An Optimization Approach of Rotor Contour for Variable Reluctance Resolver

LongFei XIAO, and Chao BI, *Senior Member, IEEE*

***Abstract*—An effective approach for optimizing the rotor contour for variable reluctance (VR) resolver is presented. Using this approach, the procedure for optimizing the rotor is divided into two parts: the establishment of initial shape curve, and then computation for the optimization. In order to simplify the process of the former, a shape function is constructed. And the latter is carried out by Taguchi optimization method and finite element method (FEM). An example of a 3-10 VR resolver is used to present the procedure of the optimization, and the testing results confirmed the effectivity of the approach.**

***Index Terms*—VR resolver, Rotor contour, Optimization, Fourier series, Taguchi, FEM.**

I. Introduction

UNDER the pressure of energy shortage and greenhouse effect, the development of the electric vehicle (EV) becomes a hot research topic in the world. In EV applications, the accuracy of the rotor-position signals obtained by angle sensors is a key factor affecting system performances [1].

There are various angle sensors such as optical encoder, resolver and so on [2]. In terms of resolution, the optical encoder has natural advantages over the VR resolver. However, the optical encoders are sensitive to its working environment, and is difficult to be used in EV as the environment conditions there are quite harsh. In EV, the internal available space is small and there is inevitably smoke, oil, particles, and so on. In addition, it is accompanied by high temperature and severe vibration at high speed. In order to cope with such harsh conditions, VR resolvers with high temperature resistance, great interference immunity and small dimensions become the best option [3]-[5].

The structural design of the VR resolver can be roughly divided into three parts: stator, rotor and winding distributions. Firstly, the design of stator is relatively simple among three parts. Determining the number stator teeth is the 1st step, which is important to the accuracy of rotor-position signals. Secondly, the winding distribution can be classified as shift winding method (SWM) and various turn number method (VTNM) [6]. It should be noted that SWM is better than VTNM in theory. But, VTNM is the current research direction in practical application. Finally, the design of rotor is still a big problem because the traditional design cannot describe the shape of the rotor mathematically for optimization.

For realizing the effective optimization of the VR, an optimal approach is proposed in the paper. The design process consists of two stages: the first is the establishment of initial rotor curve which is formulated by the shape function with Fourier series. The second is optimization combining FEM and Taguchi optimization algorithm aiming at minimizing the error of angular position of VR resolvers. The testing result of a 3-10 VR resolver is used to verify the efficiency of the design approach presented.

II. The Principle of VR Resolver

Fig. 1 shows the basic structure and principle of VR resolver, which is specifically illustrated in [6]-[8]. The most of angle sensors use only the local effects in the angle detection, and they are thus sensitive to the operation condition and environment. The signal processing of VR resolver is more complicated than these sensors. Because the direct output signals are analog, the resolver-to-digital convert (RDC) has to be used [8][9]. Nevertheless, the application fields of VR resolver is gradually increasing because VR resolver as its obvious and unique advantages on the utilization of global effects of the electromagnetic (EM) system and resistance to hostile environments [3]-[5].

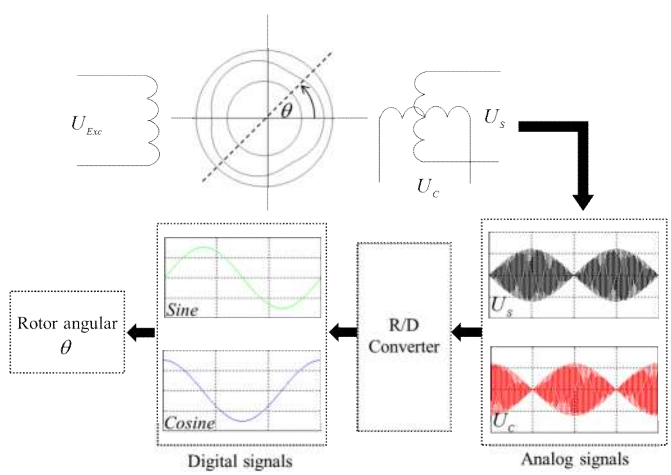


Fig. 1. The basic principle of VR resolver.

Manuscript received July 27, 2020; revised July 21, 2021; accepted August 23, 2021. date of publication September 25, 2021; date of current version September 18, 2021.

LongFei XIAO is with the researcher of Fortior Technology (Shenzhen) Co. Ltd. (e-mail: long.fei.xiao@foxmail.com).

Chao BI, is with Machinery Department, University of Shanghai for Science and Technology, Shanghai, China (e-mail: bichao@usst.edu.cn).

(Corresponding Author: LongFei XIAO)

Digital Object Identifier 10.30941/CESTEMS.2021.00029

III. The Structure of VR Resolver

The parameters of the 3-10 VR resolver are illustrated in TABLE I and Fig. 2. In terms of structure, it seems to be extremely simple. However, there are still many difficulties in the process of manufacture and design. For manufacturers, the main efforts focus on the assembling accuracy and precision production. But, these also mean the demand for complicated manufacturing technology and high cost, which may not be completely satisfied to producers. Therefore, many conditions should be considered for designers in the optimization of VR resolver.

TABLE I
Main Parameters of VR Resolver Model

Parameters	Value
Stator outer diameter (mm)	37
Stator inner diameter (mm)	20
Minimum air-gap length (mm)	0.3
Stator slots	10
Rotor pole pairs	3

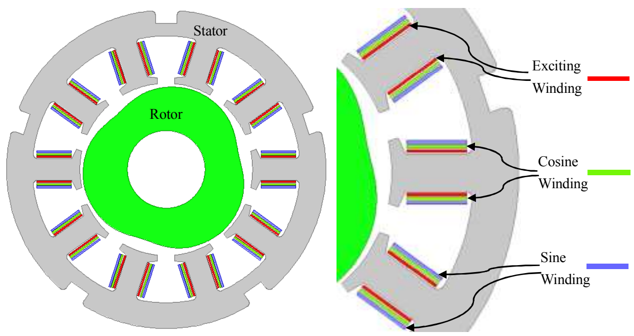


Fig. 2. 3-10 VR resolver.

A. The Number Setting of Stator Teeth

The number setting of stator teeth is the first step in the design of VR resolver, which is the significant factor for the winding arrangement and affect the upper limit of the accuracy.

The proposed 3-10 example whose stator is from a practical product has 10 stator teeth, but this is not the most suitable choice. After trial and calculation, the number of stator teeth for 3-X VR resolver can be 8, 10, 12, 14 and even more. It is obvious that the greater the number of stator teeth, the more advantages in improvement of angle errors.

B. Winding Distributions

In general, the winding methods of VR resolvers can be divided into two categories:1) SWM; and 2) VTNM.

Fig. 3 shows an example for SWM. The number of coils is uniform on each tooth. Besides, Sine and Cosine windings are distributed alternately. In other words, they are nonoverlapping in the same tooth. In theory, SWM is simple and has satisfactory performance.

Fig. 4 shows an example for VTNM. VTNM is not a patch on SWM and the difference of the maximum turn number on each tooth indicates the complication of VTNM. In general, it is time-consuming for an experienced designer to accomplish it.

However, the overall benefit should be considered by the manufacturers. They need to guarantee the versatility of parts and improve the efficiency of production. Therefore, a unified stator is used in resolvers with different pole pairs of the rotor. Under the limitation of stator structure, SWM becomes invalid and it is inevitable for designers to adopt VTNM.

As the limitation in the paper length, the example of the winding distributions of the resolver which belong to VTNM cannot be discussed too much in this paper. Polarities and the turns of windings with VTNM will be mentioned in another paper.

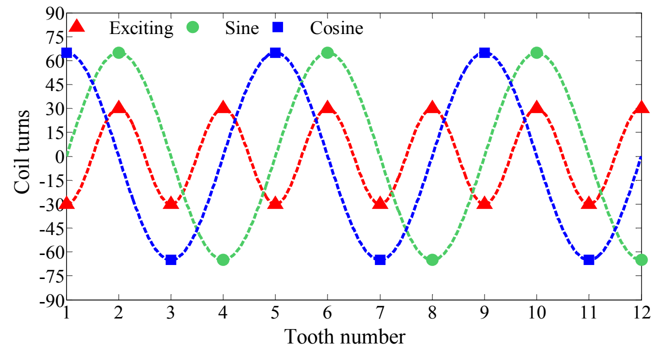


Fig. 3. An example for SWM.

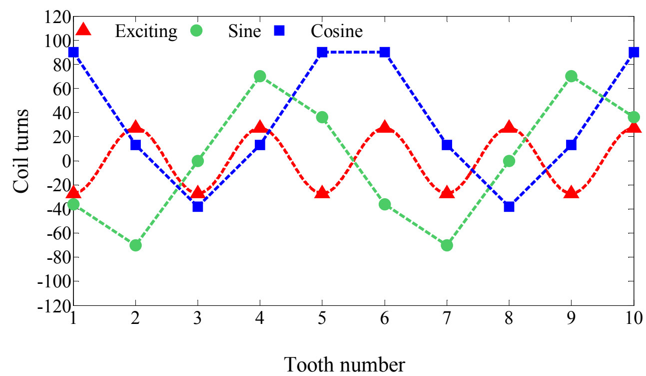


Fig. 4. An example for VTNM.

C. Establishment of Rotor Shape Function

Several practices for constructing rotor shape function are introduced in [4]. In short, the designers solely rely on practical experience or on time-consuming analysis of air gap permeance to establish the rotor shape. These practices are not desirable in terms of systematization and efficiency.

Since there is little possibility to get satisfied shape function of rotor contour in the beginning of the design, it is better to concentrate on the optimization to find the optimal parameters of the shape function of the rotor. In other words, the focus of the design should be in the second stage and the main task of the first stage is only to build an initial rotor shape function which can be described by one specific formula and is favorable for optimization.

It is clear, the shape function of the rotor contour can be expressed by

$$r(\theta) = h_0 + \sum_{i=1}^{\infty} h_i \cos(ip\theta) , \quad (1)$$

where r is the rotor radius, p is the rotor pole pairs, h_i and h_0 are the shape parameters of the rotor contour.

According to (1), the shape function of the initial rotor is shown in Fig. 5. The shape parameters of the rotor are set as the initial value in the iterative algorithm, which is necessary but not demanding.

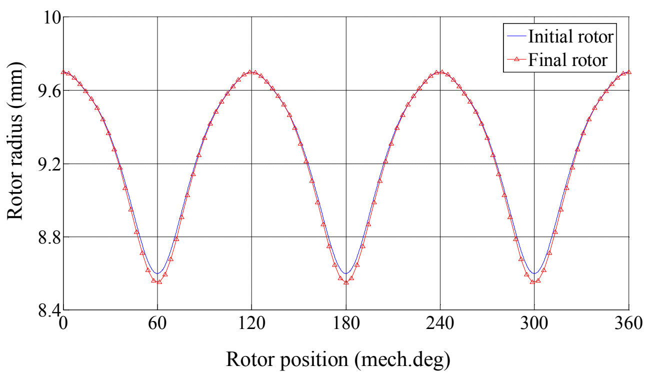


Fig. 5. The rotor contour.

IV. An Optimization Approach of VR Resolver

As the complexity of the EM structure of VR resolver, it is logical to use numerical method to analyze the characteristics of the resolver. However, as the discreteness of the numerical solution, it is a concern how to utilize fully the information possessed in the discrete patterns obtained with numerical solutions during the optimization process. In authors' research, FEM is used as the numerical tool, and Taguchi optimization method is used to explore the optimal shape parameters of the rotor contour.

A. FE Model

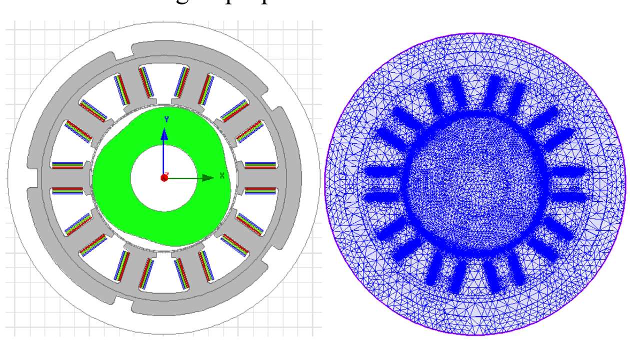
For explain the approach clearly, the 2D FE model of 3-10 VR resolver is illustrated in Fig. 6. The magnetic pole-pair of the resolver is 3. The distribution of its flux lines is also shown in the figure.

Fig. 7 shows the output voltages related to the rotor position of the resolver, which is obtained from the FE analysis. From the curve of the output voltage, the voltage harmonics of the VR resolver can also be obtained with Fourie analysis, and the results are shown in Fig. 8. The amplitude of the fundamental component of the voltage signal is set at 100. From the harmonics and the analysis by using (2), it can be known that the total harmonic distortion (THD) formulated is 0.036%,

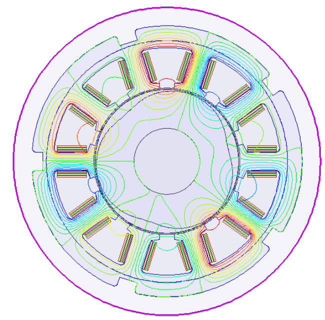
$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1}\ , \tag{2}$$

where, V_1 is the fundamental wave of output voltage, V_n is the n^{th} order harmonic.

It is obvious that both the even and odd harmonics exist in the output signals where the second and third harmonics account for the largest proportion.



(a) (b)



(c)

Fig. 6. FE model I. (a) 2D eddy current model. (b) Finite element meshing diagram. (c) Flux lines

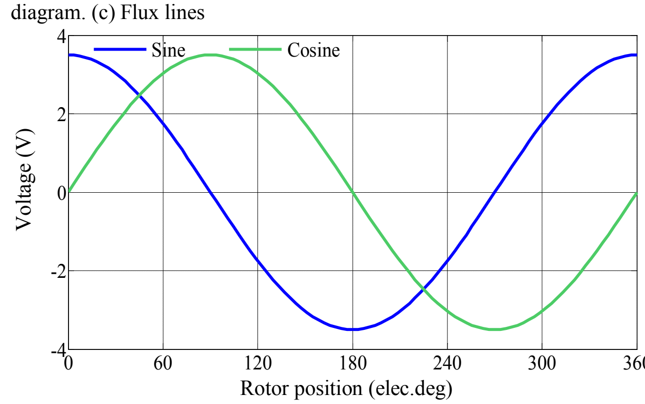


Fig. 7 The output signals of the FE model

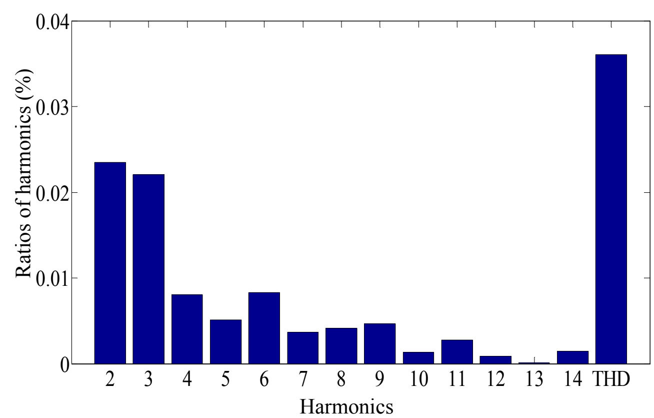


Fig. 8. Voltage harmonics for the 3-10 VR resolver (FE results).

As previously explained, the accuracy of the VR resolver is determined by the comprehensive EM structure of the resolver, which includes the structures of exciting winding, output windings, stator tooth and rotor contour. Thus, there are many underlying causes of the THD, e.g., the inappropriateness of current VTN winding distribution, the number of stator poles and so on, but the rotor contour is the major one.

B. Taguchi optimization method

Taguchi optimization method is a statistical algorithm, which can utilize the discrete patterns to do the optimization. The method has been used widely in different areas. Due to length limitation of the paper, the detailed process of Taguchi optimization can be referred to [3]-[5]. In authors' research, this method is used for the design of EM system with the FE results in VR resolver.

Fig. 9 shows the flowchart of optimization approach with Taguchi method and FEM. Its basic principle can be summari-

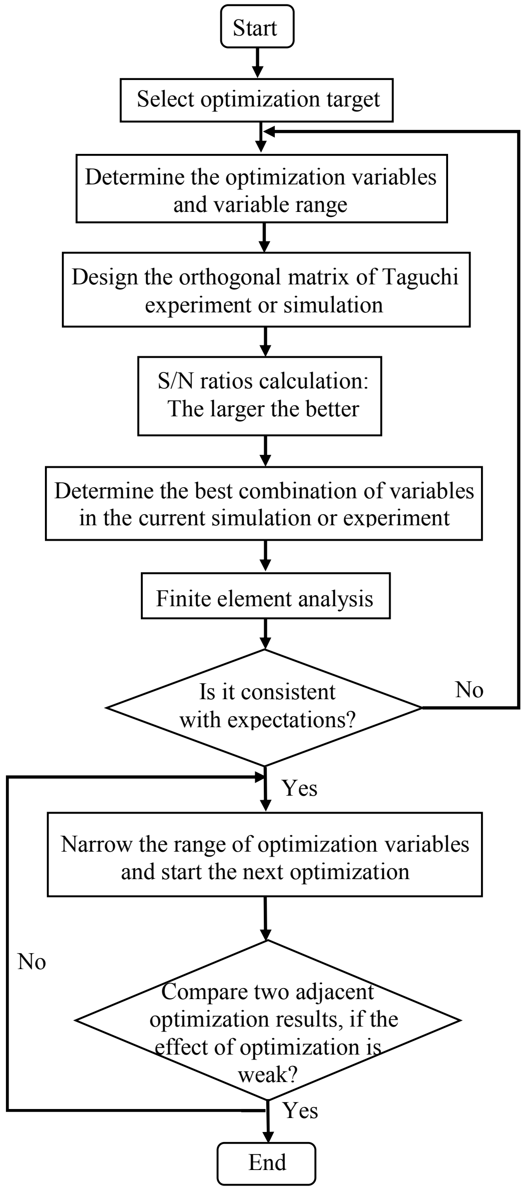


Fig. 9. The flowchart of Taguchi optimization method. [5].

zed in four parts:

1) *The establishment of optimization target function;*
2) *The design of experiments;*
3) *Analysis of effect proportion;*
4) *Optimization selection.*

In the first stage, a proper objective function is essential to the reception of the Taguchi method, which is expressed by

$$\text{Position error} = max\left|error\left(i\right)\right| , \quad (3)$$

where, *error(i)* represents the electrical angle error between the calculated value and the ideal value.

For the second part, Orthogonal Array (OA) which can promote the efficiency of FE calculation is adopt to design the experiments, i.e., the locations of the parameters of the EM system for FE calculation. Several templates and features of OA are presented in [10]-[13].

S/N radios developed by Gen'ichi Taguchi is the priority in the last two stages. Three functions of S/N radios are often utilized in analyzing the proportion sensitivities of different parameters and selecting the best combination, and they can be expressed as below,

$$\text{Nominal is Better: } SN_N = 10\log\left(\overline{y}^2/s^2\right) , \quad (4)$$

$$\text{Larger is Better: } SN_L = -10\log\left[\left(\sum_{i=1}^{n} 1/y_i^2\right)\Big/n\right] , \quad (5)$$

$$\text{Smaller is Better: } SN_S = -10\log\left[\left(\sum_{i=1}^{n} y_i^2\Big/n\right)\right], \quad (6)$$

where, n is the number of repeats in each experiment, ν_i is the output of the experiment in i^{th} repeat, $\overline{y}$ and s represent the average value and the standard deviation of objective functions respectively.

For minimizing the rotor-position errors of the resolver, (6) is selected to analyze and determine the trend of the optimization. The final rotor contour shape function optimized is shown in Fig. 5.

V. Testing Results

For verifying the optimization approach presented, a testing system was built, and is shown in

Fig. 10. The prototype of a 3-10 VR resolver, which is a commercial product and requested by the manufacturer, was used as the example for optimization and used for the verification. The prototype designed with the optimization was made, as it is shown in Fig. 11.

Fig. 12 reflects the comparison between the FE and testing results. The maximum rotor-angle errors of FE result is 0.156°and that of testing results is 0.765°. However, because idealized production is unrealistic, some errors could be inducted in the VR resolver components and production.

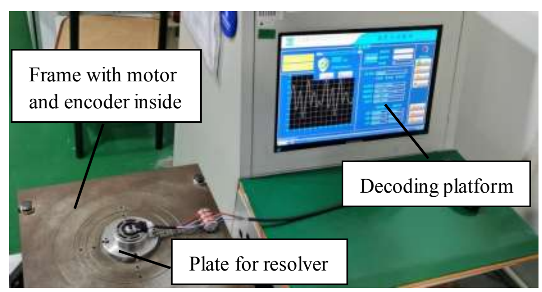


Fig. 10. The test system

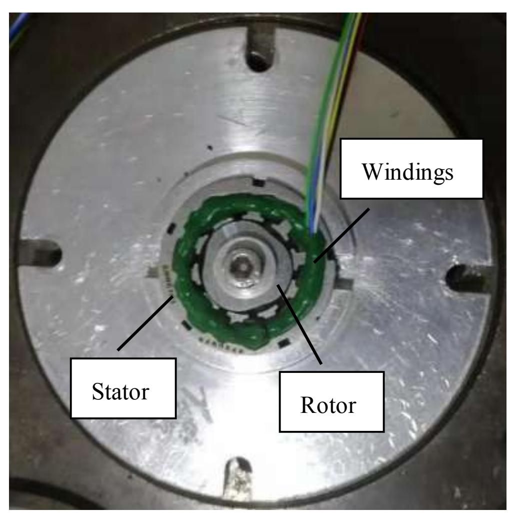


Fig. 11. The prototype of the 3-10 VR resolver

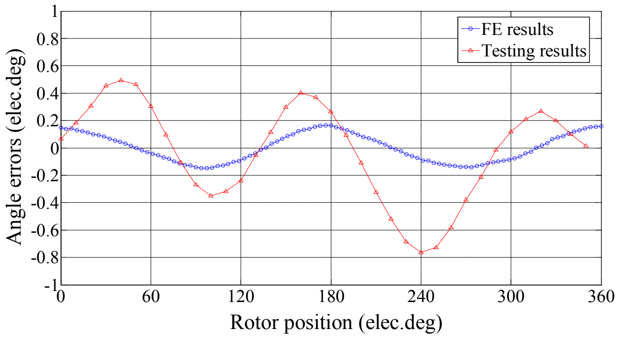


Fig. 12. The comparison between the FE and testing results

VI. CONCLUSION

A design approach of rotor contour for VR resolver is presented in this paper. This approach refrains the problems caused by time consuming and complicated calculation on air-gap permeance and voltage harmonics. The shape function formed by Fourier series can describe the complex rotor contour, and the angle errors can thus directedly connects to the rotor shape parameters. Taguchi optimization method combined with FEM are utilized to analyze the proportion sensitivities of different shape parameters, which can eventually realize the optimal rotor contour and minimize the angle errors of the VR resolver in the design stage. The testing results of a 3-10 VR resolver confirm the effectiveness of this approach. The research on the optimization by using the combination of FEM and Taguchi method shows also that, the approach should also be effective in the optimization of the EM structure of other devices.

REFERENCES

[1] X. Ge, Z.Q. Zhu, R. Ren et al., "A novel variable reluctance resolver for HEV/EV applications", *IEEE Trans. Ind. Applic.*, vol. 52, no. 4, pp. 2872-2880, 2016.

[2] R. Setbaken, "System performance and application tradeoffs determine the choice between encoders and resolvers in brushless servos", *Power Convers. Intell. Motion*, vol. 22, no. 5, pp. 69-76, 1996.

[3] LongFei Xiao, Zheng Li, Chao Bi, "Optimization of a Reluctance Resolver", 2018 Asia-Pacific Magnetic Recording Conference (APMRC)

[4] LongFei Xiao, Chao Bi, " Optimization of Absolute Variable Reluctance Resolver with Taguchi and FEM ", 2019 22nd International Conference on Electrical Machines and Systems.

[5] Longfei Xiao, Zheng Li, Chao Bi, "An Optimization Approach to Variable Reluctance Resolver", *IEEE Transactions On Magnetics,* to be published.

[6] C.-S. Jin, etc, "Proposal of improved winding method for VR resolver", *IEEE Trans. Magn*, vol. 51, no. 3, pp. 1-4, Mar. 2015.

[7] Murray, B.A. and Li, W.D., "A digital tracking R_D converter with hardware error calculation using a TMS320C14," *Power Electronics and Applications, Fifth European Conference*, 472-477 vol.4, 1993.

[8] D. C. Hanselman, "Resolver signal requirements for high accuracy resolver-to-digital conversion," *IEEE Trans. Ind. Electron*, vol. 37, no. 6, pp. 556–561, Dec. 1990.

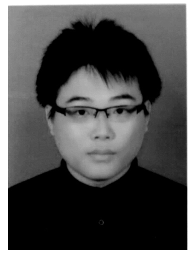
[9] "12-bit R/D Converter with Reference Oscillator", *AD2S1200 Data Sheet*, Analog Devices, Norwood, MA 2002.

[10] Pao, T, W., Phadke, M. S., and Sherrerd, C. S., "Computer Response Time Optimization Using Orthogonal Array Experiments", *IEEE International Communication Conference*, Chicago, IL(June 23-26, 1985) Conference Record, vol. 2, pp. 890-895.

[11] K.-L. Tsui, "An overview of Taguchi method and newly developed statistical methods for robust design", *IIE Trans.*, vol. 24, no. 5, pp. 44-57, Nov. 1992.

[12] Ikuo Tanabe, "Development of a Tool for the Easy Determination of Control Factor Interaction in the Design of Experiments and the Taguchi Methods", in *Proc, of 2017 International Conference on Control, Artificial Intelligence, Robotics & Optimization*, 2017, pp. 301-306.

[13] P. J. Ross, Taguchi Techniques for Quality Engineerings, McGraw-Hill Book Company, 1988.



LongFei XIAO received B.Eng. degree from Shanghai Engineering Institute, in 2016， master degree from University of Shanghai for Science and Technology in 2020. He is currently the researcher of Fortior Technology (Shenzhen) Co. Ltd. Main research interests include the optimization technology, synthesis of electrical machines, and EM system analysis.

Chao BI received his bachelor degree from Hefei University of Technology in 1982, master degree from Xi'an Jiaotong University in 1984 and doctor degree from National University of Singapore in 1994. He was a senior engineer in Western Digital, senior scientist of A*Star, adjunct Professor of National University of Singapore. He is also the senior member of IEEE.

Professor Bi has published one academic book and more than 180 papers. As the achievements in high performance motors, he was awarded the National Technology Award of Singapore in 2006 (NTA-2006). In recent years, he has been concentrated in the research of high-performance motor technology, including electromagnetic structure design of high performance motor, ultrahigh speed motor, micro-motor, drive control, control chip, precision measurement, and motor application. The research scope covers motor theory, motor engineering, drive system, electromagnetic field analysis, optimization technology, IC chip design, bioengineering and energy engineering.