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A Study on Improving the Productivity of Scrolls

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Abstract: To improve the machining efficiency and suppress the chatter occurrence, this study conducts the adaptive milling processes, comprising the adaptive feed rate control and chatter suppression, in the scroll manufacture including the rough, semi-, and fine machining processes. In the rough machining processes of scroll manufacture, the adaptive feed rate control computes the cutting area per each cutter tooth in real time to modify the feed rate and to promote the material removal rate (MRR). In the semi- and fine machining processes, this study focuses on the issue of chatter suppression. To suppress the chatter occurrence, the chatter frequencies are detected by a microphone and the spindle speeds are modified by the developed program cooperating with the controller in the milling machine. Experimental tests are also conducted to demonstrate the feasibility of the adaptive milling processes proposed in this study.

Keywords: Scroll, Adaptive milling processes, Adaptive feed rate control, Chatter suppression.

1. Introduction

The scroll-type compressors, which were first patented by Léon Creux [1] and commercialized in about 1980s, are widely used in the small- and medium-sized refrigeration and air conditioning systems. The key components of a scroll-type compressor are a pair of fixed and orbiting involute scrolls, where the fixed scroll meshes with the moving one in a revolving orbital motion. Comparing to conventional compressors, the scroll-type compressor is the only one having multiple symmetric compressing chambers during its operational periods. This has the advantages of smooth-operating and energy-saving benefits. However, the manufacture of scroll-type compressors generally needs longer machining time and higher product precision.

Considering the requirements of rapid material removal and high product precision for the manufacture of scroll components, conventional methods commonly used try and errors to approach the most appropriate machining parameters. However, those usually yielded lower efficiency and higher cost. To shorten the machining time and improve the product precision, this study conducts the adaptive milling processes, including the adaptive feed rate control and the chatter suppression, in the manufacture of scrolls.

Regarding the subjects of adaptive feed rate control, Wang simulated the three dimensional end milling processes by solid modelling, and adapted the feed rate by estimating the cutting loads and amounts to prolong the cutter life and avoid the chatter occurrence [2]. Spence and Altintas stabilized the machining conditions by constructing the first-order discrete model of adaptive feed rate control and cooperating with the auxiliary of CAD [3]. In the applications of milling complex surfaces, Lim and Menq proposed the plans of machining paths to maximize the feed rate as possible and reduce the machining time [4]. Saï, et al. conducted the simulation methods to analyze the chip thickness in the circular machining paths and suggested the adaptive feed rate basing on the chip thickness and different types of tool motions [5-6].

Considering the issues of chatter suppression, Smith and Tlusty classified six models of the milling process and compared their differences [7]. Using the frequency domain processing and the deterministic frequency domain chatter theory, Delio, et al. had shown that the microphone could provide a proper and consistent signal for reliable chatter detection and control [8]. Their study also compared the differences between the vibration frequencies of cutter and spindle, and gradually made the correction to find the most appropriate machining parameters. Smith and Tlusty dynamically simulated the relationship between the vibrations of workpiece and cutter in machining processes and compared their simulation results with those obtained in experiments [9]. Altintas and Budak proposed an analytical method to predict the stability lobes in milling processes by using dynamic equations [10]. To select the optimal machining parameters, Jensen and Shin developed the algorithm in predicting the stability lobes of face milling processes by using dynamic equations, presented experimental validation results, and discussed the influencing factors affecting the onset of chatter [11-12].

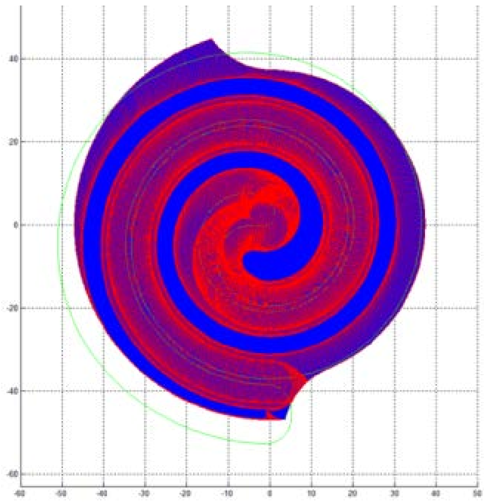
As mentioned above, this study aims at proposing the adaptive milling processes, including the adaptive feed rate control and the chatter suppression, for scroll manufacture to shorten their machining time and reduce the regeneration ripples on workpiece's surfaces. In the adaptive feed rate control, this study actually computes the cutting area per each cutter tooth to simulate the cutting amount and the feed rate adjustable in milling processes. The results can be used to increase the material removal rate and reduce the maximum cutting load in rough machining processes. In the chatter suppression, this study develops the programs basing on MATLAB to connect a PC and the Delta NC311A controller in milling machine, to process the signals of chatter frequency detected from a microphone, and to adjust the spindle speed for the purpose of suppressing the chatter occurrence. To verify the feasibility of the proposed methods, this study also conducts actual experiments and tests by using the TMV-720A vertical milling machine made by Tongtai Company.

2. Adaptive Feed Rate Control

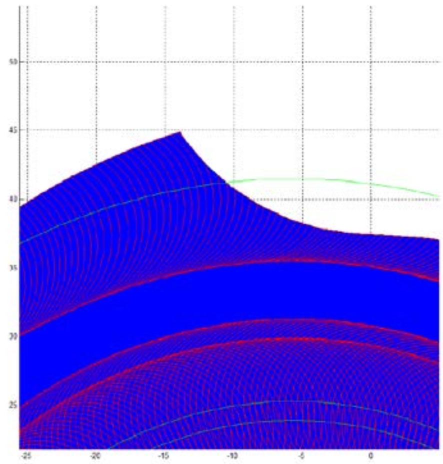
In the production of scrolls, a chunk of aluminum alloy, which is the material mostly used, would be sequentially machined in the rough, semi- and fine machining processes. Because about 65% of the whole material would be removed in the rough machining process, it is worth to increase the material removal rate to shorten the overall machining time. Conventionally to increase the material removal rate is directly to increase the feed rate in the machining processes. However, the overall stiffness of milling machine, the surface smoothness of workpiece, and the cutter life would be diminished when the feed rate is too high. In this section, comparing to the conventional solutions, the adaptive feed rate control, which can adjust the feed rate in the machining processes whose cutting loads are all close to a given value, will be proposed to increase the machining efficiency.

Earlier researches had shown that the real tooth path of a milling cutter is a trochoid [13-14]. The trochoidal tooth path could often be used to simulate and compute the chip thickness for the machining conditions with fixed cutting width and depth. In the analysis of scroll manufacture, however, the simulation of trochoidal tooth path is cumbersome and not easy for computation. Therefore, this study uses circular arc to approximately simulate the tooth path, and then to determine the cutting area which is the intersection of tooth path and workpiece's shape. From the cutting area per each cutter tooth, this study also can figure out the cutting amount per each cutter tooth since machining a scroll is also a kind of plane milling processes.

As shown in Fig. 1, the cutting area per each cutter tooth can be obtained from the calculation of the area intersected by two adjacent tooth paths, i.e., circular arc segments depicted by red curves, and workpiece's shape depicted by blue block.



(a) Whole workpiece



(b) Local enlargement

Fig.1. Cutting area intersected by tooth paths and scroll workpiece

The feed rate per each cutter tooth, denoted by F_z, and the average cutting area per each cutter tooth for each path segment, denoted by A_z, can be obtain as the following equations:

$$F_z = \frac{F}{S \cdot Z} \quad (1)$$

$$A_z = \frac{A \cdot F_Z}{l} \quad (2)$$

where F is the feed rate, S is the spindle speed, Z is the tooth number of a cutter, A is the cutting area for each path segment, and l is the length of each path segment.

Combining Eqs. (1) and (2) and eliminating F_z yields

$$F_{adp} = \frac{A_z \cdot l \cdot S \cdot Z}{A} \quad (3)$$

where F_{adp} is the adaptive feed rate, which can be deduced from the cutting area per each cutter tooth. By updating the adaptive feed rate, which are obtain from Eq. (3), to the controller of milling machine, this study can accomplish the processes of adaptive feed rate control.

3. Chatter Suppression

In the fine machining processes, most materials of the workpiece have been removed and the stiffness of a scroll would be significantly diminished. Meanwhile, the overall stiffness of milling machine would be also reduced when the spindle speed and the feed rate are raised to increase the machining efficiency. These conditions would be eventually prone to induce the occurrence of chatter. Therefore, it is worth to consider the issues of chatter suppression while confronting such the conditions of machining thin-wall workpieces of scrolls as mentioned above.

3.1. Chatter Theory and Stability Lobes

The chatter occurring in machining processes is classified as a kind of self-excited vibration between the workpiece and cutter [15]. The vibration amplitude induced by chatter will also influence the surface roughness of workpiece, the machining quality, and the cutter life. As shown in Fig. 2, a magnified view from a microscope, ripple shapes will be produced on the surface of workpiece after the milling process. The cutting ripples also determine the chip thickness, which would be generally consistent through normal processing conditions.

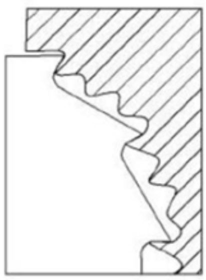


Fig.2. The cutting ripples produced after milling process [16]

In the end milling processes, as shown in Fig. 3 [16], it is assumed that the vibration model is a system with two degrees of freedom. The vibration amplitude simulated from this system can correspond to the regenerative waviness and be used to compute the chip thickness. The phase shift occurring between two tool paths will affect the chip thickness, decrease the machining quality, and vary the force on the cutting edge. Applying the varied force to the system of machining process would eventually induce the occurrence of chatter. Therefore, to stabilize the machining processes, it is necessary to hold the chip thickness and avoid the occurrence of phase shift.

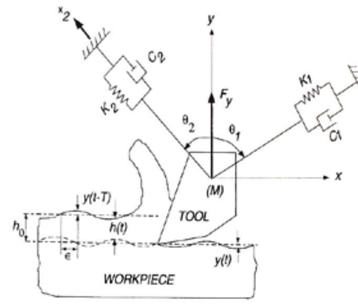


Fig.3. Vibration system in end milling [16]

The relationship between vibration frequency and tooth frequency, are shown in the following equation [17]:

$$\frac{h}{h_z} = N + \frac{\varepsilon}{2\pi} \quad (4)$$

where h is the vibration frequency, h_z is the tooth frequency, N is the number of complete waveforms between adjacent teeth, and ε is the phase shift angle between two corrugations. When chatter occurs, the vibration frequency h shown in equation (4) is also called chatter frequency. As mentioned above, the phase shift between cutting ripples induces the occurrence of regenerative waviness and chatter. It can be also observed that the ratio between vibration frequency and tooth frequency is not an integer according to Eq. (4) when chatter occurs.

As shown in Fig. 4, the relationship between the spindle speed and depth of cut, named as the stability lobes, can be obtained from the transfer function of the vibration system shown in Fig. 3. The results of Fig.4 can also be obtained by the percussion test of cutter.

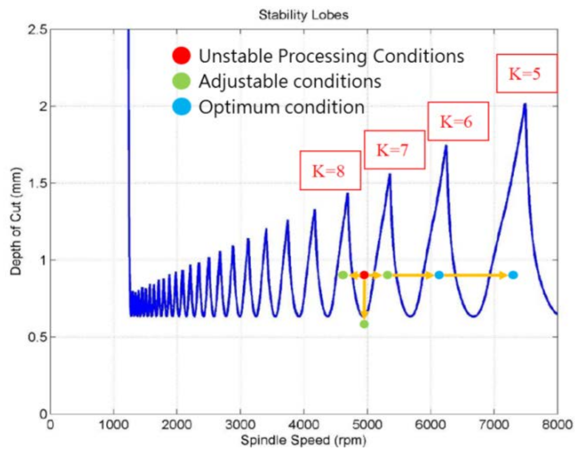


Fig.4. Stability lobes and the multiple factor K

In the milling process, the machining parameters might locate on the upper region of the stability lobes, for example, the red dot indicated in Fig. 4, and it also means that the cutting instability occurs. To prevent chatter occurrence, there are two methods can be used: one is to reduce the axial cutting depth and the other is to change the spindle speed, for example, moving the red dot to the locations of green or blue dots where mean the stable region. Because the axial cutting depth cannot be directly changed during the machining process, this study will change the spindle speed to suppress the chatter occurrence in real time.

3.2. Methods of Chatter Suppression

As mentioned above, the phase shift between the cutting ripples occurring in the milling processes, except for phase angles equal to 0° and 180°, would vary the chip thickness and be prone to induce the chatter occurrence. Earlier research [16] had proposed the method of adjusting the spindle speed to vary the phases between cutting ripples, to hold the chip thickness, and then to suppress the chatter occurrence. In this study, the audio signals captured by a microphone are used to detect the tooth frequency. The Fast Fourier Transformation (FFT) is used to convert the audio frequency from time domain to frequency domain in real time. The results can be used to observe the distribution and intensity of the tooth frequency. This study also adopts the amplitude to determine the magnitude of tooth frequency when chatter occurs, and figures out the multiple factor, denoted by K, which is the ratio between the tooth frequency and vibration frequency detected by the microphone. The multiple factor K can indicate the current machining parameter locating on the stability lobs, and can be expressed as:

$$K = \frac{60 f_c}{Z \cdot S} \tag{5}$$

where f_c is the chatter frequency detected by the microphone. When the value of K is an integer, it means that the machining parameters locate on the peak values of the stability lobes, as shown in Fig. 4, and the system vibration is a kind of forced vibrations. Besides, the chip thickness would be consistent and cutting instability can be avoided to retain the machining quality since there is no phase shift between the cutting ripples.

As mentioned in the previous section, this study will change the spindle speed to suppress chatter in real time. Furthermore, considering the stability lobes might be shifted by the effects of external disturbance and system defects, this study would give priority to increase the spindle speed to be the value, as shown in Fig. 4, where locates the peak value of multiple factor K. To avoid cutting instability, the new spindle speed, indicated by S_{new}, can be obtained as:

$$S_{new} = \frac{60 f_c}{Z \cdot K_{new}} \tag{6}$$

where K_{new} denotes the nearby peak value of K which will be input to the simulation system.

The flow chart of the PC-based program for chatter suppression, developed by using MATLAB, is illustrated in Fig. 5, and the operation interface of the program is shown in Fig. 6. The audio frequency in time domain, detected by the microphone, is shown in part (a) of Fig. 6, and user can select the amount of data displayed in the diagram. Part (b) of Fig. 6 displays the spectrum, which is instantly obtained by using FFT on the audio frequency, and user can input the conditions of background noise to filter the audio signals whose frequency or intensity is too low. Part (c) orderly lists the frequencies with top 5 intensity and reveals the current spindle speed. User can manually input the spindle speed to system or automatically read the spindle speed from the controller in milling machine. Part (d) can input the conditions of cutter and the upper bound of the cutting conditions to avoid the spindle speed or tool speed is too high. By detecting the frequency and intensity of chatter, this study will command the controller to change the spindle speed and achieve the real-time chatter suppression when chatter occurs.

4. Experimental Results and Discussion

This study utilizes the TMV-720A vertical milling machine, which is made by Tongtai Company and shown as Fig. 7, to conduct the experiments about testing the methods of adaptive feed rate control and chatter suppression interpreted in the previous sections. To verify the chatter suppression, this study also conducts a side-milling example.

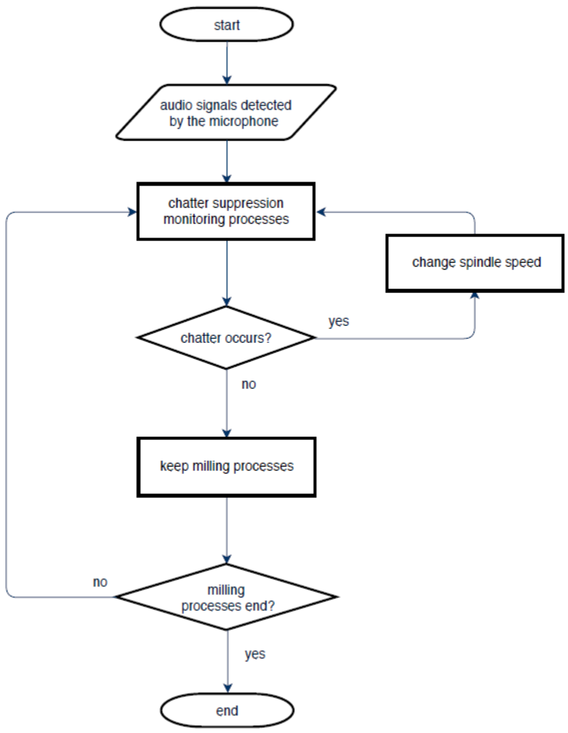


Fig.5. Flow chart of chatter suppression program

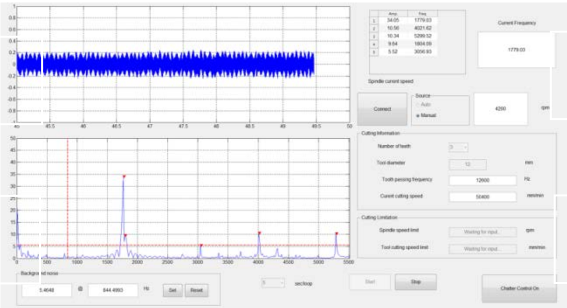


Fig.6. Operation interface of chatter suppression program

Fig.7. TMV-720A vertical milling machine

4.1. Tests of Adaptive Feed Rate Control

To verify the feasibility of the adaptive feed rate control on the promotion of machining efficiency and the consistency of machining quality, this study conducts experimental tests in the rough machining processes of scrolls. In these experiments, the material of the workpiece is aluminum-magnesium alloy Al6061, the cutter is Starpoint S2009 whose specification is revealed in Table 1. As shown in Fig. 8, the tool holder embedded with sensors is used to measure tension, bending moment, and torque. Table 2 reveals the specification of the tool holder.

Table 1. Specification of cutter Starpoint S2009

Tooth diameter (mm)	Tooth length (mm)	Cutter length (mm)	Handle diameter (mm)	Tooth
12	50	100	12	2
Cutter appearance				

Fig.8. Tool holder with sensors

Table 2. Specification of the tool holder

Signal reception		Wireless 2.45 GHz
Sampling rate		1800 Hz
Measuring range	Tension	±37.2 kN
	Bending moment	±462.6 Nm
	Torque	±584.0 Nm

The results of the cutting area per each cutter tooth calculated by the simulating method of arc tooth path is shown in Fig. 9, which is performed under a spindle speed of 6000 rpm and a feed rate of 800 mm/min.
Table 3 demonstrates the experimental results, including maximum bending moment, machining time, and material removal rate, for different cutting area per each cutter tooth and feed rate limits. These experiments are obtained under a cutting depth of 2 mm and a stretched length of 55 mm for the cutter out of holder. The bending moment can be used to evaluate the instantaneous cutting load since it is linearly proportional to the tool force under a fixed stretched length of cutter.

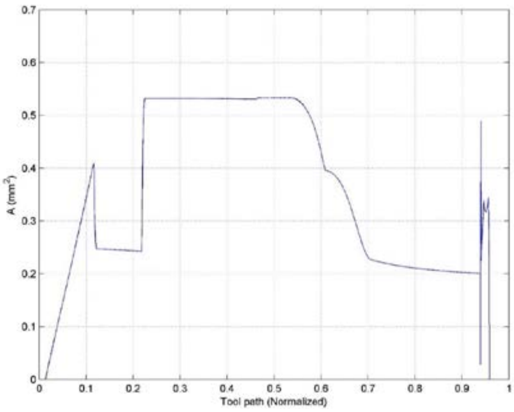


Fig.9. Cutting area per each cutter tooth in rough machining process

Table 3. Experimental results of the adaptive feed rate control

Cutting area per each cutter tooth A_z (mm²)	Feed rate limit (mm/min)	Maximum bending moment (Nm)	Machining time (sec)	Material removal rate (mm³/sec)
without adaptive feet rate control	700	26.0442	55.8152	160.4079
	800	26.8371	48.8315	183.3489
	900	28.1072	43.1722	207.3835
	1000	29.7972	39.4789	226.7844
	1100	31.2748	35.5418	251.9062
	1200	33.1184	32.9733	271.5288
0.4	700	23.74	62.164	144.0255
	800	24.3828	53.1334	168.5042
	900	25.8809	50.37	177.7487
	1000	27.1442	46.7918	191.3412
	1100	28.5757	45.0435	198.7679
	1200	31.9055	43.3346	206.6063
0.5	700	22.7196	55.9205	160.1059
	800	24.4593	49.8637	179.5535
	900	25.3372	46.1221	194.1195
	1000	26.6202	42.6877	209.7372
	1100	28.8899	41.0468	218.1218
	1200	29.9649	38.4007	233.1520
0.6	700	26.0642	56.9005	157.3484
	800	28.2414	50.0224	178.9838
	900	30.0926	44.4387	201.4730
	1000	33.0158	41.5065	215.7060
	1100	34.7375	38.676	231.4924
	1200	35.7843	36.4894	245.3644

Considering the experimental results, for example, Fig. 10 illustrates the bending moment, whose variation is similar to and depends on that of the cutting area shown in Fig. 9, and is obtained under the conditions without adaptive feed rate control. As shown in Fig. 10, period A is the region with highest bending moment since the slot milling processes occurs in this period. This study uses the adaptive feed rate control to decrease the feed rate of machining in period A, and then to reduce the cutting loads as well as to stabilize machining quality in rough machining processes. Meanwhile, period B represents the region of lower bending moment since the side milling processes. This study will also use the adjustment of adaptive feed rate control to increase the feed rate of machining according to the calculation of cutting area to promote the material removal rate and the machining efficiency. The variation of feed rate obtained by using the adaptive feed rate control for different cutting areas per each cutter tooth A_z shown in Table 3 is depicted in Fig. 11.

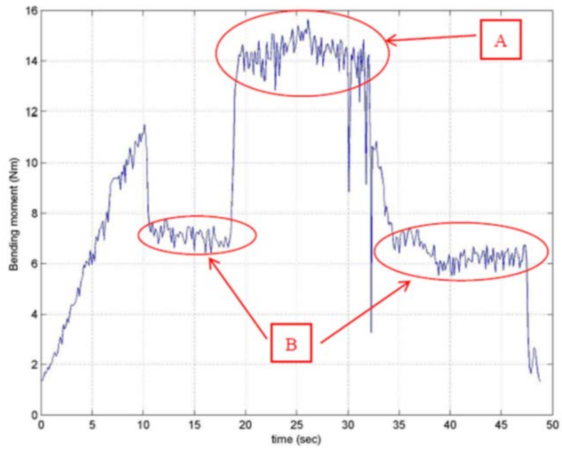


Fig.10. Variation of bending moment

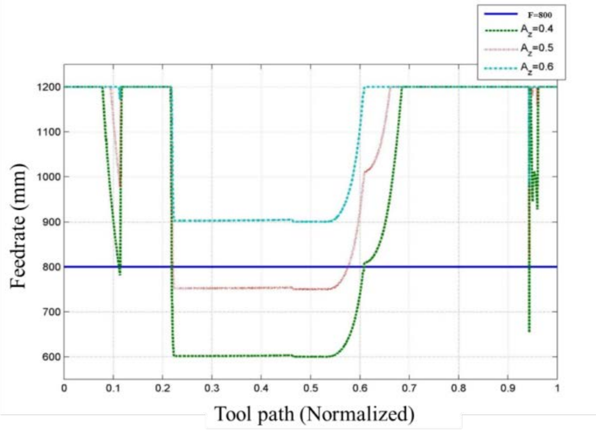


Fig.11. Variation of feed rate for different cutting areas per each cutter tooth

The comparisons between maximum bending moment, material removal rate, cutting area per each cutter tooth, and feed rate limit are classified and depicted as Figs. 12-13. It can be observed that the maximum bending moments are 26.84 Nm without the adaptive feed rate control and 26.62 Nm with the adaptive feed rate control, whose cutting area per each cutter tooth is 0.5 mm² and maximum feed rate limit is 1000 mm/min. As shown in Fig. 14, the values of bending moment are close to each other, however, the total cutting amount of material is 8953 mm^3, the material removal rate can be increased by 14%, and the cutting time is shorten by 6.14 seconds with the adjustment of adaptive feed rate control. Figure 15 is the scroll workpiece after the rough machining processes.

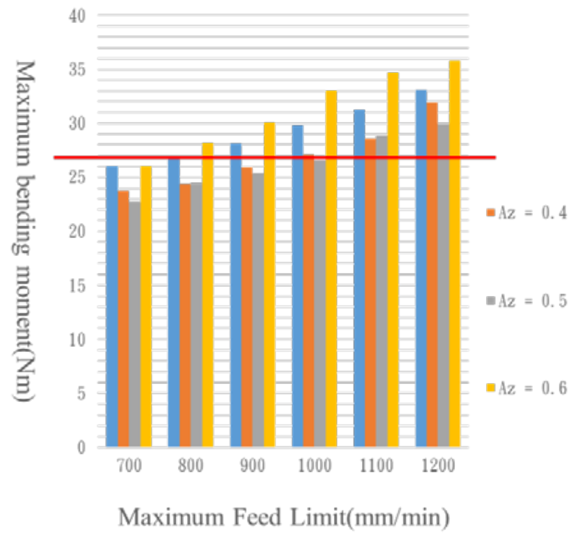


Fig.12. Comparison of maximum bending moment

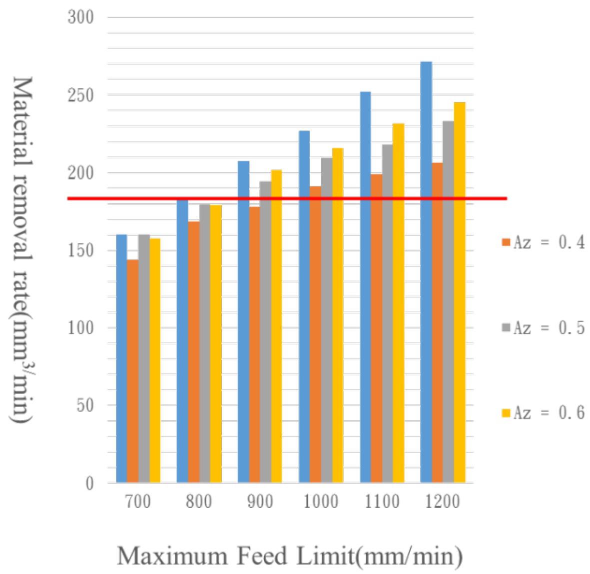


Fig.13. Comparison of material removal rates

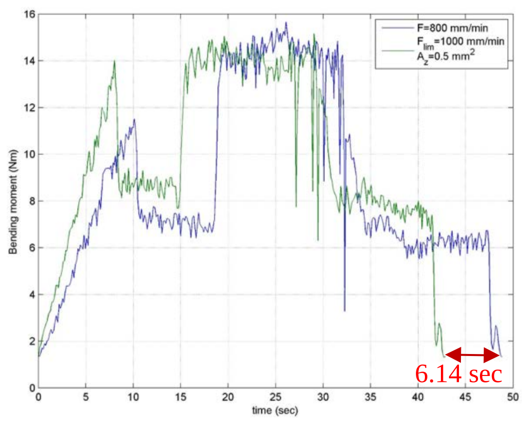


Fig.14. Comparison of experimental results with adaptive feed rate control

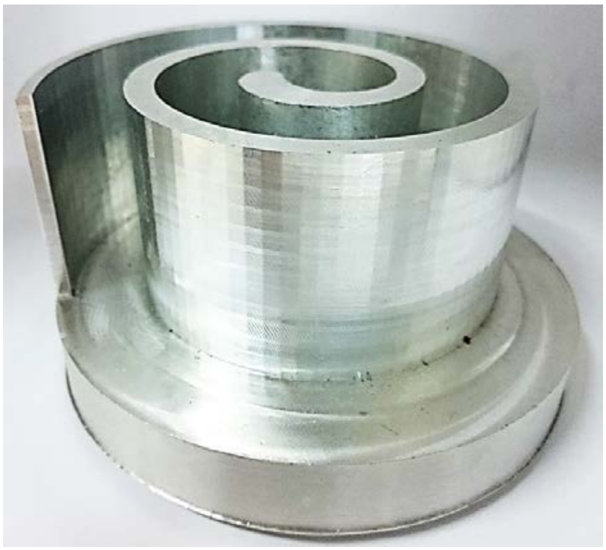


Fig.15. Scroll workpiece after rough machining processes

4.2. Experiments of Chatter Suppression

After the rough machining processes, the semi- and fine machining processes will be conducted to improve the surface roughness and precision of the scrolls. In this section, experiments of chatter suppression are conducted. This study uses a microphone to detect the audio signals and the developed program to illustrate real-time spectrum diagrams as well as to monitor the machining conditions. When chatter occurs, the command of changing speed will be given to the spindle, through the connection between Ethernet and the controller of milling machine, to suppress the chatter. The material of workpiece is aluminum-magnesium alloy Al6061, the cutter is Nachi List 6212, and the microphone used in the experiments is Audio technical AT9942. The specification of cutter and the machining parameters are listed in Table 4, the experimental results are shown in Table 5 and Figs 16-17.

Table 4. Specification of cutter and machining parameters

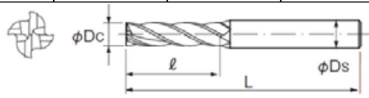
Nachi LIST 6212				
Tooth diameter ϕDc (mm)	Tooth length ℓ (mm)	Tool length L (mm)	Handle diameter ϕDs (mm)	cutter tooth
6	25	65	8	4
Cutter appearance				
Machining parameters	Spindle speed S (rpm)	Cutting depth (mm)	Cutting width (mm)	Chatter frequency (Hz)
	5000	6	0.2	2293

Table 5. Results of chatter suppression test

S (rpm)	K	Maximum amplitude	Chatter
5000	6.879	81.83	Yes
4299	8	29.92	No
4914	7	40.49	No
5733	6	38.13	No
6879	5	24.14	No
4046	8.5	61.54	Yes
4586	7.5	32.92	Yes
5292	6.5	82.72	Yes
6254	5.5	65.05	Yes

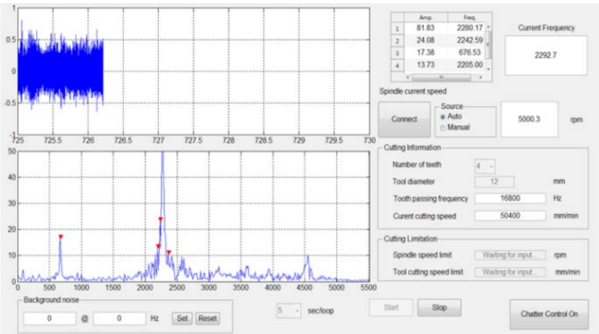


Fig.16. Experimental results displayed in the operation interface of program (S=5000 rpm)

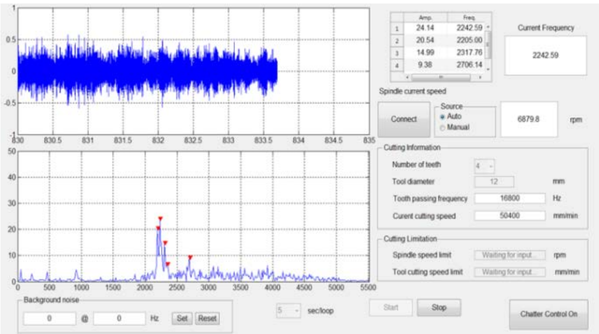


Fig.17. Experimental results displayed in the operation interface of program (S = 6879 rpm)

From the observation of experimental results, the proposed methods can reduce and disperse the energy of the chatter frequency, and stabilize the machining conditions of system by changing the spindle speed in real time. Because the signal interference from noise and the variation of workpiece stiffness in the machining processes might shift the stability lobes, it is also suggested that the increase of the spindle speed could be adopted to avoid the unstable machining conditions and to achieve the effect of chatter suppression. To conveniently demonstrate and to easily observe the effects of chatter suppression, Fig. 18 shows the block surface of aluminum alloy with and without chatter occurrence, respectively. From the observation, the left side of the block without chatter suppression reveals a significant chatter effect, and the right side with smooth surface shows the result of chatter suppression. In this example, the transition time between the variations of spindle speeds is about 80 mini-seconds (ms), the transition length on the workpiece surface without and with chatter suppression is about 1.05 mm. The obtained results can also verify the feasibility of the proposed methods in chatter suppression. Figure 19 is the scroll workpiece after the semi- and fine machining processes

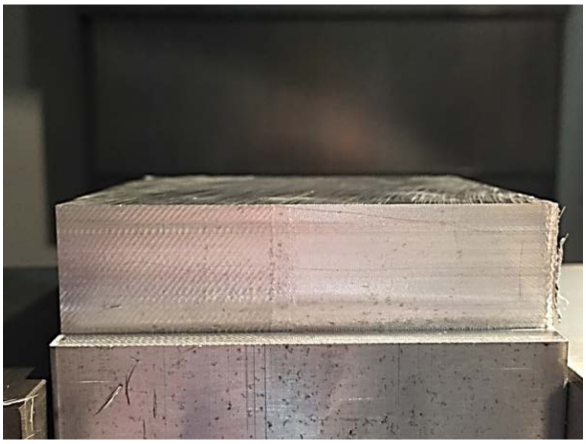


Fig.18. Effects of chatter suppression

Fig.19. Scroll workpiece after semi- and fine machining processes

5. Conclusions

To increase the machining efficiency, to retain the machining precision, and to promote the added value of scroll manufacture, this study has proposed the adaptive milling processes, which include the adaptive feed rate control in the rough machining processes, and the chatter suppression in the semi- and fine machining processes. The experimental tests also have shown that the material removal rate in rough machining processes can be raised 14%, and the proposed methods of chatter suppression are feasible in a transition time of 80ms. The developed program also can successfully perform with and connect to the controllers made by FANUC and DELTA.

6. Acknowledgement

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