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Analysis and Suppression of Chatter in Robotic Machining Process

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robotic machining, chatter, mode coupling, cutting force, structure model

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Analysis and Suppression of Chatter in Robotic Machining Process

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Abstract: One of the most challenging issues in robotic machining process is to know the vibration/chatter characteristics. To reduce the trial and error frustration, this paper presents the underline mechanism and theoretical analysis to provide physical understanding for the onset of chatter problem and principles to prevent that. First, the cutting force model and robot structure model are established for a systematic analysis of chatter mechanism. Completely different from common woes of regenerative chatter in conventional CNC machine paradigm, another type of chatter, namely, mode-coupling chatter was identified as the dominant source of vibrations in robotic machining, largely due to the inherent low structure stiffness of industrial robot. In-depth analysis for stability criteria and experimental verifications are then presented followed by the guidelines of process configuration and parameter selections to achieve chatter free machining operation.

Keywords: robotic machining, chatter, mode coupling, cutting force, structure model

1. INTRODUCTION

One of the major hurdles preventing the adoption of robot for machining process is chatter. Tobias [1] and Thusty [2] recognized that the most powerful sources of chatter and self-excitation were the regenerative and mode coupling effects. Although extensive research on chatter has been carried out, none of the existing research has focused on chatter mechanism in robotic machining process. The result is that robotic engineers and technicians are frustrated to deal with elusive and detrimental chatter issues without a good understanding or even a rule of thumb guideline. Very often, to get their process working correctly, one has to spend tremendous time on trial and error for the sheer luck of stumbling a golden setup or has to sacrifice the productivity by settling on conservative cutting parameters much lower than the possible machining capability.

This research is trying to bridge the gap by pointing out the underline chatter generation mechanism based on various experimental tests as well as detailed theoretical analysis. In this paper, the characteristics of chatter in robotic machining process are first presented. Secondly the modeling of chatter process including robot structure model and machining force model are established. Thirdly, the detailed analysis of chatter mechanism applying both regenerative and mode coupling theory is introduced and compared. Then further experimental results are provided to verify the theoretical analysis. Stability criteria and insightful guidelines for avoiding chatter in robotic machining process are presented followed by the summary and conclusion section.

2. CHARACTERISTICS OF CHATTER IN ROBOTIC MACHINING PROCESS

Severe low frequency chatter has been observed ever since when robot was first applied in machining process, nevertheless, no theoretical explanation and analysis are available in the existing literature to date. The conventional wisdom is that this is due to the obvious fact that the robot is much less stiffer than CNC machine, but no answer is provided for the further explanation.

In the present work, a robotic milling system is setup with ABB IRB6400 industrial manipulator. The spindle is mounted on robot wrist while the workpiece is fixed on the steel table. An ATI 6DOF Force/Torque sensor is set up between the robot wrist and spindle as shown in Fig. 1. After compensating the gravity of spindle and tool, 3 DOF machining force could be measured accurately. When chatter occurs, the amplitude of cutting force increases dramatically and the chatter frequency is observed from the Fast Fourier Transform of force data. The experimental conditions for robotic end milling are summarized in Table 1.

In most situations, the cutting process is stable; the work cell could conduct 4-5mm depth-of-cut (DOC) until reaching the spindle power limit. Nevertheless,
while feed in -Z direction, severe low frequency (10Hz) chatter occurs when the DOC is only 2 mm. The characteristics of this low frequency chatter are:

1. The frequency of chatter is the robot base natural frequency at 10Hz. It does not change with the variation of cutting parameters such as spindle speed, width-of-cut (WOC), feed speed and the location of workpiece.

2. When chatter occurs, the entire robot structure start to vibrate. The magnitude of vibration is so large that obvious chatter marks are left on the workpiece surface. (Fig. 2)

3. In the cutting setup of Fig. 1 and Table 1, using the exact same cutting parameters (DOC, RPM, WOC, Feed speed), chatter starts to occur when feed in –Z direction, DOC=2mm, while the process is stable when feed in +Z, ±X direction, even with the DOC=4mm.

4. The cutting process has different chatter limit at different locations in the robot workspace.

Table 1 Setup for robotic machining process

<table>
<thead>
<tr>
<th>Test</th>
<th>End milling</th>
<th>Deburring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot</td>
<td>ABB IRB6400</td>
<td>ABB IRB6400</td>
</tr>
<tr>
<td>Spindle type</td>
<td>SETCO,5HP,</td>
<td>GCOLOMBO,11HP</td>
</tr>
<tr>
<td>Tool type</td>
<td>SECO Φ52mm,</td>
<td>SANDVIK,</td>
</tr>
<tr>
<td></td>
<td>Round insert</td>
<td>Φ20mm,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Helical 2-flute</td>
</tr>
<tr>
<td>Feed rate</td>
<td>30 mm/s</td>
<td>60 mm/s</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>3600 RPM</td>
<td>18,000 RPM</td>
</tr>
<tr>
<td>DOC</td>
<td>1-4 mm</td>
<td>5mm</td>
</tr>
<tr>
<td>WOC</td>
<td>38mm</td>
<td>15mm</td>
</tr>
</tbody>
</table>

(Fig. 2). Chatter marks left on the workpiece.

3. CHATTER PROCESS MODELING

All self-excited chatter analysis techniques begin with a force model of the machining process and a dynamic model of the machine tool-workpiece structure. These two models are combined to form a closed-loop dynamic model of the machining operation.

The structure of industrial robot is quite different from a CNC machine. The serial structure of articulated robot has a much lower stiffness than that of a standard CNC machine. The stiffness for an articulated robot is usually less than 1 N/µm, while a standard CNC machine very often has stiffness greater than 50 N/µm. With a large mass, the base natural frequency of robot structure is very low, typical for a large robot, it is around 10Hz compared with several hundred Hz or even more than one thousand Hz for the moving component of a CNC machine.

With the workpiece mounted on a strong steel table, it has a much larger stiffness than that of the robot-tool structure. The structure of the workpiece could be considered as relatively stiff and its deformation is ignored in the analysis. The robot-tool structure is modeled by the transfer function in s domain and differential equation in time domain as:

\[ \{\Delta\} = [G(s)]\{F\} \]  
\[ [M]\{\dot{\Delta}\} + [C]\{\Delta\} + [K]\{\Delta\} = \{F\} \]

where \([G(s)]\) is matrix of system transfer functions, 
\([M], [C]\ and \ [K]\) are 6×6 system mass, damping and stiffness matrix respectively. Although these matrices are configuration dependent, for the convenience of analysis, while robot moves in a small range they are considered as constant.

3.1 Machining force model

In end milling process, the machining force is proportional to the DOC, Eq. (3).

\[ F = K_p d \]  

Where \(K_p\) is the process gain, which depends on the material of workpiece, current WOC, feed speed, spindle RPM, etc.

3.2 Robot mass model

The mass matrix is related to robot rotational inertia in joint space as

\[ M = J(Q)^{-T} I_r(Q) J(Q)^{-1} \]

Where \(J(Q)\) is the Jacobian matrix of the robot, \(I_r(Q)\) is a 6×6 matrix which represents the robot rotational inertia in joint space. \(I_r(Q)\) is a function of joint angle and is not a diagonal matrix. It could be derived from robot kinematic model by Newton-Euler method or Lagrangian method, if the rigid body inertia parameters are available. For a single link, if \(I_l\) and \(I_m\) represent the rotational inertias of the link and motor, the rotational inertia is given by

\[ I_q = I_l + n^2 I_m \]

where \(n\) is gear ratio of the robot joint.

3.3 Robot stiffness model

Since the compliance of robot structure mostly comes from the deformation of gear box, the robot stiffness could be represented as a time invariant model in joint space.

\[ \tau = K_q \cdot \Delta Q \]

Where: \(\tau\) is the torque load on the six joints; \(K_q\) is a 6×6 matrix; \(\Delta Q\) is the 6×1 deformation vector of all joints. \(K_q\) is diagonal and assumed to be constant, which
means the stiffness of each joint is independent to each other and is independent of it’s own revolution position.

Similar to the mass matrix, stiffness matrix in Cartesian space $K$ and joint space $K_q$ are related by Jacobian matrix of robot as:

$$K = J(Q)^{-T} K_q J(Q)^{-1}$$  \hspace{1cm} (7)

For articulated robot, $K$ is not a diagonal matrix and is configuration dependent. This means: first, the force and deformation in Cartesian space is coupled, the force applied in one direction will cause the deformation in all directions/orientations; second, at different locations, the Cartesian stiffness matrix will take different values.

The robot joint stiffness $K_q$ is identified by static payload test. With the measurement of external force and corresponding robot deformation, from Eq. (7), $K_q$ could be solved by least square method. The detailed robot stiffness modeling and identification are introduced in [4].

### 4. CHATTER ANALYSIS

#### 4.1 Regenerative mechanism

Regenerative chatter is a self-excited vibration in a machining operation resulting from the interference between the current machining pass and the wavy surface generated during previous machining passes. The energy for the chatter comes from the forward motion of the tool/workpiece. The frequency is typically slightly larger than the natural frequency of the most flexible vibration mode of the machine-tool system. The corresponding mathematical models are delay-differential equations (DDEs) or periodic differential equations (PDFs). Merritt [5] combined the regenerative theory and a feedback loop to derive a differential equations (PDFs).

A simplified one-DOF analysis could easily prove how regenerative mechanism will not introduce chatter as low as 10 Hz, while the spindle speed is 3600RPM. The transfer function of this model is:

$$G(s) = \frac{1}{ms^2 + cs + k + K_c(1-e^{-\tau s})}$$  \hspace{1cm} (8)

where $\tau$ is the time delay between the current cut and the previous cut. It is related to the spindle speed and number of teeth on the cutting tool. The stability margin is when the characteristic equation of this transfer function has pure imaginary solutions, which are:

$$d = \frac{m(\omega_n^2 + 4\omega_n \zeta \omega_s^2)}{2k_p}$$

$$\Omega = \frac{60(\omega_n \gamma)}{\omega_n - \pi (2n - 1)} \quad n = 1, 2, 3...$$  \hspace{1cm} (9, 10)

where $d$ is DOC, $\Omega$ is RPM, $\omega_n = \sqrt{k/m}$, $\zeta = c/2m$, and $\omega_s = \omega_n \sqrt{1 - \zeta^2}$. The corresponding stability lobe is plotted in Fig. 3. Obviously, with spindle speed $\Omega$=3600, robot works on the very right side of first stability lobe, where DOC is almost unlimited.

Based on regenerative chatter theory, one would not expect to observe the low frequency chatter. However, from the experimental test, such chatter behavior indeed exists, which forced us to look into other theories to explain the underline mechanism for this kind of chatter. In the following section, we would explore the mode coupling chatter theory and find that is the most reasonable explanation to the aforementioned problem.

#### 4.2 Mode coupling mechanism

Generally, from Eq. (2) and Eq. (3), the dynamic model of the system is formulated as:

$$[M][\Delta] + [C][\Delta] + [K][\Delta] = [K_p][\Delta]$$  \hspace{1cm} (11)

The stability of the system depends on the eigenvalues of the equation above. Since the focus here is to analyze the chatter due to the mode coupling effect, the following simplifications are made:

1. Since damping effect will always increase the stability of the system and it is difficult to be identified accurately, we only analyze the undamped system.

2. While round inserts are applied in robotic end milling operation, the machining force in feed direction is much smaller than the forces in cutting and normal direction. Thus while feed in Z direction, we could simplify the analysis into a 2-DOF problem in X-Y frame.

Thus, machining force model become $F=K_p Y$, with $F$ and $X$ form a angle of $\alpha + \gamma$, as shown in Fig. 4.

The 2-DOF dynamic equation of system without considering the damping effect is:

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} 0 & K_p \sin(\alpha + \gamma) \\ 0 & K_p \cos(\alpha + \gamma) \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix}$$  \hspace{1cm} (12)

A similar model was analyzed by Gasparetto [6] for wood cutting application. General solutions for Eq. (12) are available, if the coefficient matrices are identified accurately. Since mass matrix $[M]$ is symmetric and positive definite, stiffness matrix $[K]$ is symmetric and
semi-positive definite, there exists a matrix $[V]$ which diagonalize $[K]$.

By perform this similarity transformation, Eq. (12) becomes

$$\dot{[q]} + \{K_q\} = [V]^{-1} [K] [V] [q]$$

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The characteristic equation of Eq. (16) is:

$$\lambda^2 + \frac{K_{q1} + K_{q2}}{M} \lambda + \frac{K_{q1} K_{q2} - \frac{1}{4} K_p^2 \sin(2\gamma) \sin(2\alpha)}{M^2} = 0$$

(17)

The solution of Eq. (17) gives:

$$\lambda^2 = \frac{-((K_{q1} + K_{q2}) \pm \sqrt{(K_{q1} - K_{q2})^2 + K_p^2 \sin(2\gamma) \sin(2\alpha)}}{2M}$$

(18)

Fig. 4. 2D model of mode coupling chatter system

Generally $[V]$ is not an orthogonal matrix, which means the axes of generalized coordinate $[q]$ are not perpendicular to each other. The stability of the system depends on the eigenvalues of matrix $[V]^T [K_p] [V] - \{K_q\}$. If all the eigenvalues of this matrix are negative real number, the system is stable; otherwise, if this matrix has complex eigenvalues, the system will be unstable.

For better explanation of the problem, without loss of generality, we assume that $[M]$ is diagonal without transformation and model mass for each direction is the same.

$$[M] = \begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}$$

(14)

In this case, $[V]$ is an orthogonal matrix, that is $[V]^T = [V]^{-1}$, similarity transformation is equal to rotation of the original frame. Thus, the uncoupled principle stiffness directions are perpendicular to each other. In Fig. 4, $X$ and $Y$ represent frame $\{\Delta\}$; $X_1$ and $Y_1$ represent frame $\{q\}$. Cutting process is operated in frame $\{\Delta\}$ with cutting force in $X$ direction and normal force in $Y$ direction (direction of DOC). In frame $\{q\}$, both $[M]$ and $[K]$ are diagonal. The transformation from $\{\Delta\}$ to $\{q\}$ is defined as $\{q\} = [V]^{-1} \{\Delta\}$, where

$$[V]^{-1} = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

(15)

Then the system equation in the frame $\{q\}$ is:

$$\begin{bmatrix} \dot{X_1} \\ \dot{Y_1} \end{bmatrix} = \begin{bmatrix} \frac{K_x \cos(\gamma) \sin(\alpha) - K_p}{M} & \frac{K_x \cos(\gamma) \cos(\alpha)}{M} \\ \frac{K_p \sin(\gamma) \sin(\alpha)}{M} & \frac{K_p \sin(\gamma) \cos(\alpha) - K_p}{M} \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \end{bmatrix}$$

(16)

Let

$$K_{q1} = K_x - K_p \cos(\gamma) \sin(\alpha)$$

$$K_{q2} = K_x - K_p \sin(\gamma) \cos(\alpha)$$

By perform this similarity transformation, Eq. (12) becomes

$$\dot{[q]} + \{K_q\} = [V]^{-1} [K] [V] [q]$$

(13)

$K_q = K_x - K_p \sin(\gamma) \cos(\alpha)$

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The characteristic equation of Eq. (16) is:

$$\lambda^2 + \frac{K_{q1} + K_{q2}}{M} \lambda + \frac{K_{q1} K_{q2} - \frac{1}{4} K_p^2 \sin(2\gamma) \sin(2\alpha)}{M^2} = 0$$

(17)

The solution of Eq. (17) gives:

$$\lambda^2 = \frac{-((K_{q1} + K_{q2}) \pm \sqrt{(K_{q1} - K_{q2})^2 + K_p^2 \sin(2\gamma) \sin(2\alpha)}}{2M}$$

(18)

In practice, $K_x, K_p >> K_p'$ is always satisfied, otherwise, cutting process could not be executed. Thus $K_{q1} = K_x$ and $K_{q2} = K_p$.

If $(K_{q1} - K_{q2})^2 + K_p^2 \sin(2\gamma) \sin(2\alpha) > 0$, then the two $\lambda^2$ are real negative numbers. In this case the four eigenvalues of the system located on the imaginary axis, symmetric with respect to real axis. The solution of system is Lissajous curves. The system results stable in a BIBO sense. Moreover, since the system damping always exist, the structure damping of the real system will shift the eigenvalues of the system toward left in the complex plan, therefore giving exponentially decaying modes.

If $(K_{q1} - K_{q2})^2 + K_p^2 \sin(2\gamma) \sin(2\alpha) < 0$, then two $\lambda^2$ are complex number with negative real part. In this case the four eigenvalues of the system are located symmetrically with respect to the origin of the complex plane, so two of them have positive real part. Therefore, instability occurs in this case. The solution of system is exponential increasing. While the damping effect is considered, the locus of TCP is an ellipse.

Unstable region could be represented as:

$$\sin(2\gamma) < \frac{\left(K_{q1} - K_{q2} + K_p \sin(\gamma - \alpha)\right)^2}{-K_p^2 \sin(2\alpha)}$$

(23)

An important result here is that unstable condition is only possible when $K_p \gg K_x - K_p$. That means the mode coupling chatter only occurs when the process stiffness is larger than the difference of two principle stiffness of robot. The physical meaning of the equation gives us the general stability criterion. If a machining system can be modeled by a two degree of freedom mass-spring system, the dynamic motion of the TCP can take an elliptical path. If the axis with the smaller stiffness lies within the angle formed by the total cutting force and the normal to the workpiece surface, energy can be transferred into the machine-tool structure, thus producing mode coupling chatter. The depth of cut for the threshold of stable operation is directly dependent upon the difference between the two principal stiffness values, and chatter tends to occur when the two principal stiffness are close in magnitude.

For CNC machine, the structure stiffness $k$ is on the level of $10^8$ N/m, and the process stiffness $K_p$ is usually...
in the range of $10^5$–$10^6$ N/m. As a result, any small difference of $k$ in each principle directions is much larger than $K_p$. Before the occurrence of mode coupling chatter, spindle power limit or regenerative chatter limit already reached.

The story is totally different for industrial robot, where stiffness $k$ is on the level of $10^6$ N/m and has close magnitude in each direction. Since the process stiffness $K_p$ of machining aluminum workpiece is usually on the level of $10^6$ N/m, the mode stiffness of each principle direction could be smaller than process stiffness in certain robot configuration. The mode coupling chatter will then occur even in very light cutting condition. The vibration limit of robotic milling operation depends on the relative angels between machining force vector and the direction of the principle mode stiffness.

The above analysis also coincide with a rule of thumb in the machine tool industry, that the stiffness of two directions should at least has 10% difference to prevent chatter.

![Fig. 5. Locus of force vector while chatter happens.](image)

The characteristics of low frequency chatter summarized in section two could be perfectly explained by mode coupling mechanism.

1. The frequency of mode coupling chatter is the same as the base frequency of the machine. The process parameters such as spindle speed, width-of-cut (WOC), and feed speed won't change the frequency of chatter.

2. In unstable condition, the solution of the system will exponentially increase until it is balanced by damping effects or just crash (Fig. 2). The locus of force vector is drawn in Fig. 5 The locus of tool tip movement will take the same elliptical path.

3. An unstable cutting process could become stable by only changing the feed direction because the direction of force vector is changed while machine structure keeps the same.

4. Chatter limit of the process is configuration dependent due to the coupled robot structure. The mass matrix and stiffness matrix are not constant; they take different values at different robot configurations. As a result, although the force vector is the same, the chatter limit is different since the machine structure is different.

### 5. EXPERIMENTAL RESULTS AND ANALYSIS

Further experimental verification of the theoretical analysis described in the foregoing section was observed in robotic deburring tests. The same type of robot is applied for deburring test of aluminum workpiece; the detailed cutting condition is given in Table 1.

In the deburring test, side milling using two-flute helical mill were carried out. Fig. 6 presents four machining cases with exactly same cutting parameters except for different feed direction. The cutting conditions and measured machining forces are listed in Table 2. Experimental results show that chatter only happens in case 1, while the processes are stable for the rest of the cases. In Fig. 6, four force vectors are plotted in the fixed frame $X-Y$. $K_S$ and $K_L$ represent the smaller and larger principle stiffness of robot calculated from robot structure model, $Y_{(1-2)}$ and $Y_{(3-4)}$ represent the normal direction to the workpiece in vertical and horizontal cutting tests. From the stability criteria established in section four, mode coupling chatter will occur when axis with the smaller stiffness lies within the angle formed by the total cutting force and the normal to the workpiece surface. From Fig. 6, stability criteria predict that chatter will only occur in case 1, which perfectly matches the experimental results.

![Table 2 Summary of deburring test](image)

![Fig. 6. Stability analysis of deburring](image)

Another important result worth mentioning here is the effect of up-milling and down-milling on mode coupling chatter in robotic machining process. As shown in Fig. 7, the direction of cutting force is in a
range that is perpendicular to the normal of workpiece in up-milling while the direction of cutting force is almost the same as normal of workpiece in down-milling. Thus, it is more likely for axis with the smaller stiffness to lie between the force vector and the workpiece normal direction during up-milling than down-milling. As a result, chatter point of view, down-milling is preferred for robotic machining process.

![Fig. 7. Up-milling vs. down-milling in mode coupling chatter analysis](image)

After investigating the intrinsic mechanism of low frequency chatter, practical guidelines for chatter-free robotic machining process is summarized here.

1. Select the proper cutting tool. The tool or inserts with different geometry will distribute machining force to different directions. Round insert always generates larger normal force (DOC direction) compared to square insert with zero degree lead angle. Since DOC is the most sensitive parameter related to machining force, chatter may arise more easily if the process has larger normal force. Thus Round insert is not recommended for robotic machining although it has many advantages and is widely using by CNC machine.

2. Plan the proper work space. Since the robot displays different mechanical properties, which are mass, stiffness and damping, at different locations in the workspace, selecting a proper machining location that will have higher chatter limit.

3. Plan the proper path and feed direction. Changing the feed direction is the easiest way to re-direct machining force without affecting the existing setup. Based on the theoretical analysis and experimental results, this is an effective method to avoid mode coupling chatter. The relative orientation of the force vector and the principle stiffness axes of the robot is the dominant factor affects the stability of machining process. Methods such as changing the feed direction, using different robot configuration or changing another type of tool are all worth trying. Based on the theoretical investigation and verified with practical tests, we believe this research leads to a deeper understanding of the chatter phenomenon in robotic machining process and provides a guideline as well as practical solutions to avoid such problems.

6. SUMMARY AND CONCLUSION

Vibration of robot-tool structure is the major limitation of robotic machining capacities. The low frequency mode coupling chatter will shake the entire robot body and cause dramatic damage to the system. This paper provides the investigation of the chatter analysis in robotic machining process for the first time. Both regenerative chatter and mode coupling chatter theory are investigated here to explain the drastic low frequency vibration in certain machining setup.

Although regenerative chatter is the most widely accepted reason for high frequency vibration in machining process, it has little relationship with low frequency structure vibration during robotic machining process. An analysis of mode coupling chatter shows that if the structure stiffness is not significantly higher than process stiffness, mode coupling chatter may happen. Since the stiffness of the CNC machine is usually hundreds of times larger than process stiffness, mode coupling chatter rarely happen. For robot, the difference is only 5 to 10 times. This mode coupling effect is the dominant reason for structure vibration in robotic machining process.

The occurrence of mode coupling chatter depends on the direction as well as the magnitude of the machining force. Since reducing the magnitude of the force will usually decrease the material removal rate and increase cycle time, it is not a preferred solution to avoid mode coupling chatter. The relative orientation of the force vector and the principle stiffness axes of the robot is the dominant factor affects the stability of machining process. Methods such as changing the feed direction, using different robot configuration or changing another type of tool are all worth trying. Based on the theoretical investigation and verified with practical tests, we believe this research leads to a deeper understanding of the chatter phenomenon in robotic machining process and provides a guideline as well as practical solutions to avoid such problems.

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