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Design of A Drive Scheme for Untethered Magnetic Manipulation Polishing

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Abstract. Based on the untethered magnetic manipulation polishing device, this paper proposes a reasonable driving scheme, which makes the teleoperation process of the device more stable and easy to implement. The change of the position of the external permanent magnet can drive the internal polishing tool to produce corresponding changes. The comparison is made between the axial and radial driving modes, and finally the axial driving mode is selected for control.

1. Introduction

The existing polishing method is applied to the free-form surface of aluminum alloy. The non-contact driving of magnetic field is applied to the free-surface polishing. Based on the theory of dynamic magnetic field drive, the principle of polishing method for untethered magnetic manipulation polishing device is proposed. As shown in **Figure1**, the external permanent magnet is driven by the mechanical structure to realize the movement of multiple degrees of freedom and the rotation of the shaft to generate a dynamic magnetic field. The polishing tool is rotated by the dynamic magnetic field and rotates in the same direction as the external permanent magnet, and the magnetic pressure is pressed. The magnetic polishing liquid inside the workbench is also subjected to a magnetic field. The magnetic particles in the polishing liquid form a chain structure along the direction of the magnetic field, and the coated abrasive grains move in the direction of the magnetic field gradient, gather around the polishing tool and the polishing area, and generate with the dynamic magnetic field. The vortex flows and flows dynamically around the polishing zone; the polishing abrasive particles in the vortex flow are pressed against the workpiece by the magnetic force F of the polishing tool, and the material of the polishing region is taken away from the surface of the workpiece to realize the removal of the surface material of the workpiece.

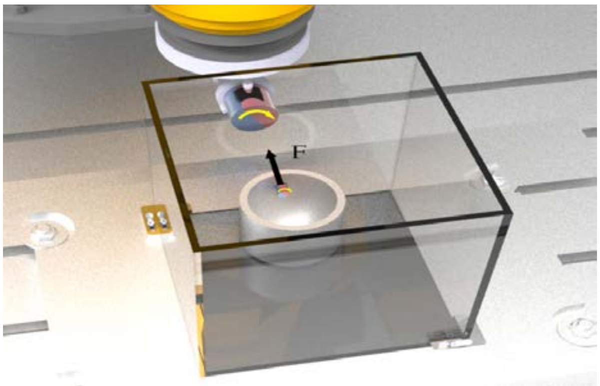

Figure 1. Schematic Diagram of Untethered Magnetic Manipulation Polishing

The remote steering drive process of the device should be stable and easy to implement, and the change of the position of the external permanent magnet can drive the internal polishing tool to produce corresponding changes. When the external polishing tool is in the axial or radial position of the external permanent magnet, the rotation axis of the polishing tool is parallel to the external permanent magnet, that is, w=1, and the control of the polishing tool is the simplest, so the polishing tool is used in two The torque and force under driving are analyzed. The relative positions of the external permanent magnets and polishing tools in the two drive modes are shown in **Figure2** and **Figure3**.

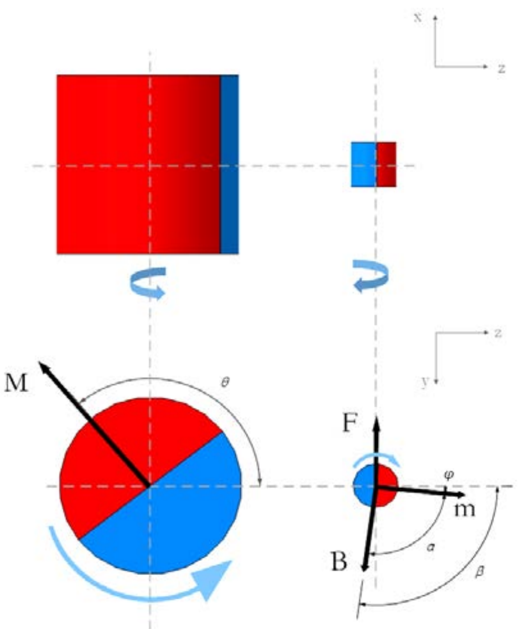

Figure 2. Radial Drive Schematic

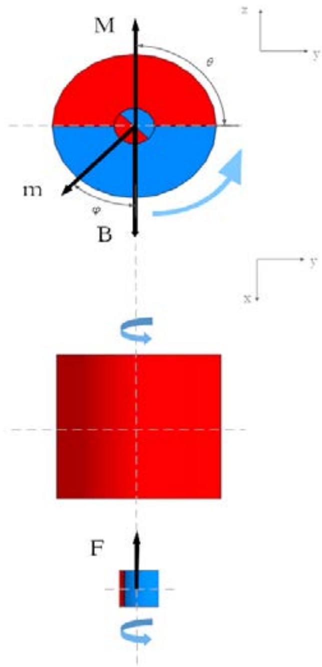

Figure3. Axial Drive Schematic

2. Analysis of Force and Torque of Polishing Tools in Radial Drive

When the polishing tool is placed in the radial direction of the outer permanent magnet, the polishing tool rotates in the opposite direction to the outer permanent magnet, as shown in Figure2. It is assumed that the polishing tool is limited to the positive z-axis direction of the external permanent magnet, that is, the unit position vector $\mathbf{p}^T = (0,0,1)$, and the magnetic formula is simplified and obtained:

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$$\mathbf{B} = \frac{\mu_l |\mathbf{M}|}{4\pi |\mathbf{p}|^3} \begin{bmatrix} 0 \\ \sin\theta \\ 2\cos\theta \end{bmatrix} \tag{1}$$

Where θ is the angle between the magnetic moment M of the external permanent magnet and the positive direction of the z-axis.

During the operation of the device, the axial direction of the control external permanent magnet is always parallel to the x-axis direction of the space rectangular coordinate system, and the polishing tool is rotated by the torque applied by the dynamic magnetic field generated by the external permanent magnet. The magnetic field torque τ_M to which the polishing tool is subjected is:

$$\tau_M = |\mathbf{m}||\mathbf{B}_l|\sin\alpha = \frac{\mu_l |\mathbf{m}||\mathbf{M}|\sin\alpha\sqrt{1+3\cos^2\theta}}{4\pi|\mathbf{p}|^3} \tag{2}$$

Where $\mathbf{m}$ is the dipole moment of the permanent magnet inside the polishing tool, α is the angle between the magnetic moment $\mathbf{m}$ of the polishing tool and its magnetic induction $\mathbf{B}$.

The polishing fluid near the polishing tool produces a resistive torque τ_f for the polishing tool, which is linearly related to the rotational speed of the polishing tool:

$$\tau_f = -c\dot{\varphi} \tag{3}$$

Where c is the coefficient of drag of the polishing fluid and $\dot{\varphi}$ is the rotational angular velocity of the polishing tool.

If inertia is neglected, when the system is in steady state, the polishing tool rotates at a constant speed, and the received magnetic field torque τ_M is equal to the resistance torque τ_f :

$$\tau_M + \tau_f = |\mathbf{m}||\mathbf{B}_l|\sin\alpha - c\dot{\varphi} = 0 \tag{4}$$

In order to maximize the angular velocity $\dot{\varphi}$ of the polishing tool in equilibrium, it is necessary to always maintain $\alpha = 90°$, which has the maximum polishing efficiency. From the geometric relationship $\beta = \alpha + \varphi$, we know that $\dot{\beta} = \dot{\varphi}$. And $\tan\beta = \frac{\sin\theta}{2\cos\theta} = \frac{1}{2}\tan\theta$, so:

$$\dot{\beta} = \frac{1}{1+(\frac{1}{2}\tan\theta)^2} \times \frac{1}{2\cos^2\theta} \times \dot{\theta} = \frac{2}{1+3\cos^2\theta} \times \dot{\theta} \tag{5}$$

Substituting $\alpha = 90°$ into equation (11):

$$|\tau| = |\mathbf{m}||\mathbf{B}_l|\sin\alpha = |\mathbf{m}|\frac{\mu_l |\mathbf{M}|}{4\pi|\mathbf{p}|^3}\sqrt{1+3\cos^2\theta} \tag{6}$$

Finishing out the driving equation for the external permanent magnet is:

$$\dot{\theta} = \frac{\mu_l |\mathbf{m}||\mathbf{M}|}{8\pi|\mathbf{p}|^3 c}(1+3\cos^2\theta)^{\frac{3}{2}} \tag{7}$$

The relationship between the rotational speed and the rotation angle is shown in **Figure4**. The abscissa is the rotation angle θ and the ordinate is the rotational speed $\dot{\theta}$. In this drive mode, the

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polishing tool maintains the fastest and most stable motion. In this state of motion, according to the polishing tool in the magnetic field, the force is $\mathbf{F}=(\mathbf{m}\cdot\nabla)\mathbf{B}$, and the magnetic force of the polishing tool can be obtained by substituting the parameters:

$$\mathbf{F}=\frac{3\mu_l|\mathbf{m}||\mathbf{M}|}{4\pi|\mathbf{p}|^4}\left(\frac{1+\cos^2\theta}{\sqrt{1+3\cos^2\theta}}\right)\begin{bmatrix}0\\-1\\0\end{bmatrix} \tag{8}$$

When $|\mathbf{p}|=5\text{cm}$, the relationship between the magnetic force $\mathbf{F}$ and the rotation angle θ is shown in **Figure5**. In the figure, the abscissa is the force $\mathbf{F}$ of the polishing tool and the ordinate is the outer permanent magnet rotation angle θ. The magnetic force of the polishing tool is always in the negative direction of the y-axis, and its value changes with the change of θ. The variation range of $\mathbf{F}$ fluctuates with the rotation angle θ between 94%-100%. In this driving mode, the instantaneous acceleration of the permanent magnet is large, and the polishing tool is unstable, and it is difficult to realize the driving method.

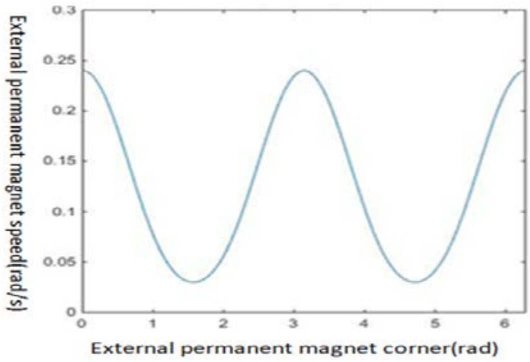

Figure 4. Relationship between Permanent Magnet Rotation Speed and Rotation Angle

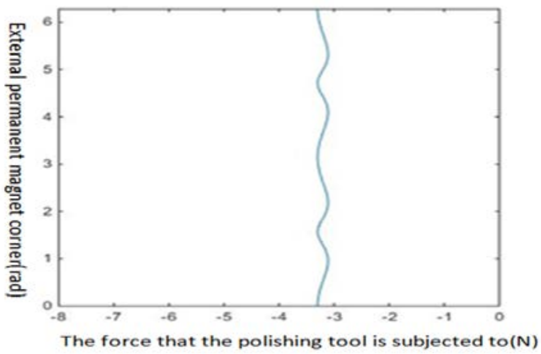

Figure 5. Polishing Tool Force and Angle Relationship

3. Analysis of Force and Torque of Polishing Tools in Axial Drive

When the polishing tool is placed in the radial direction of the outer permanent magnet, the polishing tool is opposite to the direction of rotation of the outer permanent magnet, as shown in **Figure3**. It is assumed that the polishing tool is limited to the positive z-axis direction of the external permanent magnet, that is, the unit position vector $\mathbf{p}^T=(0,0,1)$, which can be obtained:

$$\mathbf{B}=\frac{\mu_l|\mathbf{M}|}{4\pi|\mathbf{p}|^3}\begin{bmatrix}0\\ \sin\theta\\ 2\cos\theta\end{bmatrix} \tag{9}$$

In a certain range of speeds, the polishing tool and the external permanent magnet can be rotated synchronously, and the retardation angle of the polishing tool dipole moment $\mathbf{m}$ and the magnetic induction intensity $\mathbf{B}$ it receives is φ. At this time, the polishing tool dipole moment $\mathbf{m}$ is:

$$\mathbf{m}=|\mathbf{m}|\begin{bmatrix}0\\ -\cos(\theta+\varphi)\\ -\sin(\theta+\varphi)\end{bmatrix} \tag{10}$$

The axially driven lower polishing tool is also subjected to the magnetic field torque τ_M and the resistive torque τ_f, which are equal when the constant speed is stably rotated, as shown by equation (12). At this time, the magnitude of the torque τ_M to which the polishing tool is subjected is:

$$\tau_M = |\mathbf{m}||\mathbf{B}_l|\sin\varphi = \frac{\mu_l |\mathbf{m}||\mathbf{M}|\sin\varphi}{4\pi|\mathbf{p}|^3} \tag{11}$$

The magnetic force $\mathbf{F}$ obtained by the finishing tool can be:

$$\mathbf{F} = \frac{3\mu_l |\mathbf{m}||\mathbf{M}|\cos\varphi}{4\pi|\mathbf{p}|^4}\begin{bmatrix}-1\\0\\0\end{bmatrix} \tag{12}$$

It can be seen from the formula (12) that the direction of the magnetic force $\mathbf{F}$ received by the polishing tool is always in the negative direction of the x-axis.

The magnitude of the magnetic field torque τ_M and the magnetic force $\mathbf{F}$ of the polishing tool depend on the hysteresis angle φ. When $\varphi = 0$, the magnetic force is the largest of $\varphi = 90°$, and the magnetic field torque is 0; when the magnetic force is zero, the magnetic field torque is the largest. During the actual polishing process, the magnitude of the hysteresis angle φ is related to the external permanent magnet and the rotational speed of the polishing tool. When the rotational speed is kept constant, the size of the polishing tool can be kept constant.

When $\varphi = 45°$, the relationship between the magnetic force $\mathbf{F}$ and the distance $|\mathbf{p}|$ of the polishing tool is as shown in **Figure6**. When the distance $|\mathbf{p}|$ is less than 5 cm, the polishing tool is subjected to a significant magnetic force; when the distance is greater than 10 cm, the polishing tool is subjected to a magnetic force of almost zero. Therefore, in order to subject the polishing tool to a sufficient magnetic force, the distance between the center of the outer permanent magnet and the center of the polishing tool should be kept as close as possible.

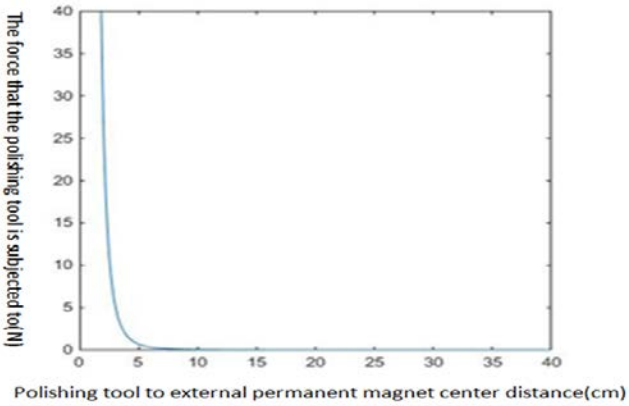

Figure 6. Polishing Tool Magnetic Force and Distance Diagram

4. Conclusion

The two driving schemes of radial driving and axial driving are analyzed. In the radial driving mode, in order to ensure synchronous rotation, the external permanent magnet is controlled to rotate non-uniformly, and the polishing tool is periodically floated; the axial driving mode is polished. The tool is magnetically attractive, more controllable and stable. Therefore, this paper chooses the axial driving method for the polishing tool.

5. Acknowledgments
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