Research on the Influence of Cutting Speed on Vibration Cutting Force

Liang Yang and Mingzhao Zhang

ABSTRACT

In this paper, the effect of cutting speed on vibration cutting force is studied from two aspects of theory and experiment. In vibration cutting, for the determined vibration parameters, the change of cutting speed will affect the relative velocity between the tool and chip during the interaction, especially at the initial contact time. The ultrasonic vibration assisted turning experiment of aluminum rod was designed, and the cutting force were obtained under different cutting speed conditions. The experimental results show that when the cutting speed is about 0.3 times of the critical cutting speed, the cutting force is the smallest within the test range. The experimental results are in good agreement with the theoretical analysis, i.e., the larger the relative velocity, the smaller the cutting force during the interaction between the tool and the chip.

INTRODUCTION

The experimental results [1] show that the amplitude, feed rate and cutting speed are important parameters affecting the residual stress. Nategh M J et al. [2] found that the vibration cutting force is lower than the corresponding ordinary cutting force, especially under the condition of large amplitude. Lotfi M et al. [3] found that the velocity is positively related to the Mises stress in a certain range, while the vibration amplitude is negatively related to the Mises stress. Razavi H et al. [4] found that the increase of amplitude or the decrease of cutting speed will reduce the ratio of vibration cutting force to common cutting force. In addition, Cakir F H et al. [5] confirmed that the ultrasonic assisted turning changes the cutting conditions by influencing the cutting speed. In this paper, the relative velocity during the contact

1Liang Yang, Mingzhao Zhang, Dalian Jiaotong University, Dalian, Liaoning, China, 116028.
between tool and chip is analyzed theoretically, and then the influence of relative velocity on machining is experimentally studied.

THEORETICAL STUDY ON RELATIVE VELOCITY

In the vibration assisted cutting, the product of the amplitude ‘A’ and the angular frequency ‘ω’ (ω=2πf) is defined as the critical cutting speed ‘Aω’, and the ratio of the cutting speed ‘v0’ to the critical cutting speed is defined as the cutting speed factor ‘k’ [6]. Cutting speed can be expressed as:

\[
v_0 = kA\omega
\]  

(1)

Figure 1 (left) shows the relative displacement of cutter and workpiece in a vibration period (assuming the workpiece does not move, and the cutter reciprocating forward). Each cycle consists of three stages: drawing back (A1-S1), moving forward without cutting (S1-B1) and cutting (B1-A2). The displacement curve of the tool relative to the workpiece is shown in Figure 1 (right). The thick real line means that the tool keeps contact with the chip, and the fine dotted line means they are in the separated state. The two points of ‘A1’ and ‘A2’ are the maximum displacement points of the two adjacent periods, and the corresponding moments are also the separation time between the cutter and the chip. The two points of ‘B1’ and ‘B2’ are the same as ‘A1’ and ‘A2’ respectively, and the difference is that the tool is approaching the chip, instead of far from the chip.

The relative displacement and relative velocity of ‘A1’ moment can be obtained by formula (1) and formula (2) respectively:

\[
s(t_{A1}) = kA\omega t_{A1} + Asin(\omega t_{A1})
\]  

(2)

\[
v(t_{A1}) = kA\omega + A\omega cos(\omega t_{A1})
\]  

(3)

The separation time ‘tA1’ is calculated by \(v(tA1)=0\):

\[
t_{A1} = \frac{arccos(-k)}{\omega}
\]  

(4)
Since the displacement of ‘A1’ is the same as that of ‘B1’, there is an equation:

\[ \sin(\omega t_{A1}) + k\omega t_{A1} = \sin(\omega t_{B1}) + k\omega t_{B1} \] (5)

The relation between cutting speed coefficient ‘k’ and the initial contact time ‘tB1’ can be obtained by substituting formula (4) into (5):

\[ \sqrt{1-k^2} + k \cdot \arccos(-k) = \sin(\omega t_{B1}) + k\omega t_{B1} \] (6)

On the other hand, it is assumed that the relative velocity at the initial contact time ‘ν(tB1)’ is \( \lambda \) times of the critical cutting speed ‘Aω’:

\[ \nu(t_{B1}) = kA\omega + \cos(\omega t_{B1}) A\omega = \lambda A\omega \] (7)

\[ \lambda = k + \cos(\omega t_{B1}) \] (8)

For the objective function \( \lambda(k,t_{B1}) \), there are the following constraints:

\[ \begin{cases} 0 < k < 1 \\ 0.5T < t_{B1} < 1.5T \\ \sqrt{1-k^2} + k \cdot \arccos(-k) = \sin(\omega t_{B1}) + k\omega t_{B1} \end{cases} \] (9)

With the help of the commercial software ‘1stOpt’ and its accompanying algorithms "Quasi Newton method & General global optimization method", the maximum value of ‘\( \lambda \)’ and the corresponding speed coefficient ‘k (\( \lambda_{\text{max}} \)’ under constraint conditions (9) can be obtained:

\[ \begin{cases} \lambda_{\text{max}} \approx 1.26 \\ k(\lambda_{\text{max}}) = 0.308 \end{cases} \] (10)

Since the relative velocity is a periodic function, the velocity \( \nu(t_{Bi})(i=1, 2, 3) \) of each cycle is the same, and it can be replaced by ‘\( \nu_B \)’. That is to say, for the separative vibration cutting, when the cutting speed coefficient ‘k’ is about 0.308, the relative velocity of the initial contact time reaches the maximum value ‘1.26 Aω’.

**VIBRATION TURNING EXPERIMENT**

The composition of the experimental platform is shown in Figureure2 (left). As shown in Figure 2 (right), the radial, axial and tangential directions of the workpiece
are defined as X, Y and Z respectively. In the vibration cutting experiment, the same vibration parameters and different rotating speeds are used to carry out multiple vibration cutting on the same bar. The cemented carbide cutting tool geometry is as follows: the rake angle is 10°, and the relief angle is 5°. The amplitude is 5μm, and the frequency is 19.5 KHz. In addition, the feed rate is 0.01 mm/r, and depth of cut is 0.4 mm. The aluminum Al6061 bar with a diameter of 25mm is clamped on the three jaw chuck. The cutting speed coefficient ‘k’ are shown in Table II.

![Figure 2](image-url)  
**Figure 2.** Vibration turning experiment platform (a-Ultrasonic generator; b-Ultrasonic vibrator; c- Dynamometer; d-Workpiece; e-Lathe; f-Computer; g-Amplifier) and directions.

**EXPERIMENTAL RESULTS**

For the determined ‘k’, the corresponding numerical solution of the relative velocity at initial contact time ‘vB’ can also be obtained by formula (7) ~ (9). Table II lists the 9 velocity coefficients in the range of 0~1 involved in this test, and all the corresponding ‘vB’. All the cutting force results are also shown in TABLEII. In the size, the feed resistance ‘Fy’ and the main cutting force ‘Fz’ are larger, while the radial thrust force ‘Fx’ is smaller. But, the main cutting force ‘Fz’ fluctuates very little.

Figure 3 reflects the variation of the relative speed and cutting forces (radial thrust force ‘Fx’ and axial thrust force ‘Fy’) with the speed coefficient. By comparing the radial thrust force ‘Fx’ and axial thrust force ‘Fy’ with the relative velocity ‘vB’ of initial contact time, for the separating type vibration cutting, it can be seen that the bigger the relative velocity of initial contact time, the smaller the cutting force.
**TABLE II. RELATIVE VELOCITY AND AVERAGE CUTTING FORCE.**

<table>
<thead>
<tr>
<th>Serial number</th>
<th>$n$ (r/min)</th>
<th>$k$</th>
<th>$v_B$ ($A_0\omega$)</th>
<th>$F_x$ (N)</th>
<th>$F_y$ (N)</th>
<th>$F_z$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.5</td>
<td>0.026</td>
<td>0.551</td>
<td>4.466</td>
<td>115.970</td>
<td>76.009</td>
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<tr>
<td>2</td>
<td>80</td>
<td>0.172</td>
<td>1.157</td>
<td>4.001</td>
<td>116.436</td>
<td>78.204</td>
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<tr>
<td>3</td>
<td>100</td>
<td>0.215</td>
<td>1.215</td>
<td>1.145</td>
<td>14.671</td>
<td>79.067</td>
</tr>
<tr>
<td>4</td>
<td>160</td>
<td>0.343</td>
<td>1.254</td>
<td>1.541</td>
<td>16.068</td>
<td>80.282</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>0.430</td>
<td>1.202</td>
<td>2.063</td>
<td>106.422</td>
<td>78.636</td>
</tr>
<tr>
<td>6</td>
<td>250</td>
<td>0.537</td>
<td>1.074</td>
<td>3.117</td>
<td>81.738</td>
<td>79.263</td>
</tr>
<tr>
<td>7</td>
<td>320</td>
<td>0.688</td>
<td>0.803</td>
<td>3.638</td>
<td>105.724</td>
<td>80.282</td>
</tr>
<tr>
<td>8</td>
<td>400</td>
<td>0.860</td>
<td>0.395</td>
<td>4.012</td>
<td>118.532</td>
<td>78.283</td>
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<tr>
<td>9</td>
<td>450</td>
<td>0.967</td>
<td>0.098</td>
<td>4.454</td>
<td>139.024</td>
<td>77.460</td>
</tr>
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</table>

**CONCLUSIONS**

The change of cutting speed has a significant influence on the cutting force in separating type vibration cutting. Theoretical analysis and experimental results show that when the cutting speed coefficient $k$ is about 0.3, the relative velocity of initial contact time is relatively large which is beneficial to reduce the cutting force. In addition, for the separating type vibration cutting, the cutting force decreases, on the whole, with the increasing relative velocity at the initial contact time.
ACKNOWLEDGEMENTS

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REFERENCES


