Experimental study on robotic rotary ultrasonic drilling of CFRP/aluminum stacks

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Abstract. In order to solve the problem of significant chatter vibration and large drilling force when drilling stacked materials by industrial robot, a new method is proposed. It combines rotary ultrasonic drilling with robotic machining to achieve high efficiency and low damage for CFRP/aluminum stacks. In this paper, comparative experiments of robotic rotary ultrasonic drilling (RRUD) and robotic conventional drilling (RCD) on drilling CFRP/aluminum stacks are carried out in a KUKA six-axis industrial robot. Drilling force, drilling chatter and aperture deviation are measured and analyzed. The experimental results illustrate that high-frequency vibration can not only reduce drilling force effectively, but also have a good inhibitory effect on robotic drilling flutter. In addition, the improvement effect of ultrasonic vibration on aperture deviation for CFRP is more significant than that for aluminium.

1. Introduction
In order to meet the demand for higher flight performance, the demand for high-performance materials such as carbon fiber materials (CFRP), stacked materials are increasing continuously [1], [2]. However, the differences in the physical properties of both aluminum and CFRP materials pose a huge challenge to the aviation manufacture. There are about 1 million rivets for each large aircraft, whose drilling and assembly may occupy 35% to 45% of the manufacturing workload. In addition, 70% of aircraft failures owing to the damage of connection holes. Therefore, there are more and more researchers and companies try to use industrial robots to achieve the stacked materials drilling. DeVlieg et al. [2] developed a robot automatic hole making system based on KUKA industrial robot. This system was used for the ailerons of the Boeing 737 with the positioning accuracy of ±0.508mm. Wang et al. [3] developed a robotic automatic boring system based on ABB industrial robots to meet the requirement
of complex aviation parts. Bu et al. [4] developed a robotic automatic riveting on-line inspection system according to the characteristics and actual needs of robotic riveting system. FrommKnecht et al. [5] optimized robotic drilling quality by multi-sensor measurement. This method improved the average positioning accuracy to 0.334mm and vertical accuracy to 0.29°. Shi et al. [6] designed a robot end-effector and carried out the drilling experiments for aluminium, titanium and CFRP. The aperture error and surface roughness was restricted by 0.04mm and 2.0μm, respectively. Guo et al. [7] analysed the stability of robotic boring and proposed that pressure unit could restrain chattering effectively.

However, weaken rigidity is the deadly defect of robotic drilling. It will generate significant flutter especially in drilling the stacked material which restricts the further improvement of precision and efficiency. Therefore, it is urgently to propose a new method for robotic machining, which could reduce the drilling force and suppress chatter. In recent years, rotary ultrasonic machining technology has been approved to be an effective method for machining structural ceramics and composites gradually [8]. The assistant of high frequency vibration and impact in the axial direction could not only reduce the cutting force effectively, but also achieve high-precision and low-damage machining results. Therefore, it is an important and effective way to solve these problems by combining the robotic drilling and rotary ultrasonic drilling.

2. Experimental Condition

CFRP (CCF300) and Aluminum (Al7075-T7) are used in these experiments with the size of 200×100×3.1mm. The material properties of CFRP and aluminum are shown in Table 1. Experiments were carried out on a six-axis industrial robot (KUKA KR210 R2700 EXTRA, Germany). Its attitude is shown in Table 2.

The miniaturized ultrasonic vibration system shown in Fig. 1 is used in robotic drilling. The frequency of current signal is increased from 50 Hz to 20 kHz by ultrasonic generator and transmitted to the transducer. The piezoelectric ceramic transducer converts electrical energy into mechanical vibration. The amplitude of the vibration is amplified by horn and tool. Ultrasonic amplitude increases with increasing ultrasonic current. When the current is 0mA, rotary ultrasonic drilling transforms into ordinary drilling. The tool used in the experiment is a carbide twist drill with the diameter of 4.5mm. Kistler 9119AA2 dynamic dynamometer is used to measure the whole process of cutting force. The dynamometer installs between the workbench and workpiece. US API R-50 Radian laser tracker is used to collect the end-effector position coordinates. The amplitude of the end effector is calculated from the change in position coordinates. Single-factor experimental scheme is selected in order to analyze the processing parameters and ultrasonic current on the laminated material hole quality. The experimental parameters are shown in Table 3.
Figure 1. Illustration of RRUD system

| Table 1. Material properties of CFRP and aluminum |
|-----------------------------------------------|
| Mechanical properties | Material       |
|-----------------------|----------------|
|                       | CCF300         | Al7075-T7     |
| Tensile strength (Mpa) | 3950           | 572           |
| Elastic modulus (Gpa)  | 232            | 71.7          |
| Density (g/cm^3)       | 1.76           | 2.81          |
| Elongation (%)         | 1.7            | 12            |

| Table 2. Robotic attitude parameters |
|--------------------------------------|
| Coordinate axis | Coordinate value(mm) | Rotation axis | Angle(deg) |
|-----------------|----------------------|---------------|------------|
| X               | 1820.28              | A             | 165        |
| Y               | 118.33               | B             | 0          |
| Z               | 1436.04              | C             | 180        |

| Table 3. Experimental factors and levels |
|-----------------------------------------|
| Factors       | Unit      | Level | A   | B   | C   | D   |
|---------------|-----------|-------|-----|-----|-----|-----|
| Spindle speed | r/min     |       | 2000| 3000| 4000| 5000|
| Feed rate     | mm/min    |       | 60  | 78  | 96  | 114 |
| Ultrasonic current | mA |       | 150 | 175 | 200 | 225 |

3. Results and Discussion

3.1 Effect of ultrasonic vibration on robotic drilling force
Axial force affect the stability of robot drilling system directly. It is an important factor not only leading to the delamination of CFRP holes, hole burr, hole wall damage and aluminum export burr, but also influence the quality of drilling. It can be seen from Fig. 2(a) and 2(b) that the introduction of ultrasonic vibration reduces the axial force effectively. On the one hand, the periodic separation between the tool and the workpiece in separate rotary ultrasonic drilling makes the contact time shorter than that of ordinary drilling. When the tool is separated from the workpiece, there is no axial force in rotary ultrasonic drilling. Additional, the kinematics of the tool will change when rotary ultrasonic drilling is not separated. In one cycle, the average cutting thickness of rotary ultrasonic drilling is less than ordinary drilling. Therefore, drilling force is reduced. Meanwhile, It can be seen that with the increase of spindle speed, the force reduction is weakening gradually in rotary ultrasonic drilling. This is because when spindle speed increases, the separation phenomenon of tool and workpiece reduces. It weakens the effect of ultrasonic vibration during drilling. Due to the gradual reduction of the feed per revolution, the thickness of the cutting layer is reduced to the critical
thickness in non-separating rotary ultrasonic drilling. Its kinematics have no obvious effect on the average drilling thickness. Additional, axial forces of RRUD and RCD show a downward trend with the increase of spindle speed.

![Figure 2](image.png)

**Figure 2.** Machining parameters vs. robot drilling force

Figs. 2(c) and 2(d) show the comparison of the robot drilling force when feed rate changes. It is obvious that RRUD reduces axial forces effectively, when the feed rate increased from 60 mm/min to 114 mm/min. The reduction rate of CFRP and Aluminum under RRUD increased from 8.26% to 17.25% and 4.89% to 12.23%, respectively. Fig. 2(e) and 2(f) show the effect of ultrasonic current on the drilling force. It can be seen that axial force decreases as the ultrasonic current increasing. While the current exceeds 200mA, it increases gradually. As the ultrasonic current increases, the amplitude becomes larger. If the amplitude is oversize, the friction force and extrusion force between tool and workpiece are increased obviously, which lead to the drilling instability. Therefore, increasing ultrasonic current appropriately can improving drilling stability.

### 3.2 Effect of ultrasonic vibration on robot flutter

Robot effector is easy to flutter by the weak stiffness which affects the quality of the drilling process seriously. The laser tracker is used to measure the amplitude of the robot end-effector. The comparison of the robotic flutter amplitude with the spindle speed by RRUD and RCD are shown in Fig. 3(a) and 3(b). It can be seen that flutter amplitudes of RRUD are smaller than RCD generally, it reduces the chatter significantly. With the increase of spindle speed, flutter amplitude approached gradually between RRUD and RCD. It means that the effect of ultrasonic vibration is weakened. According to the dynamics analysis of the robotic drilling system, value and dynamic variation of the drilling force affect the stability directly and sensitively. Therefore, there are the coincident trend for chatter amplitude and drilling force with the increasing of spindle speed. This also verifies the rationality of kinetic analysis. The influence of feed rate on RRUD and RCD are shown in Figs. 3(c) and 3(d). As
the feed rate rise, the amplitude increased obviously in RRUD and RCD. This is consistent with the trend of drilling axial force. Additional, the effect of ultrasonic vibration on chatter is not affected by the increasing of feed rate.

Fig. 3(e) and 3(f) show the effect of ultrasonic current on the flutter amplitude. It can be seen that when the ultrasonic current is increased from 150mA to 175mA, the chatter amplitude presents a decreasing trend in horizontal direction. When exceeding 200mA, it tends to be stable. The trend of the amplitude of the vertical direction is similar to the axial force. Therefore, increasing ultrasonic current appropriately can reduce the robotic amplitude.

![Figure 3](image)

**Figure 3.** Machining parameters vs. robotic flutter

3.3 **Effect of ultrasonic vibration on aperture deviation**

Aperture deviation is an important factor for evaluating the hole quality of stacked materials. Japan Mitutoyo Internal Diameter Micrometer is used to measure the entrance of CFRP and export of Aluminum. The measurement of aperture deviation is shown in Fig. 4. It can be seen from Fig. 4(a) that RRUD reduce the aperture deviation for the entrance of CFRP. In robotic drilling systems, the drill must have sufficient overhang to complete the machining due to the limitations of the end effector. The axis of the drill bit is skewed due to its weak rigidity. The addition of ultrasonic vibration changes a continuous drilling into multiple pulse drilling. When the drill bit is separated from workpiece, the bit drilled again after attenuated and straightened. During stable drilling, the robot body and effector flutter while the bit is bended. This causes the entrance diameter of CFRP increasing. It can be seen that the drilling axial force is reduced effectively in rotary ultrasonic drilling. It reduces vibration flutter of the robot and bends value of the drill bit. Finally, the aperture for entrance is improved. At the export of aluminum, the influence of RUD on aperture deviation is not significant. However, it is less than that for the entrance of the CFRP. The reason is that axial forces reduced rapidly during
drilling out of aluminum and the stability of the robotic drilling system increased. As a result, the force reduction of RRUD is not obvious.

![Graphs showing machining parameters vs. aperture deviation](image)

**Figure 4.** Machining parameters vs. aperture deviation

The comparisons of the aperture deviation of CFRP and aluminum with the feed rate increasing in RRUD and RCD are shown in Fig. 4(c) and 4(d). It can be seen that the deviation of CFRP in RRUD is smaller than that in RCD. However, the influence on aperture deviation of aluminum is not obvious. At the entrance of CFRP, the aperture deviation decreases first and then rises with the increasing of spindle speed in RCD. While it fluctuates within a small range in RRUD. At the export of aluminum, the aperture deviation decreases with the rising of feed rate in both RRUD and RCD.

Fig. 4(e) and 4(f) show the effect of ultrasonic current on aperture deviation. It can be seen that the aperture deviation of CFRP grows slowly with the ultrasonic current increases. While it fluctuates within a small range of aluminum. As the ultrasonic current increases, the amplitude of the ultrasonic rises slightly. The impact and friction on the rear face of the main cutting edge are increased. As a result, the machining stability of the drill bit decline. Eventually, the aperture deviation for the entrance of CFRP increased slowly. However, the rear face and the material separated gradually at the export of aluminum. So the increase of amplitude has little effect on it.

4. Conclusion

Based on the experiments of RRUD and RCD on CFRP/ aluminum stacks, this paper draws the following conclusions:
The addition of RUD on robotic drilling stacks reduces the cutting force effectively. It grows with the increasing of ultrasonic current. However, excessive ultrasonic current will affect the stability of the drilling process.

(2) The addition of RUD could restrain flutter. The flutter amplitude decreases with the ultrasonic current rises. The stability of robotic drilling is improved by increasing the ultrasonic current appropriately.

(3) High-frequency vibration impact could improve the aperture deviation of CFRP. As the bit drilling out of aluminum, the cutting force reduced significantly and the stability is improved. Therefore, the influence of ultrasonic vibration on the aperture deviation of the aluminum is not significant.

5. References
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