COMPUTATIONAL RESEARCH PROGRESS IN APPLIED SCIENCE & ENGINEERING (CRPASE)

CRPASE: TRANSACTIONS OF MECHANICAL ENGINEERING

Journal homepage: http://www.crpase.com

CRPASE: Transactions of Mechanical Engineering 8 (4) Article ID: 2826, 1–7, December 2022 ISSN 2423-4591

Research Article

# Using Kinematic Models to Improve the Performance of Wing Root Drilling Processes

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**Keywords**

Parallel kinematic machine,
Digitized process,
Exechon kinematic model,
Wing root drilling.

## Abstract

As one of the advanced parallel kinematic machines, the Exechon machine is used in advanced drilling process in the aerospace manufacturing industry. In order to investigate the trajectory and drilling accuracy of the Exechon machine, it is necessary to study and develop the kinematic model of the Exechon intended for future digitized drilling process of robotic wing root. Previous studies have explored the kinematics and errors of the Exechon in depth, but have not revealed the effect of errors on the Exechon drilling process, nor any method for evaluating the drilling accuracy. In this paper, based on the mechanical structure and robot kinematics of the Exechon machine, a kinematic model is identified and developed to predict the drilling performance and observe the trajectory under various additional errors. In addition, an evaluation method of the Exechon drilling accuracy was developed to validate the model with an average error of 0.023 mm, which is close to the performance of the Loxin machine. The kinematic model of Exechon proposed in this paper can approximate the digitized process of wing root drilling well, which impels a reference for error analysis and drilling accuracy evaluation of the Exechon machine.

## 1. Introduction

Wing roots drilling is regarded as a very essential process in aircraft manufacturing. Large volume aerospace manufacturing companies are looking for solutions to meet the requirements of high efficiency and quality [1]. Parallel kinematic machines (PKMs) are considered to offer advantages in terms of dynamic load, operation speed and accuracy [2]. In recent years, drilling operations have adopted a significant amount of automation in aerospace manufacturing industry. However, this automation is highly based on customized machine tools rather than real and flexible automation [3]. As one of the advanced parallel kinematic machines, the Exechon machine was used for wing roots drilling at Airbus. In order to design a flexible and automatically controlled drilling process, the manufacturing machine should be much stricter and have higher accuracy than present machines.

Before discussing the drilling accuracy of the Exechon machine, it is necessary to analyze and model the kinematics [4]. Bi et al. [2] developed a parallel kinematic model of Exechon with a simplified structure that defined the motion degrees of freedom and simulation model of Exechon machine. They claimed that the position of the end-effector of Exechon determined the only way the actuator moved and discussed the kinematic model of Exechon with simplified model, control method and motion planning. Additionally, Bi [5] proposed a stiffness modelling of the Exechon machine, which was advantageous to research the relationship between stiffness and the motion of the end-effector. It can also be used in trajectory planning and Exechon shapes. Ding et al. [6] designed and analyzed the simplified structure and kinematics of Exechon workspace

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Received: 28 October 2022; Revised: 25 November 2022; Accepted: 28 November 2022
https://doi.org/10.52547/crpase.8.4.2826

Academic Editor: **He Li**

Please cite this article as: Y. Liu, X. Zhou, Q. Li, S. Huang, Using Kinematic Models to Improve the Performance of Wing Root Drilling Processes, Computational Research Progress in Applied Science & Engineering, CRPASE: Transactions of Mechanical Engineering 8 (2022) 1–7, Article ID: 2826.

and gave the results of working models of machine tools. This model applied an algorithm to predict the reachable workspace of machine tool.

Error modeling is the basis of kinematic calibration and the main method to ensure the accuracy of robot motion trajectories. Using a well-identifiable error model could improve the accuracy of robot motion [7]. Zhao et al. [8] used a large amount of error models based on one joint position in their experiments, considered angles and positions. It provided a good experience in error modeling to facilitate the definition and reduction of errors. Cui et al. [9] built a kinematic model of a parallel robot with significantly high accuracy by combining Jacobian matrix and error modeling. Liu et al. [10] developed a numerical error modeling method for parallel kinematic machines based on inverse kinematic solutions to avoid the computation of complex Jacobian matrix, which is easier, clearer, more convenient and more widely used than other modeling methods. Besides, errors in CNC system, including those arising from complex joints and actuators, should be considered seriously [11].

In terms of robot trajectory control methods, Fu et al. [12] gave the opinion of simplifying the robot inverse kinematic model and reducing the model components, which was considered to reduce the geometric/kinematic errors in PKM. Zhang et al. [13] provided an open-loop method to reduce geometrical kinematic parameter errors so that any measuring device could obtain the position of the end-effector, while using the least square method to adjust kinematic error parameters. Taghiabadi [14] discussed robotic inverse kinematics of the robot, used kinematic control for the behavior of robot arm and analyzed the Jacobian conditioning by least squares method to limit the errors. However, this method requires a large number of variables. Ahmadian et al. [15] proposed an adaptive control method based on the state space model of robot, which provided high stability and accuracy. Pham and Yildirim [16] indicated and compared four methods of robot trajectory control: PID control, computed torque control, inverse model control and internal model control. It claimed that inverse model control was difficult to implement, while PID control method performed better than computed torque control under experiments. Hsiao and Huang [17] proposed an iterative learning control approach for trajectory tracking by robot modeling, robot trajectory control and planning.

Previous studies have pointed out the different errors that might occur in Exechon drilling process, and the different control methods used in various errors. However, few studies pointed out how the different errors affected the Exechon process or evaluated the drilling accuracy of digitized Exechon model. In this paper, a novel kinematic model of the Exechon machine was developed that took into account the errors generated in the drilling process to predict its performance. In addition, the results of new kinematic model were verified by comparison with actual drilling data.

## 2. Kinematics Analysis of Exechon Machine

### 2.1. Exechon Machine Structure Analysis

The structure of the Exechon machine can be considered as a rather complex and flexible model. The three legs move and control the movement of the bottom plane during the drilling process by means of three universal joints connected. The connection between the planes of the two rotary axes and the three legs, the end-effector and machine tool used for drilling, compose a parallel structure. In actual CNC machine tool machining, the two rotary axes can be extended by mounting them on an extended frame.

Figure 1 shows a simplified structure of Exechon parallel kinematic machine. $A_1$, $A_2$ and $A_3$ are three joints of leg_1, leg_2 and leg_3. Based on joints $A_1$, $A_2$ and $A_3$, the coordinate system O-XYZ is established while O is the midpoint between $A_1A_3$. The direction of the vector $OA_3$ is taken as the X-axis and the direction of the vector $OA_2$ as the Y-axis, while $OA_3$ and $OA_2$ are perpendicular in the plane of $A_1A_2A_3$. The Z-axis can be taken from the vector $OO_2$, $O_2$ is the end-effector which connected to the machine tools. The three joints $B_1$, $B_2$ and $B_3$ are junctions between the end-effector plane and three legs. By extending $B_1B_3$ and Z-axis, $O_1$ is the midpoint of $B_1B_3$, which is located on Z-axis. Since plane $A_1A_2A_3$ and plane $B_1B_2B_3$ are parallel, $O_1B_2$ and $B_1B_3$ are also perpendicular.

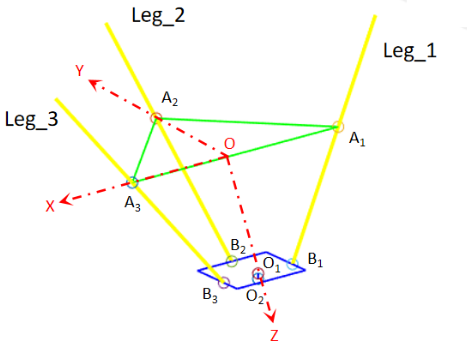

**Figure 1.** Simplified structure of Exechon machine

In terms of the overall structure of Exechon, Leg_1 and Leg_3 are two legs which connected to a same axis, and they are symmetrical in the Z-axis. Leg_1 and Leg_3 have rotational degrees of freedom centered on the X-axis, and Leg_2 has one rotational degree of freedom centered on the Y-axis. When the Exechon machine is operating, joints $A_1$ and $A_3$, also regarded as axis $A_1A_3$, control the end-effector plane movement through the Y-axis by the joints $B_1$ and $B_3$. Joints $A_2$, controls the motion of end-effector plane through X-axis. Additionally, the three legs are free to move through fixed joints $A_1$, $A_2$ and $A_3$, which control the length of $A_1B_1$, $A_2B_2$ and $A_3B_3$. The length of $A_1B_1$ and $A_3B_3$ could affect the angle between end-effector plane and X-axis, and the length of $A_2B_2$ could affect the angle between end-effector plane and Y-axis.

The forward kinematics of Exechon parallel kinematic machine is determined by entering the state of the joints, including position, angle and velocity; and the length of $A_1B_1$, $A_2B_2$ and $A_3B_3$. Then, the status of end-effector plane are calculated, including the position of $O_1$, $B_1$, $B_2$, $B_3$ and the angle between plane $B_1B_2B_3$ and $A_1A_2A_3$. In this algorithm, the positions of $A_1$, $A_2$ and $A_3$ are known and the angle between joints $A_1$, $A_2$, $A_3$ and plane $A_1A_2A_3$ is affected by the s position of the end-effector and the length of $A_1B_1$,

$A_2B_2$ and $A_3B_3$. The inverse kinematics of Exechon parallel kinematic machine is used to output the position of the movable joint by inputting the position of the end-effector, which is predicted position of drilling tool. In this paper, forward kinematics is used to calculate the machining trajectory of the machine bed and reverse kinematics is used for control and verification. Also, the task of the Exechon machine is set to drill holes in a plane parallel to plane $B_1B_2B_3$. Thus, when the plane $A_1A_2A_3$ is parallel to $B_1B_2B_3$, the lengths of $A_1B_1$, $A_2B_2$ and $A_3B_3$ are only change during the drilling action, which change the z-axis coordinate of the end-effector plane.

### *2.2. IDEF0 Structure Construction*

IDEF0 (Icam DEFinition for Function Modeling) is a modelling method of describing manufacturing functions. It can be used to model various control systems. Before a control system determined, IDEF0 can be used to classify and define contents and functions of each part. The basic structure of IDEF0 box format include input, mechanism, control and output.

In Exechon machine, three motors are installed on three legs to control their action. To analyze the motion of Exechon parallel kinematic machine, the movement of each leg can be realized as a change of angle plus the movement of leg in one direction. Hence, the inputs can be realized as six parameters: angle alpha, beta and theta respectively represent the angles between leg_1, leg_2, leg_3 and Z-axis; the lengths of Bar1, Bar2 and Bar3 represent the lengths of $A_1B_1$, $A_2B_2$ and $A_3B_3$ in Figure 1, but not the physical length of three legs. The various errors are the different predicted noises input to the system. After observing and analyzing the result of errors, a control method will be used to reduce them.

However, as discussed above, the lengths of Bar1, Bar2 and Bar3 are mainly affected by the action of drilling. To simplify the Exechon kinematic model and make the experimental results clear, these three parameters would not be inputted to the system. In testing the accuracy of angular input of the inverse kinematics, the length of three bars are used. In addition, bar1 and bar3 are connected on the same axis and the angles between bar1, bar3 and Z-axis are equal and can be represented by β. The updated IDEF0 structure is shown in Figure 2.

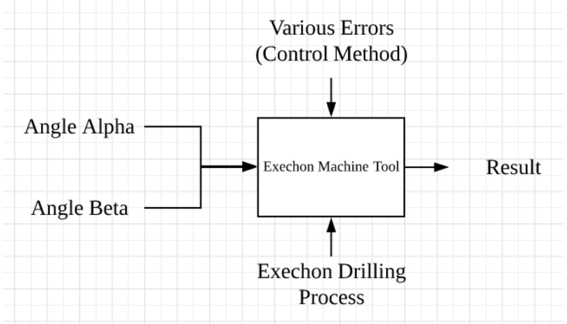

**Figure 2.** IDEF0 updated structure

### *2.3. Model for Experiments Construction*

According to the forward kinematics and inverse kinematics of Exechon machine, and the demands of drilling processes. A simplified model can be created to predict the performance of Exechon drilling processes. Jin et al. [1] announced a method of designing parameters. In figure 1, $d_1$, $d_2$, $d_3$ and $d_4$ can be used to represent the lengths of $A_1A_3$, $OA_2$, $B_1B_3$ and $O_1B_2$. The distance travelled by the actuator can be represented by $d_5$. Four intermediate variables which are used to determine the dimensions of Exechon simplified model can be defined as Eqs. (1-4)

$$p_1 = 0.5 * d_1/d_5 \tag{1}$$

$$p_2 = d_2/d_1 \tag{2}$$

$$p_3 = 2 * d_3/d_1 \tag{3}$$

$$p_4 = d_4/d_3 \tag{4}$$

These four intermediate variables are defined as: $0.5 \leq p_1 \leq 0.8$, $0.5 \leq p_2 \leq 1$, $0.5 \leq p_3 \leq 1$ and $p_4 = 0.75$. Depending on the range of these intermediate variables, the Exechon kinematic model can have a suitable structure of high stiffness, flexible motion and wider range of motion.

The simplified model used for experiments is shown in Figure 3. Two variables, angle α and angle β could present and generalize the input information from the actual drilling process. The position of the plane $B_1B_2B_3$ is depended on the input angles, while $O_e$ is the midpoint of $B_1B_3$. In experiments, the point $O_e$ was considered as the machine tool, the trajectory and accuracy of $O_e$ was observed and discussed to evaluate the performance of Exechon machine model.

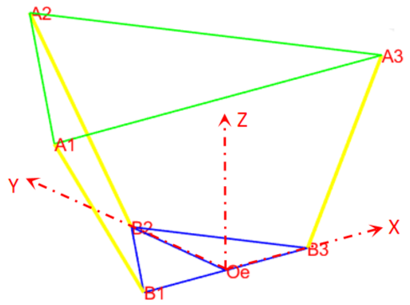

**Figure 3.** Simplified model for experiments

## 3. Noise Importation and Analysis

### *3.1. Experiment Definition*

As discussed above, two parameters, angles α and β are input value of experiments. Hence, the values of angles α and β are independent variables, the position of end-effector is dependent variables, the position of upper plane and the length of bars could be regarded as constant in the experiments. According to factorial experiment, the effects of errors can be designed into four experiments for each type of error:

(1) No error

(2) An error in angle α

(3) An error in angle β

(4) Errors in both angle α and β

The expected trajectory of Exechon drilling process is defined as a rectangle. The expected point $O_e$ starts from one corner, goes around one circle back to the starting point, and drills four holes at four corners. Various types of noise are then input to this system, and the drilling accuracy at point C will be mainly discussed. In order to clearly observe the trajectory under the noises input, the input noises will be enlarged in observing trajectory experiment.

### *3.2. Experiment Implement and Analysis*

Sine wave noise can be considered as a continuous, periodic noise. It is characterized by a continuous variation of the noise and a small rate of the noise except for peaks. It can be considered as a continuous, periodic force which affects the machine during the actual drilling process. Figure 4 shows the results of sine wave input. It is clear that the figure of 'an error in beta' is the closest result to expected trajectory. Therefore, with the same input value of angle α and angle β, the effect of angle α is bigger than angle β. It might be caused by the difference of expected angle input. For example, when angle α and angle β increase by 1 rad at the same time, the displacement on X-axis is larger.

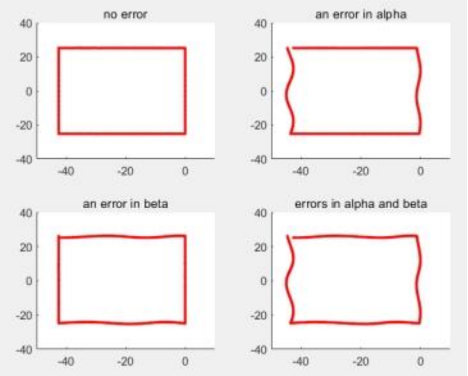

**Figure 4.** The result of sine wave noise input

White Gaussian noise can be considered as an absolutely random and irregular noise in actual drilling process. Figure 5 shows the input result of additive white Gaussian noise. Compared with Figure 4, the trajectory of white Gaussian input tends to irregular. The changing rate of white Gaussian noise input is larger than in Figure 4 because of its irregular model. Additionally, the position error will be accumulated under the effect of additive white Gaussian noise. The error at the end of trajectory is much larger than which at the beginning.

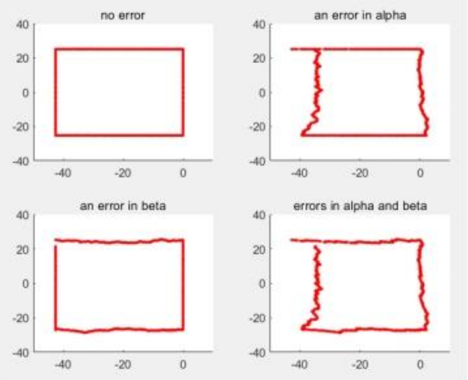

**Figure 5.** The result of additive white Gaussian noise input

Second order noise can be defined as a continuous force which affect the acceleration of angular velocity of Exechon legs. If no control method is used in digitized Exechon machine, its influence will be increasing. The trajectory can be divided into two parts, when the value of noise is negative, the trajectory of end-effector will be located in the third quadrant. When the value of noise is positive, the trajectory of end-effector will be located in the first quadrant. The rate of change of the second-order noise is obvious compared to the sine wave noise and the white Gaussian noise. It can be known that the second order noise have a greater impact on robot kinematics.

To sum up, the effects in angle α are more obvious than in angle β because the Exechon machine's moving range in x-axis is wider than in y-axis. The sine wave noise directly affects the trajectory, while the second order noise cause a huge effect on result. As a random noise signal, the white Gaussian noise affects the trajectory of machine tool by additive errors. The behavior of various noises input can give experience to actual drilling processes and help the operators to identify and resolve the mistakes in Exechon drilling process. Due to the randomness and irregular features, the experiments below will be based on white Gaussian noise input.

## 4. Evaluation of Error Control Method

### *4.1. Experiment Definition*

Exechon error control could be divided into two main tasks: error measurement and error correction. In Exechon drilling processes, the error correction could be considered as the correction of machine position. However, only the task of error correction will be discussed in this paper. Error measurement will be ignored and it is assumed that the accuracy of error measurement is 100%. Therefore, the error in this paper can be considered as the difference between the experimental value and predicted value.

The experiments are used to compare the accuracy of the last drilling point in the simulated drilling trajectory to initially evaluate the different control methods. Due to the randomness of the white Gaussian noise, the result of Exechon drilling processes is different in each simulation. Therefore, 10 experiments were simulated under different control methods to calculate and compare the average error at the last point of the trajectory.

### *4.2. Experiment Implement and Analysis*

Iterative learning control is a method for reducing the errors in input variables through an iterative training process. According to Norrlof [18], the iterative learning control can be divided into open-loop iterative learning control and closed-loop iterative learning control. One advantage of iterative learning control is that the error will gradually decrease and converge to zero as the number of iteration increases. Its mathematical function can be described as Eq. (5)

$$u_{p+1} = u_p + K * e_p \tag{5}$$

While $u_p$ is the $p$th result of control system and $u_{p+1}$ is the result of $(p+1)$ th iteration. The parameter $e_p$ is the error against the target value and $K$ is a set parameter for $e_p$. A series of iteration is required to reach the requirement (the expected robot trajectory). This control method also uses robot inverse kinematics, where the output value will be explored and adjusted under the threshold. When the output value satisfies the condition, it can be transformed into independent variables by means of robotic inverse kinematics. In this method, the times of iterative should be considered.

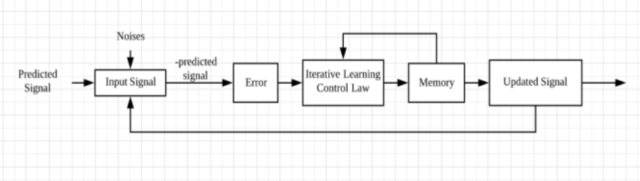

**Figure 6.** Structure of iterative learning control

Figure 6 shows the structure of iterative learning control method for Exechon trajectory control. The input signal consists of a predictive signal and noises input. After the position of end-effector has been calculated by Exechon forward kinematics, the error can be obtained from the actual position and predicted position. Iterative learning control is then used and at each iteration the error is reduced by an iterative learning law with predetermined value $K$. The updated signal will be retained as a memory to the next iteration and passed to the Exechon machine.

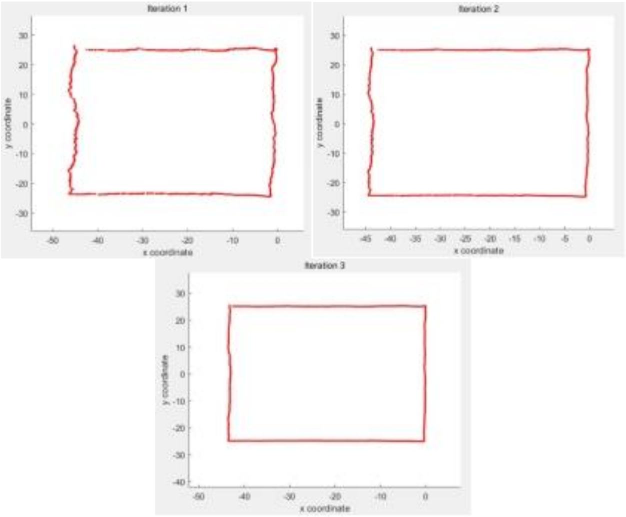

**Figure 7.** Result of using iterative learning control (iteration = 1, 2, 3)

Figure 7 shows the results of using iterations 1, 2 and 3 by iterative learning control. In iteration 1, the trajectory has a large error and behaves badly. In iteration 2, the error is reduced and behaves better than iteration 1. In iteration 3, the machine trajectory performs well and the updated trajectory tends to the expected trajectory. However there is an obvious gap between the last point and the start of the trajectory. This means that the error in angle alpha is not small enough, and the input signal need more training iterations. After 10 simulations of the model using three iterations, the average error of iterative learning control was 0.123mm.

The PID controller has many advantages: it is highly adaptable, robust and resistant to interference. It is widely used in robot trajectory control. The PID controller could real-time control the input signal by its algorithm and deliver updated signal. The basic equation of PID control method is defined as Eq. (6):

$$u(t) = K_p e(t) + K_i \int_0^t e(t')dt' + K_d \frac{de(t)}{dt} \tag{6}$$

While $u(t)$ is output of PID controller, $e(t)$ is the error calculated from the actual and expected signals, $K_p$ is the proportional gain, $K_i$ is the gain of integrator and $K_d$ is the gain of derivative. However, the Exechon drilling process need to be efficient and fast, the PID controller needs time to predict and reduce errors. As an advantage of rapid control speed, PI controller will be used in the experiments. The result shows that the trajectory performs well with the PI controller. After 10 simulations of the model using PI controller, the average error of PI control is 0.071mm.

To look up the trajectory under iterative learning control and PI control, these two methods perform well. Comparing the average error between iterative learning control and PI control, the average error of PI control is smaller than that of iterative learning control. However, the average error of iterative control was calculated at 3 iterations. If the number of iteration increased, the error will be smaller and smaller. During the actual Exechon drilling process, it is able to train input signal several times in Exechon drilling experiments. To keep the processing time and error as small as possible, iterative learning control is selected for the trajectory control of the Exechon digital model.

### *4.3. Exechon Drilling Accuracy Analysis*

In this paper, iterative learning control method is considered for the drilling accuracy experiments. However, the number of iterations will be increased to 5 to ensure that the error is sufficiently small. To test the accuracy in different positions and orientations, the Exechon kinematic model will be asked to drill 25 holes in one operation, as shown in Figure 8.

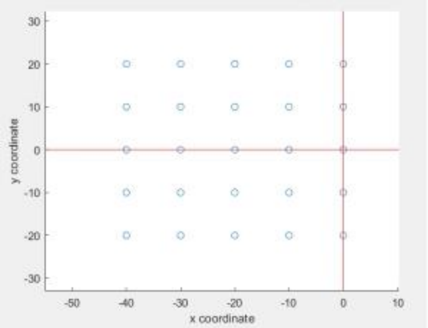

**Figure 8.** Expected points of Exechon drilling process

Figure 9 shows the results of zero order and first order white Gaussian noise. Except for the zero value (starting point), the error ranges for two different noises are (0.01, 0.07) and (0.02, 0.11). The mean value of the error under first order Gaussian noise is larger than in zero order Gaussian noise due to the variation of noise signal and error accumulation. In both plots, the errors at the edge of the trajetory are larger than those at the center. This is because the error is greater when machine changes direction than when it moves in a straight line. In general, the Exechon machine has high accuracy in 25 holes drilling experiment.

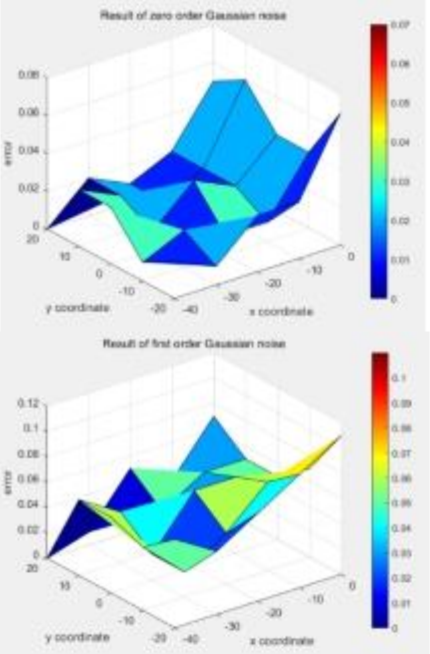

**Figure 9.** Result of zero and first order white Gaussian noise

This paper consulted a method of experimenting the accuracy of five-axis drilling machine’s drilling process by using actual machine. In this experiment, 0.03mm is the tolerance of error. A circle which radius is 0.03 is drawn to measure the distance between the actual drilling positions and the intended drilling target. Experimental values greater than 0.03 are considered to be incorrect, otherwise they are correct. Experimental results from the actual machine showed that the Mazak machine was 100% correct with an average error of 0.011417 and the Loxin machine was 80.0% correct with an average error of 0.024466.

Through using the same experimental approach, the result of Exechon kinematic model is shown in Figure 10. According the experimental rules, there are 8 red crosses outside the circle and 37 red crosses inside the circle. So, the correct rate is 82.2%. And the average of error is 0.023614.

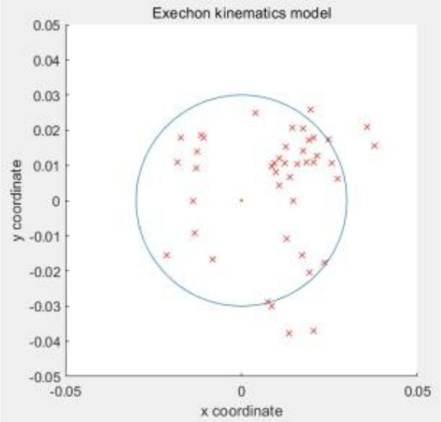

**Figure 10.** Drilling result of Exechon kinematic model

The drilling results of the Exechon kinematic model were compared with the results of the Mazak machine (advanced drilling machine) and the Loxin machine (less expensive drilling machine). The performance of the digital Exechon machine was not as good as that of the Mazak machine. However, the performance of the Exechon kinematic model and the Loxin machine were approximate, having similar values of correctness and average error.

## 5. Conclusion and Limitation

In this paper, a simplified model of the Exechon parallel motion machine with bivariate control was developed. The forward kinematics, reverse kinematics and mechanical structure of the Exechon machine were highly analyzed and generated. In the noise input test of the Exechon drilling process, the effects of different noises on the robot trajectory were obtained and a preliminary analysis of the extent and causes of the effects was carried out, which could well provide experience in the wing root drilling process as a way to identify errors in the drilling process faster. At the same time, this paper explored the effect of different control methods on the trajectory control of the digital model of the Exechon robot. Iterative learning control was more accurate in trajectory with sufficient number of iterations and higher drilling accuracy, and was suitable for the trajectory control of the Exechon kinematic model. In drilling accuracy tests and analysis, the average drilling error of this model was 0.023 mm, with drilling accuracy higher than 80%. Compared to the advanced Mazak machine tool and the cheaper Loxin machine tool, the drilling accuracy and motion performance of the Exechon kinematic model were not as good as those of the Mazak machine tool, but better than those of the Loxin machine tool. All the results indicated that the Exechon kinematic model proposed in this paper could approximate the digitized process of wing root drilling well with good fit and accuracy, and was a good reference for the trajectory control and noise analysis of the Exechon machine.

In order to make the trajectory of the robot clear, the model of the Exechon machine has been somewhat simplified in this paper, and variables such as angular velocity and angular acceleration have been neglected to reduce additional errors. In future work, efforts should be made to make the model more complete.

## Conflict of Interest Statement

The authors declare no conflict of interest.

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