Deformation analysis and hole diameter error compensation for hybrid robot based helical milling

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Abstract
As an innovative machining process for hole-making, helical milling (also known as orbital drilling) presents great potential in machining aircraft structures due to temperature and cutting force reduction, flexible kinematics, and improved borehole quality. Meanwhile, the application of hybrid robot with their high accuracy and better stiffness are increased in aircraft assembly machining operations. Combining these two advanced technologies, this paper focuses primarily on the investigation of the TriMule hybrid robot elastic deformation during helical milling hole-making process and its influence on the diameter error of machined hole. The elastic deformation of series and parallel parts under cutting force condition was investigated by finite element simulation software SAMCEF. The TriMule robot helical milling experiments were also carried out to determine the variation of hole diameter error, and an offline compensation method with modifying the eccentricity at different hole depth was proposed based on the established diameter error model. From experimental verification results, it can be found that the hole diameter error of TriMule robot helical milling can be reduced and the consistency of hole diameter accuracy can be significantly improved by proposed error compensation method.

Keywords: Hybrid robot, Helical milling, SAMCEF, Error compensation, Hole-making

1. Introduction

The aerospace industry is an important productive sector capable of absorbing new technologies and materials (Eguti and Trabasso, 2014). All aircraft manufacturers are striving to increase their production rate while making their products greener and cheaper. To reduce the weight, the use of titanium alloys, carbon fiber reinforced plastic and their stacks are expanding for structural aerospace applications, especially where high mechanical loads exist such as for aircraft wing and tail-plane components (Shyha, et al., 2011). Here, the production of bolt/fixation holes is essential to the assemble process, which is also considered as the most time-consuming process, as pointed out by zou and Liu (2011). Currently, in the assembly of aircraft structures, all internal and external parts are fixed by solid rivet or fasteners, and most of them are still installed by manual multi-shot method, which involves a series of drilling, reaming, disassembly, deburring and reassembly operations. In these processes, drilling is a critical procedure and conventional twist drilling is mostly used in the aircraft manufacturing (Zhang, et al., 2008 and Liu, et al., 2012). However, the conventional drilling process for titanium alloys and carbon fiber reinforced plastic also presents several drawbacks, such as high loads over the workpiece, high thrust force, severe burr formation, difficult chip evacuation, difficult heat dissipation, poor dimensional and geometrical accuracy, poor surface quality, and catastrophic tool wear (Melentiev, et al., 2016). Meanwhile, in the case of CFRP hole-making, conventional drilling can lead to the formation of delamination, matrix damage and fiber pull-out (Sadek, et al. 2012). As a result, conventional drilling is associated with rework, low process capability, structural impairment and extra product costs. Considering these problems, helical milling (also known as orbital drilling) can be used as an alternative to conventional drilling due to many significant
advantages (Pereira, et al., 2017). As an innovative machining process for hole-making, helical milling presents great potential in machining aircraft structures due to temperature and cutting force reduction, flexible kinematics, and improved borehole quality. With these characteristics, the helical milling hole-making in the aircraft structures does not require further disassembly for deburring, removal of chips, or cleaning to remove contamination from coolants or lubricants (Whinnem, et al. 2009).

On the other hand, to enhance aircraft manufacturing productivity, flexible automation technology has been intensively investigated for implementing automated aircraft assembly. For example, the design and experimental study of an end-effector (Liang, et al., 2010), exploiting task redundancy (Zanchettin, et al., 2011), and assessment of the positioning performance (Slamani, et al., 2012) in drilling operations have been studied in details. Meanwhile, for the robotic helical milling process, the process of developing an automatic helical milling device, its functions, and corresponding tests have been investigated in details (Eguti and Trabasso, 2014). The standard robotic manipulators used in above investigations provide high degrees of flexibility to enable manufacture parts with large or/and complex geometries. However, there are limitations to the serial robotic system as flexibility and accuracy are inversely correlated (DeVlieg and Sitton, 2002). Due to their weak and varied stiffness along the hole axis direction, industrial serial robots are more suitable for lower cutting force related machining process, but not for drilling/maching the hard-to-cut titanium alloy materials which is accompanied by large cutting force. Theoretical and experimental studies have shown that the stiffness for a serial robot is less than 1N/μm, while a standard CNC machine has stiffness greater than 50N/μm (Pan, et al., 2006). Therefore, the application of parallel kinematic machines (PKMs) with their high accuracy and better stiffness are increased in aircraft assembly machining operations (Shang and Butterfield, 2011). For instance, invented by Neumann, the Tricept robot is the most popular hybrid PKM machine, and over 300 have been put into production in Boeing, EADS and Bombardier. Another new hybrid PKM is Exechon machine (Neumann, 2014), and its prototyping system has been developed and its improved performance has been demonstrated through primary experiments (Jin, et al., 2015).

In the machining process, static deformation may significantly reduce the robot localization accuracy, and dynamic deformation will lead to poor machining surface quality (Zhang, et al., 2016). Therefore, stiffness analysis has been major subjects studied in the fields of robotics and machining, in particularly, for the relationship between stiffness and machining accuracy. Zaeh et al. (2014) developed a real-time stiffness model of a KR240 R2500 industrial robot considering all relevant compliances of the structure, and the milling tool path-deviation was adjusted based on the milling force. Klimchik et al. (2015) identified manipulator stiffness model parameters in a practical industrial environment and found that the essential improvement of the milling precision can be obtained by using the developed low-order stiffness model for the compliance error compensation. Meanwhile, as an essential step in the aircraft assembly, there have also been many studies on robotic drilling operation. Bu et al. (2017) proposed a Cartesian compliance model to describe the drilling robot stiffness, and a quantitative evaluation index of the robots processing performance is defined. With the optimization of performance index in the cutting tool direction, higher accuracy of machined hole can be obtained. Olsson et al. (2010) equip the drilling end effector with a force feedback device which calculates real-time terminal force and feeds back data of robot controller and thus improves the hole-making accuracy. It can be found that the automatic hole-making in the published literatures are realized by combing the series robot and drilling end effector, however, there have been few studies focused on the new hybrid PKM hole-making method. In this paper, a novel 5-DOF hybrid robot based helical milling process is first investigated.

It can be found that diameter error, shape error and position error are the three most important evaluation indexes for the machined hole. In this paper, the correlation between TriMule robotic elastic deformation and machined hole diameter error is revealed, and corresponding compensation method is also presented. The paper is structured as follows. In section 2, hybrid robot elastic deformation under cutting force loading during the helical milling process is studied by using SAMCEF. In section 3, the experimental platform for TriMule hybrid robot helical milling is built to verify the validity of the hole diameter error compensation method. In section 4, the simulation results for robot elastic deformation is discussed and an offline compensation method is proposed. Finally, the paper is concluded in section 5.

2. Robot deformation during the helical milling process
2.1 Robot operating stiffness analysis

In order to establish the compensation strategy for hole diameter error in robotic helical milling, the robot operation stiffness needs to be analyzed first. The robot used in this paper is a novel 5-DOF hybrid robot named TriMule which
have been proposed by Tian et al. (2017). As shown in Fig. 1(a), the robot is composed of a 3-DOF R(2-RPS&RP)&UPS parallel mechanism plus a A/C wrist. Here, R, P, U, and S represent revolute, prismatic, universal, and spherical joints, respectively; and P denotes an actuated prismatic joint. The parallel mechanism comprises a spatial limb plus a 2-RPS&RP planar linkage, connected by a pair of R joint to the machine frame at either side of the base link which is elaborately designed into a three-in-one part. The A/C wrist have two rotary axes, which are marked by two blue dotted line in Fig.1(a). A motorized spindle is mounted on A/C wrist to realize the helical milling machining operation. For product used in this paper, the angular stiffness for the A axis is 3.85e5 Nm/rad, and the angular stiffness for the C axis is 3.37e5 Nm/rad. The volume of TriMule robot is about X=±0.6m, Y=±0.22m, Z=±0.6m. Figure 1(b) shows the elastic model of the TriMule robot, where compliances of all joints and links are considered. The 3-DOF parallel mechanism within the robot can be decomposed into two sub-chains, i.e., a UPS limb and a 2-RPS&RP planar linkage whose base link is connected by a common rear R joint with the machine frame. In order to facilitate the stiffness analyzing, the 2-RPS&RP planar linkage is treated as a 2-DOF actuated compound joint by considering the compatibility conditions of three limbs situated on the base link (Gao, et al., 2002). In this way, stiffness of the compound joint can be formulated first, and the stiffness model of the 3-DOF parallel mechanism can be built by the method developed by Liu et al. (2017). Then, the stiffness matrix of the robot as a whole, denoted by $K$, can be obtained by means of the superposition principle, which can be presented by

$$K = (K_p^{-1} + K_s^{-1})^{-1}$$

where $K_p$ is the stiffness matrix of the 3-DOF parallel mechanism, $K_s$ is the 6×6 component stiffness matrix evaluated in its body-fixed frames, and $T_{AC}$ and $T_{m_s,d}$ are the adjoint transformation matrix of $\{R_{AC}\}$ and $\{R_{m_s,d}\}$ with respect to $\{R_{C}\}$. The detail information about stiffness calculation can refer to Dong et al. (2017), and the stiffness distribution of the TriMule in the task workspace can be obtained. Based on the above stiffness analysis, the robot elastic deformation during the helical milling will be investigated by finite element simulation method in the following section.

### 2.2 Simulation for robot deformation during the helical milling process

As a critical factor for the machining accuracy, the robot deformation caused by cutting force need to be investigated first. In this paper, the robot deformation during the helical milling process will be obtained by the commercial FEA software SAMCEF. The main process of the simulation includes CAD model importation, definition of the data assigned to each component, assembly of the moving parts, mesh of the mechanical parts, definition of the settings for the solution, and post-processing for the results. It is more difficult to directly building 3D model in the SAMCEF, therefore, a solid model of the TriMule robot was created by SolidWorks first, and then imported into the SAMCEF via the STEP format. While the detail features of the model, such as the small holes, openings, and small size convex and grooves, etc., are all simplified or removed to reduce the simulation time. After importing the simplified model, the cell properties, material properties, motion pairs, and constraints for each part was assigned. There are two
methods for mesh generation: free meshing and mapped meshing. Due to the structure of hybrid robot component is relatively simple and there is no limit to the shape of the element, the free meshing method is applied in this case, and the result is shown in Fig. 2a. After setting all the simulation data, the post-processing for the results can be obtained in the solving monitor as shown in Fig. 2b.

![Fig. 2 (a) TriMule model after meshing, and (b) simulation solver monitoring and result data.](image)

In this paper, the helical milling hole-making process is achieved under a fixed robot pose, as shown in Fig. 3a, the axis of motorized spindle is perpendicular to the XOY plane. In this case, the tool diameter is 12mm, the diameter of machined hole is 19.05 mm. In order to make the simulation closer to the actual helical milling, the helical milling force signal was obtained, as shown in Fig. 3c. In order to make the simulation results closer to the actual hole-making, two different force loading methods were applied. The first one is constant force loading. The maximum value in X, Y direction (\(F_x\), \(F_y\)) and mean value in Z direction (\(F_z\)) were calculated to act as loading force, therefore, the constant force applied to the robot in this simulation is \(F_x=250\)N, \(F_y=260\)N, and \(F_z=200\)N. The second one is variable force loading method. Within a revolution period of helical milling, the variation of cutting force in x and y direction is shown in Fig.3d. In order to obtain the robot elastic deformation during the entire hole-making process, the deformation at 8 positions (marked as 1, 2,..., 8 in Fig. 3b) in each 0.2mm depth were calculated, Since the hole depth is set to 5mm in this paper, the deformation for 200 different poses in the hole-making process are obtained.

### 3. Experimental set-up

The experimental platform for TriMule hybrid robot helical milling was built as shown in Fig. 4(a). The detail of TriMule has been mentioned in Section 2.1. The carbide helical milling tool (K44 UF) was selected for the helical milling tests, and the geometric parameters of cutting tool are listed in Table 1. The alpha-beta titanium alloy Ti-6Al-4V plates were used as workpiece materials in this study, the physical and mechanical properties of Ti-6Al-4V is shown in Table 2. As shown in figure, a Kistler three-direction dynamometer (9257A) and supporting charge amplifier (type 5070), and data acquisition system and Kistler software were utilized for the helical milling cutting force measurement. The measurement of diameter accuracy and roundness error was achieved using coordinate measuring machine (Wenzel LH 65). The optimized helical milling parameter is used in this paper, where spindle speed is 2000rpm, the tangential feed speed is 0.04mm/tooth, and axial feed per helical revolution is 0.2mm/rev. In order to validate the simulation model, an experiment for measuring the static stiffness of the robot both in X and Y directions was conducted, as shown in Fig. 4(b). Because it is difficult to directly impose a stable force on the end of cutting tool, the point C (marked as blue in the figure) was selected as the stiffness measuring point.

| Tool Diameter | Number of flutes | Rake angle | Clearance angle | Helix angle |
|---------------|------------------|------------|-----------------|------------|
| 12mm          | 4                | 8°         | 15°             | 38°        |

Table 1 Geometric parameters of helical milling tool
4. Results and discussion

4.1 Elastic deformation analysis of hybrid robot parallel part

In order to study the parallel structure part elastic deformation caused by the cutting force during the helical milling process, the cutting force load is applied at end of parallel structure (point A in the Figure 1a). As mentioned in the Section 2.2, the deformation under 200 different poses in one hole-making process are obtained, and these 200 different poses also correspond to different hole depth which is from 0mm to 5mm. Therefore, the variation of deformation in the point A with increasing of hole depth can be obtained, as shown in Fig 5. It can be seen from the figure that the deformation amount for the point A in the X direction tends to be stable as the increasing of the hole depth, and deformation for the point A in the Y direction increases with the increasing of hole depth. It is because that the robot is in a cantilever state, and the length of cantilever will increase during the hole machining process, which leads to an
increase in the amount structure deformation. Meanwhile, it also can be found out that the deformation in the X direction is significantly larger than that in the Y direction. It reveals that the ability to resist deformation is different in the X and Y direction, and this might affect the dimensional accuracy and roundness error of the machined hole. Further analysis shows that the deformation in both X and Y direction presents a periodic variation. This is due to the revolving characteristics in the helical milling process. The robot has a variable stiffness in a single revolution period, while for every revolution period, it has similar stiffness variation characteristics. For the deformation at different robot poses in the hole-making process, the simulation analysis results are shown in Fig. 6. It can be seen that the linear increase of elastic deformation was presented for the 8 different robot poses as the increasing of hole depth during the helical milling process. This will likely lead to the inconsistent of hole diameter in the different depth of machined hole, which may cause the appearance of funnel-shaped holes.

4.2 Elastic deformation analysis of spindle end during helical milling process

Firstly, the constant force is applied to the spindle end (point B in the Fig. 1a) to investigate the deformation of whole hybrid robot in the helical milling process. For the constant loading condition, the constant force of $+F_x+F_y$, $+F_x-F_y$, $-F_x+F_y$, and $-F_x-F_y$ were applied to point B, and the corresponding simulation results were obtained, as shown in Fig. 7. Comparing the simulation results between condition a, c with c, d, it can be clearly seen that the direction of $F_y$ has a great influence on the deformation in the Y direction comparing with the deformation in X direction, while the effect of direction of $F_x$ on the amount of deformation is not obvious. This indicates that the deformation of A/C wrist will have a significant change when the cutting force in Y direction is changed. This will affect the roundness error in the hybrid robot helical milling process. On the other hand, it also can be found out that the deformation in the X direction is always larger than that in the Y direction, which is consistent with the previous analysis results. Secondly, the variable force (as shown in Fig. 3d) is also applied in the point B to analyze the influence robot deformation on the dimensional accuracy of machined hole, and the corresponding loading force for each robot pose is shown in Table 3.
Fig. 8 shows the simulation results of whole hybrid robot deformation in one revolution cycle of helical milling. The whole robot elastic deformation distribution for both series and parallel part under different poses during the hole machining process can be clearly presented. For the overall view of the hybrid robot structure, the deformation in the series part (A/C wrist) is always larger than that in the parallel part regardless of the loading and pose condition. Furthermore, it was indicated that the motorized spindle is inclined in the certain poses (such as pose 1, 2, 7 and 8), which will affect the machining accuracy, and lead to the formation of funnel-shaped hole.

Fig. 7 Comparison of robot elastic deformation simulation results under different cutting forces conditions.

### Table 3 Cutting force parameters at 8 discrete robot poses in the helical milling process

| Position | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
|----------|------|------|------|------|------|------|------|------|
| Fx (N)   | 0    | -176.8 | -250 | -176.8 | 0    | +176.8 | +250 | +176.8 |
| Fy (N)   | +260 | +183.9 | 0    | -183.9 | -260 | -183.9 | 0    | +183.9 |

Fig. 8 Simulation results of whole robot structure deformation under different poses in one revolution cycle of helical milling.
Based on the above simulation results, the deformation at hybrid robot end in two helical milling revolution cycle is shown in Fig. 9(a). It was indicated that variation of deformation at the end of hybrid robot is periodically during the whole helical milling process, and the initial phase difference of the deformation amount in the X and Y direction is $\pi=2$, which is consistent with the cutting force character in X and Y direction for helical milling. In addition, the deformation in X direction has positive and negative in one cycle, while the deformation in Y direction is always positive. This is determined by the structure characteristic of the hybrid robot. Because the deformation at the motorized spindle is mainly affected by the series part, and the structure of series A/C wrist is symmetric in the X direction, the positive and negative deformation will appear. However, for the Y direction, the A/C wrist cannot rotate in at negative angle direction, so the deformation in Y direction is positive. Meanwhile, the difference of stiffness in X and Y directions will generate the roundness error for the machined hole. As shown in the Fig. 9(b), the profile of machined hole for 1.5mm hole depth was presented. It can be found that the hole diameter in the Y direction is relatively larger than that in the X direction, and this is caused by the stiffness difference in the X and Y directions. The deformation at hybrid robot end (point B) in the X direction is larger than that in the Y direction, which will lead to the diameter deviation in the Y direction is smaller than that in the X direction.

The experimental and simulation results for robot static stiffness in point C were presented in the Fig. 10. It was indicated that the stiffness variation trend obtained by the simulation model is consistent with the experimental results, that is, the stiffness decreases with the increase of the hole depth. However, the stiffness values obtained by the simulation model are all larger than the measurement results. The error between the simulation and experimental might be caused by the simplification of the robot structure, and the failure to consider the influence of assembly clearance in the simulation model.

Fig. 9 (a) Deformation at hybrid robot end (point B) in two helical milling revolution cycle and (b) diameter deviation when the hole depth is 1.5mm (been magnified for better display).

Fig. 10 Comparing between the simulation and experimental results for robot static stiffness.
4.3 Error compensation for hole diameter in hybrid robot helical milling

There are two kinds of machining error compensation methods: offline compensation and online compensation. Online compensation is to measure the machining error in real time, analyze the measurement results, compare it with the ideal target and perform real time compensation. Offline compensation is suitable for the machining have a stable change rule, therefore, the offline compensation is used in this paper to improve the hole accuracy in hybrid robot helical milling. Based on the previous simulating and analyzing results, it can be found that the elastic deformation at end of robot increases with the increasing of the machining depth. This will result in the diameter error increasing as the hole depth increases. The hybrid robot helical milling experiments for 10mm thick titanium alloy were carried out to build the diameter error model. As shown in Fig. 11, diameter variation of the four holes with increasing of hole depth were obtained. It can be seen from figure that the hole diameter has an approximate linear reduction with increasing of hole depth, and the actual diameter is less than the nominal size (19.05 mm) when the hole depth is reaches 5mm.

Based on the above four test results, the mathematical relationship between the diameter error and hole depth \( h \) can be obtained by linear fitting, which is shown in Eq. (2)

\[
\begin{align*}
\Delta_1 &= 0.0433 - 0.0111 \cdot h \\
\Delta_2 &= 0.0397 - 0.0102 \cdot h \\
\Delta_3 &= 0.0352 - 0.0086 \cdot h \\
\Delta_4 &= 0.0282 - 0.0069 \cdot h
\end{align*}
\tag{2}
\]

Therefore, the diameter error model for hybrid robot helical milling can be obtained by averaging the above formulas:

\[
\Delta_n = 0.03665 - 0.0092 \cdot h \quad (0 \leq h \leq 10 \text{mm})
\tag{3}
\]

Based on the above diameter error model, the tool path compensation model can be established, and the discrete coordinate value of the error compensation tool path can be determined as:

\[
[(1 - \frac{\Delta_n}{2R_i}) \cdot X_i, (1 - \frac{\Delta_n}{2R_i}) \cdot Y_i, Z_i]
\tag{4}
\]

where \( R_i \) is the radius of helical milling tool path in the hole-making. Considering the practical feasibility of the hybrid robot helical milling operation, the compensation method with modifying the eccentricity was used in this paper. According to the established error model, the error value at different hole depth is calculated, and it can be converted to the corresponding eccentricity value for the error compensation \( e_c \), which is shown in Eq. (5).

\[
e_c = e - \Delta_n
\tag{5}\]
where \( e \) is the original eccentricity before compensation. Combined with the above eccentricity value, the NC code for helical milling can be modified to realize the error compensation. The original and modified NC code for hybrid robot helical milling is shown in Fig. 12(b).

In order to verify the validity of the above compensation method, the hybrid robot helical milling experiments with modified NC program were carried. In the verification tests, the hole depth is 10mm, and the hole diameter nominal size is 19.05mm. The variation diameter and roundness of machined holes with hole depth is presented in Fig. 13. It can be found that the diameter error is reduced and the consistency of hole diameter accuracy is significantly improved comparing with the original machined holes (no error compensation). For the 19.05 mm diameter hole, a helical milling accuracy of H8 (19.05\(+0.033\)) can be achieved for most of machined hole by adopting the above error compensation method. In addition, as shown in the Fig. 13(b), the variation of machined hole roundness with increasing of hole depth before and after compensation is also presented. It was indicated that the roundness is increased with increasing of hole depth when no error compensation was conducted. This is caused by the combined effects of stiffness difference in X/ Y direction and deterioration of cutting conditions (such as higher cutting temperature, higher cutting force, bad chip removal and vibration of machining system et al.) with increasing of hole depth. Meanwhile, it can be found out that the mentioned compensation method can also increase the consistency of machined hole roundness to a certain extent.

Fig. 13 Variation of diameter and roundness with hole depth before and after error compensation.

5. Conclusion

The subject of this paper is to investigate the elastic deformation of the TriMule hybrid robot during helical milling.
hole-making and its influence on the diameter error of machined hole. From the SAMCEF simulation analysis and experimental results, it was indicated that the deformation in the series part (A/C wrist) is always larger than that in the parallel parts, and the deformation of robot has a linear increase as the increasing of hole depth during the helical milling process, which will result in the diameter error increasing as the hole depth increases. In order to obtain the better dimensional accuracy, the variation of hole diameter in the helical milling process was investigated, and an offline compensation method with modifying the eccentricity is proposed based on the established diameter error model. In order to verify the validity of above compensation method, the hybrid robot helical milling experiments with modified NC program were carried. From the experimental results, it can be indicated that the proposed error compensation method can effectively reduce the machined hole diameter error and significantly improve the consistency of hole diameter accuracy and roundness in the TriMule robot helical milling hole-making process. However, there are many factors can affect the hole accuracy in the robot-based hole-making process, such as dynamic stiffness, vibration of machining system, tool wear, cutting conditions et al. Their acting mechanism and corresponding compensation method will be investigated in the future.

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