popular finite element analysis software.

ANSYS Maxwell and ANSYS Workbench are simulation software that can provide individual and coupled calculations of multiple physical fields such as electromagnetic fields, temperature fields, structural fields, and sound fields.

3.1 Electromagnetic field simulation based on Maxwell

After actual measurement, the basic parameters of the permanent magnet synchronous motor are shown in the table:

Tab. 1. PMSM main parameters table

name of parameter	parameter values
Rated power	0.75KW
Rated speed	3000r/min
Rated torque	2.4N.m
Rated current	4.2A
Number of rotor poles	4
Stator slots	18
The outer (inner) diameter of the stator	74（42）mm
Rotor outside (inside) diameter	39（22）mm
Stator total length	55mm

According to the actual measurement data, a 1:1 2D model of the permanent magnet synchronous motor is established in ANSYS Maxwell. The electromagnetic simulation analysis of the permanent magnet synchronous motor is carried out to obtain the electromagnetic field data of the permanent magnet synchronous motor at various speed states.

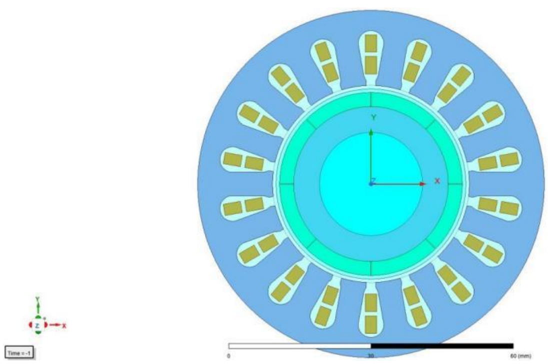

Fig. 3. Digital twin system architecture model

(1) A series of equations of permanent magnet synchronous motor in the three-phase natural stationary coordinate system are as follows:

The voltage equation is:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} \quad (3\text{-}1)$$

Among them, u_a, u_b and u_c are the terminal voltage, i_a, i_b and i_c are the current of the three-phase winding, ψ_a, ψ_b and ψ_c are the flux of the three-phase winding, and R_s is the phase resistance.

The flux linkage equation is:

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} cos\theta \\ \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{4\pi}{3}) \end{bmatrix} \psi_f \quad (3\text{-}2)$$

Among them, L_{aa}, L_{bb} and L_{cc} are one-phase winding self-inductance, $L_{ab} = L_{ba}, L_{bc} = L_{cb}$ and $L_{ac} = L_{ca}$ are mutual inductance of three-phase winding, ψ_f is permanent magnet flux in the rotor and θ is the angular displacement of the rotor.

(2) In a permanent magnet synchronous motor, the permanent magnet generates a constant magnetic field in the air gap, and a rotating magnetic field is generated when alternating current is applied to the three-phase stator winding. The interaction between these two magnetic fields is the source of electromagnetic torque.

(3) For a permanent magnet synchronous motor, the stator flux ψ can be expressed as the sum of the permanent magnet flux ψ f and the flux generated by the stator current. However, in many simplified models, we mainly consider the interaction between the permanent magnet flux linkage and the direct axis component (D-axis) of the stator current.

$$\psi = \psi_f + L_d i_d \quad (3\text{-}3)$$

WhereL_d is the D-axis inductance and i_d is the D-axis current component.

(4) Electromagnetic power P_{em} is the product of electromagnetic torque Tem and rotor angular velocity ω.

$$P_{em} = T_{em}\omega \quad (3\text{-}4)$$

The electromagnetic power can also be expressed as the product of the stator voltage v and the stator current i minus the loss on the stator resistance.

$$P_{em} = \text{vi} - i^2 R \quad (3\text{-}5)$$

In the case of steady-state and ignoring resistance loss, it can be simplified as:

$$P_{em} = \text{vi} \quad (3\text{-}6)$$

(5) The expression of electromagnetic power is combined with the relation between electromagnetic torque and angular velocity. We get:

$$T_{em} = \frac{P_{em}}{\omega} = \frac{vi}{\omega} \quad (3\text{-}7)$$

Here v and i are instantaneous values, and in order to get a more intuitive expression, we consider using the relationship between flux and current. In motor theory, the voltage v can be expressed as the sum of the flux change rate and the resistance voltage drop.

$$\text{v} = \frac{d\psi}{dt} + Ri \quad (3\text{-}8)$$

Since we ignore the resistance loss, the above formula simplifies to:

$$\text{v} \approx \frac{d\psi}{dt} \quad (3\text{-}9)$$

Substituting the expression for the flux linkage into the above equation, and considering that ψ_f is a constant, we get:

$$\text{v} \approx L_d \frac{di_d}{dt} \quad (3\text{-}10)$$

But what we really need here is an expression that is directly related to electromagnetic torque. In the d q axis model, electromagnetic torque can be expressed as:

$$T_{em} = \frac{3}{2} p(\psi_f i_q + (L_d - L_q) i_d i_q) (3\text{-}11)$$

Where p is the number of poles, i_q is the Q-axis current component, and L_q is the Q-axis inductance. For surface mount permanent magnet synchronous motor ($L_d = L_q$). The above formula is simplified as:

$$T_{em} = \frac{3}{2} p \psi_f i_q \quad (3\text{-}12)$$

The stator current excitation is set as current source excitation, and the stator winding current is set as steady state. At this time, the performance of the motor at the initial moment, such as torque, power, etc., is in a stable state. The electromagnetic state of the permanent magnet synchronous motor under multi-speed conditions is generated by the parametric scanning method. Grid division and boundary conditions were set for each part of the motor, and the simulation time of the solver was set to 4 electrical cycles. The motor speed is set from 30r/min to 3000r/min, and the calculation parameterization scan is performed every 30. When the motor current RMS value is 1.4A, the simulation results show that the distribution of magnetic field lines is more uniform and symmetrical, and the direction of magnetic induction lines is correct. The average torque of the digital twin motor is 0.8N·m.

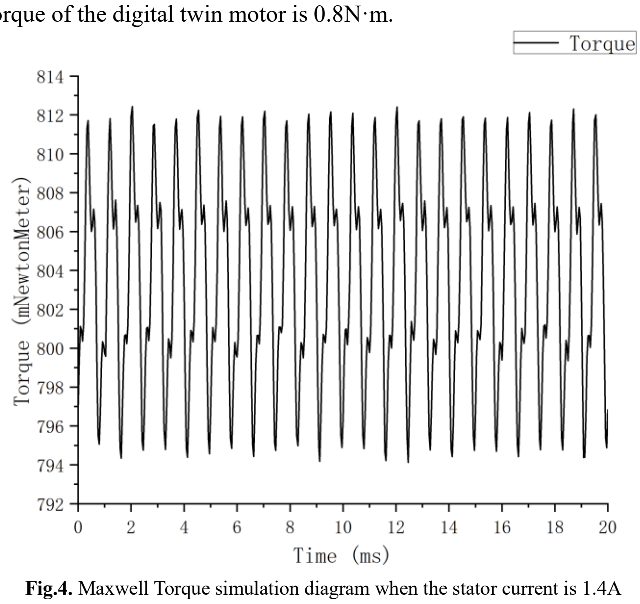

Fig.4. Maxwell Torque simulation diagram when the stator current is 1.4A

The measured torque is about 2.5N·m (the motor is equipped with a 1:3.25 reducer). There is little difference between the simulation data and the experimental data, and the digital twin motor constructed by simulation is consistent with the solid motor.

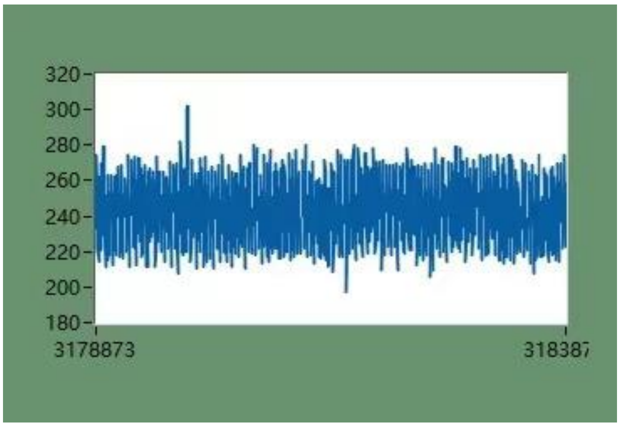

Fig. 5. The stator current is 1.4A torque diagram actually measured by the torque sensor

3.2 Harmonic response field simulation based on workbench Mechanical

In terms of excitation, the electromagnetic vibration and noise are generated by the radial electromagnetic wave of the built-in permanent magnet synchronous motor acting on the stator structure. The electromagnetic wave is approximately proportional to the radial air gap magnetic density square of the motor, and the output torque of the motor is also proportional to the radial air gap magnetic density. Therefore, electromagnetic vibration and noise are an inherent property of the motor. As long as the motor needs to output torque, electromagnetic vibration must exist. Maxwell simulation results were put into the Ansys Workbench platform for joint simulation with Mechanical to obtain the harmonious response frequency diagram of the deformation diagram of the stator and shell of the motor under different speed conditions when the motor was working.

At present, when the calculation method of permanent magnet synchronous electromechanical force is discussed, the two main methods include the analytical method and the finite element method. The analytical method relies on accurate field analytical calculation methods, aiming to obtain the radial and tangential expressions of the magnetic density of the air gap, and then derive the analytical expressions of the electromagnetic force based on the Maxwell stress equation. On the other hand, finite element methods are usually based on two-dimensional electromagnetic field calculations, combined with techniques such as equivalent magnetic current, equivalent magnetic charge, or Maxwell stress methods to solve the electromagnetic force.

For the permanent magnet synchronous motor with surface attached rotor structure described in this paper, the analytical method is a suitable choice because of its clear concept and simple formula. Considering that the circumferential flux density of permanent magnet synchronous motor is relatively small, it is usually negligible in qualitative analysis. In summary, the analytical method provides an effective and intuitive method for understanding and calculating the electromagnetic force of permanent magnet synchronous motors with surface-mounted rotor structures.

Based on Maxwell stress tensor theory, the equation for calculating radial electromagnetic waves is as follows [12];

$$P_n(\theta,t)=\frac{b^2(\theta,t)}{2\mu_0} \tag{3-13}$$

In the formula:

$P_n(\theta,t)$--Radial electromagnetic wave(pa or N/M^2);

$b(\theta,t)$--Radial flux density wave;

μ_0--air permeability;

When the motor is running without load, the air gap magnetic field is;

$$b_1(\theta,t)=\sum_{\mu} B_\mu \overline{\Lambda_0}\cos\left(\mu\frac{\omega_1}{P}t-\mu\theta\right)$$

$$+\sum_\mu\sum_k(-1)^{k+1}\frac{1}{2}B_\mu\overline{\Lambda_0}\cos[\mu\frac{\omega_1}{P}t-(\mu\pm kZ_1)\theta] \tag{3-14}$$

In the formula:

B_μ--The density amplitude of the μTH power magnetic field;

Λ_0--Air gap ratio permeability;

Λ_k--KTH air gap permeability;

ω_1--line frequency;

θ--phase angle;

P--Number of motor poles;

Z_1--Stator slots;

When a symmetrical current flows through the stator winding, in addition to the magnetic field generated by the no-load state, an additional armature reaction magnetic field will be generated due to the action of the current. These armature reaction magnetic fields will affect the magnetic density in the air gap and form a specific magnetic density distribution of the air gap.

$$b_2(\theta,t)=\sum_v b_v\cos[\omega_1 t-v\theta-(\phi-90°)] \tag{3-15}$$

In the formula:

b_v--Armature field v harmonic density value;

ϕ--Motor power Angle;

When the permanent magnet synchronous motor is running under load, its radial force wave is:

$$P_n(\theta,t)=\frac{b_2^2(\theta,t)}{\mu_0} \tag{3-16}$$

A series of important characteristics about radial force waves can be derived by integrating trigonometric functions and difference transformations of equation (3-16) These features include their source, amplitude, spatial order, and frequency characteristics.

The electromagnetic simulation model of permanent magnet synchronous motor established in workbench platform was set up for speed parameterization. Through this operation, the simulation results of the motor from 30-3000 RPM at every 30 RPM are calculated, and the electromagnetic force is calculated. The electromagnetic force calculation results are imported into the harmonic response analysis module to establish the electromagnetic-structure coupling analysis model.

The deformation of the motor housing and stator at 30 to 3000 RPM every 30 RPM is exported and saved.

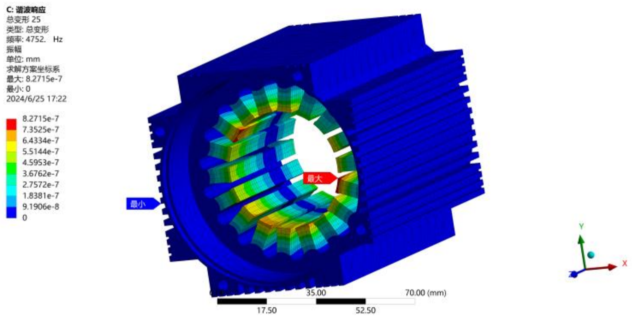

Fig. 6. Distortion diagram of motor shell and stator in harmonic response field at A2970r/min

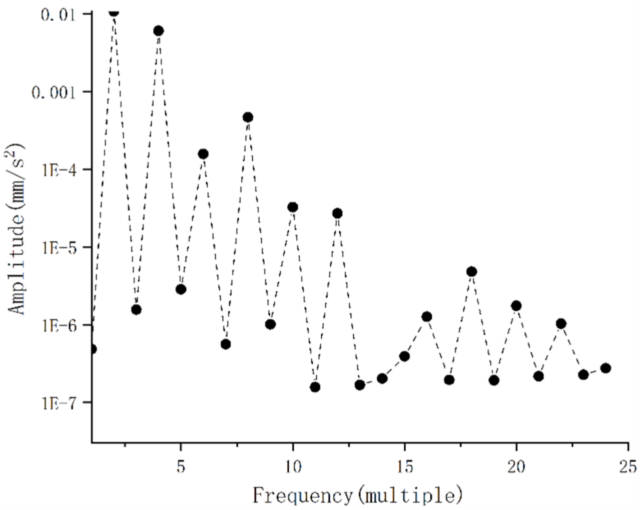

Fig. 7. Amplitude and frequency diagram of A2970r/min time-harmonic response field

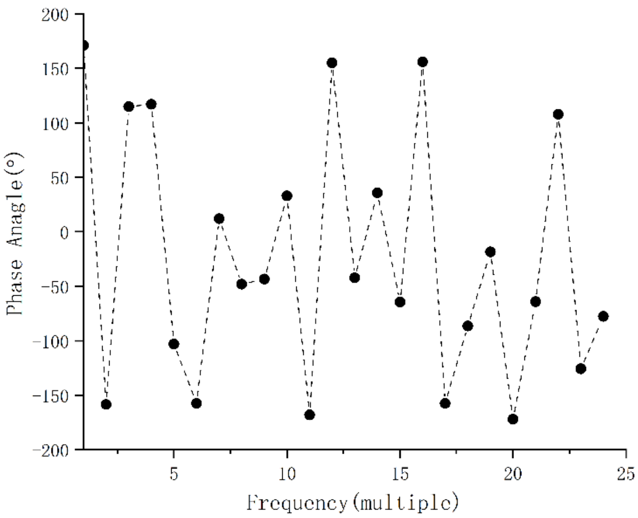

Fig. 8. Phase Angle and frequency diagram of A2970r/min time-harmonic response field

4. Data processing and communication connections

Because the accuracy of data is pursued in Mechanical simulation, the grid is divided as much as possible. The number of simulated nodes is 173140 and the number of cells is 49963. The finite element simulation results obtained by Mechanical simulation were derived and called as the source data model. However, due to the upper limit of the number of model points in unity3d and a large number of facets, the calculation amount is too large and the software is stuck. Therefore, the model is simplified to the number of nodes is 22449 and the number of units is 4233, and the corresponding model nodes are derived and called the simplified data model.

Using Python to create a data processing and prediction system, involving data import, processing, modeling, and prediction, while realizing the function of data prediction through the network interface. First, the model node data is processed. Then, the radial basis function (RBF) interpolation is used to operate on each point in the simplified data model, that is, an RBF interpolator is created using the coordinates of several nearest neighbors of the simplified data model points in the source data model set and the obtained deformation values. The RBF interpolator uses the Gaussian function as the basis function to calculate the deformation value of each node in the simplified data model based on the distance between the original data point and the nearest neighbor. Then, the preprocessed data is read and the radial basis function interpolation (RBF) algorithm is constructed to train the interpolation model. This approach can effectively predict the finite element data of the model node under the missing rotational speed condition, and save the trained model to a file using Joblib. Finally, TCP service is established through Socket to receive data request from network. Predictions are made based on the received data requests and the results are returned to the requestor over the network. This program constitutes a complete data processing, modeling and forecasting system, allowing users to obtain real-time prediction results through a network interface.

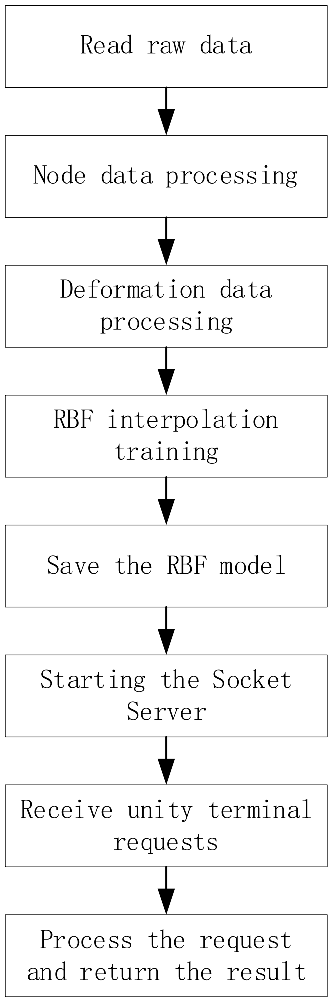

Fig. 9. Flowchart of RBF algorithm

4.1 K-nearest neighbor algorithm (KNN)

The KNN algorithm is used to find K neighbors closest to a certain point. Here, we use K=5, that is, to find the nearest neighbor deformation data point of each data point. The modeling method can be simplified to avoid nonlinear and non-Gaussian problems. The calculation amount is reduced and the time of fault diagnosis is shortened by dimensionality reduction. To solve the non-protection distance problem of principal component dimensionality reduction in transition mode, further mining the information of sampling data and improving the utilization rate of transition mode data. [13]

Specific steps are as follows:

For each simplified data point$X_i = (x_i, y_i, z_i)$, set label $y_i = 1$.

For each raw data point$d_j = (x_j, y_j, z_j)$, Find its nearest neighbor data points using KNN$X_{nearset}$, suffice:

$$X_{nearset} = argmin\|X_j - d_j\| \tag{4-1}$$

4.2 Radial Basis function (RBF) interpolation

The radial Basis Function (RBF) interpolation method is a kind of commonly used multidimensional data interpolation method. This method does not require that the sampling points (that is, the input Data) have a structured grid form in space, and is a class of Scattered Data Interpolation methods, which is a method of estimating the value of a point by a weighted average of the surrounding points, often used for interpolation and smoothing. Here, using the Gaussian radial basis function, the formula is:

$$f(x) = \sum_{i=1}^{n} \phi(\|x - x_i\|) \cdot \omega_i \tag{4-2}$$

$x = (x, y, z)$ is the point of the original model interpolation. $X_i = (x_i, y_i, z_i)$ is a simplified data model point. $\phi(r) = e^{-(\epsilon\gamma)^2}$ is a Gaussian radial basis function, and ω_i is the weight.

When the nearest neighbor data points are found through KNN, the radial basis function interpolation will use the values and weights of these adjacent points for interpolation calculation to generate estimates of missing data points. By training the radial basis function interpolation model, it can effectively learn from the data of a given point and multiple speeds and predict the missing unknown speed data points.

4.3 Communicating junctions

Use Python to transfer real-time data of the trained radial basis function interpolation model. Multi-threading is used to connect with the client to ensure that the server processes requests from multiple clients at the same time, and will not affect the response of other connections due to blocking. In addition, the client of the Unity3d platform sends data requests to the server to obtain corresponding results.

Serial communication is used to connect the motor body, driver, sensor, and unity3d host computer platform. The upper computer platform can control the motor speed, forward reversal, running, and stopping functions by controlling the driver and receiving the motor DC bus voltage, stator current, and other data collected by the sensor.

5. Unity 3D platform construction

Unity3D is a cross-platform game development tool developed by Unity Technologies. It is feature-rich and can provide powerful 3D modeling and rendering functions. Users can model basic 3D objects directly in Unity, or import complex models created by external modeling software [14]. Unity3D also has good kinematics and dynamics simulation functions, which can be used for virtual simulation of robot kinematics, dynamics, and navigation algorithms [15]. Unity3D has a complete built-in physics engine, which supports physical simulation functions such as rigid body dynamics, collision detection, and joint constraint, enabling developers to easily achieve complex physical interaction effects. Unity3D provides a wealth of user interaction design tools, such as UI system, input manager, etc., enabling developers to design user-friendly interactive interfaces and interaction logic conveniently. Unity3D supports programming with C#, JavaScript, and other scripting languages, enabling developers to flexibly implement various complex game logic and interactive functions.

Unity3D has a high visualization degree, strong interaction, supports cross-platform publishing, high development efficiency, and strong scalability.

This system adopts Unity3D technology, and its architecture mainly includes modules such as scene construction, control interface, state display, and finite element display.

The system mainly consists of the following parts:

① Sensor data upload module: The sensor is used to detect the running state of the motor in real-time, and the important data of the current state of the motor is uploaded to the user for display. It mainly includes DC bus voltage, motor speed, three-phase stator current value, and speed control operand, and gives the motor working mode and motor running state through DSP analysis.

The modes are:

(1) Ran: Displayed as "run0".

(2) Stop: Displayed as "stop".

The states are respectively:

(1) Normal: Displayed as " normal000".

(2) Protection: Displayed as " protect00".

(3) Hall fault: Displayed as " hallfault".

(4) overcurrent: Displayed as " current00".

(5) Fault: Displayed as " fault0000".

② Control interface: 8 keys were set through the UI of Unity3D. When the key is pressed, Unity3D will send corresponding data to the serial port according to the script program. When the DSP2812 control board receives the data, it will realize the control of the permanent magnet synchronous motor entity according to the written program.

The functions that can be realized by the key are:

(1) Forward rotation.

(2) Operation.

(3) Key operation +10 (300 RPM increase).

(4) Key operation +1 (30 RPM increase).

(5) For inversion.

(6) Stop.

(7) Key operand -10 (speed reduced by 300 RPM).

(8) Key operand -1 (30 RPM reduction).

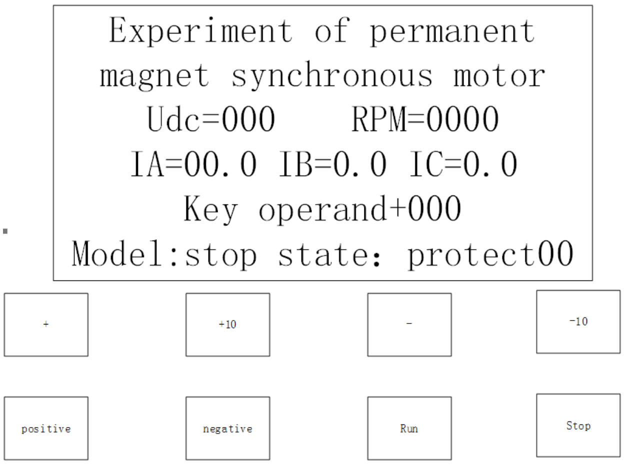

Fig. 10. Virtual and real interface of Unity3DUI panel

③ Motor model: First, the model was modeled 1:1 according to the real data of the motor by SolidWorks, rendered by 3DMAX, and then imported into the unity3D platform. It shows the physical characteristics of the motor, the structure and operation of each part, and can run synchronously according to the real speed of the motor, showing the real operation of the motor;

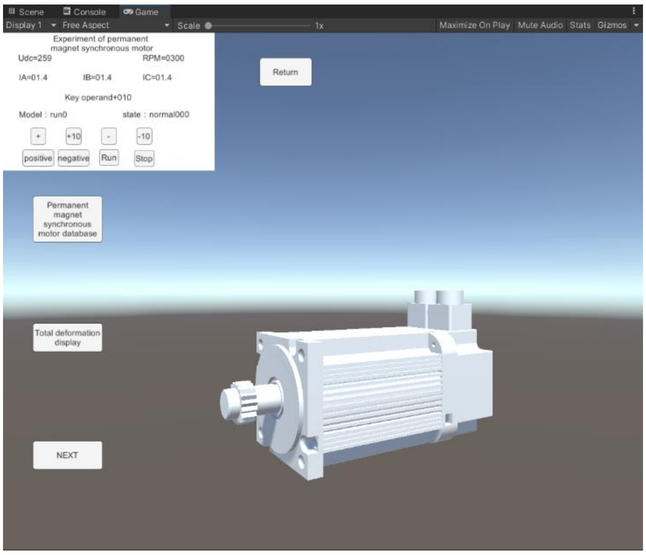

Fig. 11. Interface of Unity3D digital twin system

④ Permanent magnet synchronous motor database module: It is used to introduce the situation and information of each component of permanent magnet synchronous motor. Established a permanent magnet synchronous motor database, the basic information of each component of the motor can be displayed on the platform, click and pop up a separate model display can be viewed in stereo and the database introduction content.

⑤Finite element dynamic display module: The finite element data of PMSM at each speed state obtained by ANSYS finite element analysis and RBF algorithm and the real-time speed data of the motor uploaded by the sensor can be used to control the display state of the digital twin model of the PMSM and synchronize the data update display. The real virtual display of the motor shell and stator in the figure can be obtained, and the digital mapping of the finite element data of the permanent magnet synchronous motor is preliminarily realized.

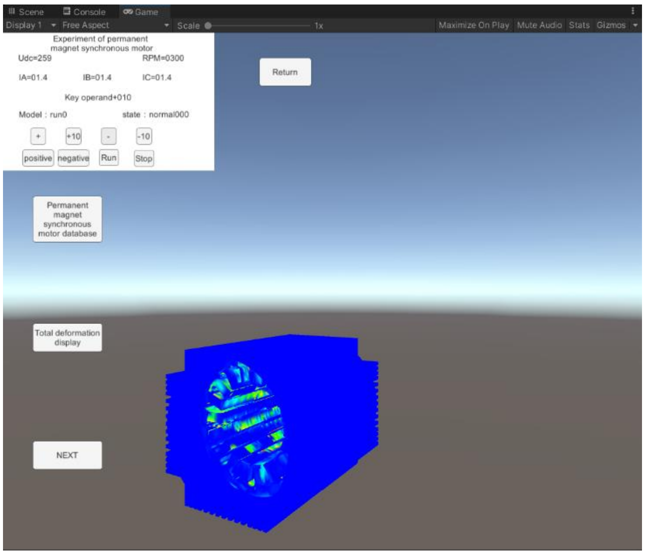

Fig.12. Unity3D finite element display interface

6. Summarize

As the core power source of modern industry and electric vehicle field, the performance optimization and operation efficiency improvement of permanent magnet synchronous motor are of great significance to promote industrial upgrading. The core of digital twin technology is to build a virtual model that is highly mirrored to the physical entity.

The digital twin system of permanent magnet synchronous motor simulates the electromagnetic field and harmonic response field of 30-3000 revolution every 30 revolution in the specified working condition in advance, and stores the data under each working condition. In order to fill the data gap between simulation points, the Radial Basis Function (RBF) algorithm is introduced for interpolation and prediction. RBF algorithm, with its powerful nonlinear approximation ability and fast learning speed, can effectively predict the speed condition without direct simulation according to the existing simulation data. This step not only significantly reduces the computational cost of direct simulation, but also significantly improves the continuity and integrity of the data, making it possible to predict the performance of the motor in the full-speed range. RBF algorithm is used to calculate the speed condition that is not simulated, and the operation data of the motor at full speed can be obtained, which can be provided to the Unity3D host computer platform for calling. Through Unity3D, users can intuitively see the 3D model of the motor, and dynamically adjust the perspective according to demand to obtain the best observation experience. More importantly, the Unity3D platform integrates the communication interface with physical entities and realizes real-time data exchange between virtual models and PMSM physical entities through serial ports or other communication protocols. This means that any operation or adjustment done by the user on the Unity3D interface can be immediately reflected on the physical motor to achieve virtual and real mutual control; At the same time, the real-time running state data of the motor can also be synchronously returned to the Unity3D interface for user monitoring and analysis. Through the Unity3D host computer platform, various functions such as virtual-real interaction, data mapping, and so on are integrated, which facilitates users' information acquisition, intuitive viewing, real-time control, and data-driven functions.

References

Jinfeng An, 2021. Design of Model Predictive Control System for Permanent Magnet Synchronous Linear Motor Based on Adaptive Observer. J. International Journal of Applied Mathematics in Control Engineering, 4(1):135-141.

Yijian Liu, 2023. Extended State Observer Based on Fixed Time Sliding Mode Control of Permanent Magnet Synchronous Motor. J. International Journal of Applied Mathematics in Control Engineering, 6(1):158-165.

Feng Zhiqiang, Guo Li, Liao Yu, et al. Twin Model for Monitoring Stator Temperature Rise of Permanent Magnet Synchronous Motor [J/OL]. Control Engineering, 1-9 [2024-06-25]. https://doi.org/10.14107/j.cnki.kzgc.20220585.

Zhang Xiaodan, Duan Bin, Liu Changjie, Chen Yueping. An Open-Circuit Fault Diagnosis Method for Permanent Magnet Synchronous Motor Drive System Based on Body Tracking [J]. Transactions of China Electrotechnical Society, 2022, 37(13): 3341-3349+3360.

Grieves, M. (2005). Product Lifecycle Management: The New Paradigm for Enterprises. Nuclear Engineering and Design, 235(10), 1063-1080.

Zhang Xun, Wang Jiansheng, Kang Xianmin, et al. Construction and Temperature Prediction of Digital Twin Model for Electric Motors [J]. Mechanical Engineering and Automation, 2024, (01): 11-13.

Grieves, M. Digital Twin: Manufacturing Excellence through Virtual Factory Replication [J]. 2015.

Shafto M, Conroy M, Doyle R, et al. Modeling, Simulation, Information Technology and Processing Roadmap [J]. 2010.

Shen Chen, Cao Qianni, Jia Mengshuo, et al. Concept, Characteristics, and Application Prospects of Digital Twin in Power Systems [J]. Proceedings of the CSEE, 2022(002): 042.

Tao Fei, Zhang Meng, Cheng Jiangfeng, et al. Digital Twin Workshop: A New Mode of Workshop Operation in the Future [J]. Computer Integrated Manufacturing Systems, 2017, 23(1): 9. DOI: 10.13196/j.cims.2017.01.001.

Tao Fei, Huang Zuguang, Ma Xin, et al. Five-Dimensional Model of Digital Twin and Its Applications in Ten Domains [J]. Computer Integrated Manufacturing Systems, 2019, 025(001): 1-18.

Liang Y, Hu Y, Liu X, et al. Calculation and Analysis of Can Losses of Canned Induction Motor [J]. IEEE Transactions on Industrial Electronics, 2014, 61(9): 4531-4538. DOI: 10.1109/TIE.2013.2290762.

Mengya Shao, 2018. KNN Transition Period Fault Detection Based on Random Projection.J. International Journal of Applied Mathematics in Control Engineering, 1(2):172-179.

Guo Haixiang, Zhu Ling, Jiang Jiannan. Research on Digital Twin Robotic Arm Grasping System Based on Unity3D [J/OL]. Journal of Qiqihar University (Natural Science Edition), 2024, (02): 1-7 [2024-06-26]. https://doi.org/10.20171/j.cnki.23-1419/n.2024.02.014.

Qin Chaolong, Song Aiguo, Wu Changcheng, et al. Scenario Interaction System for Rehabilitation Training Robot Based on Unity3D and Kinect [J]. Chinese Journal of Scientific Instrument, 2017, 38(3): 530-536.

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