

Structural stability estimation of whirling unit

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Abstract: Whirling is a cutting process in which a series of cutting edges on whirling ring remove material by turning over a rotating workpiece. In this study static and dynamic stability of whirling unit was estimated by using ADAMS and NASTRAN softwares. Each maximum force acting on the bearing attached to the spindle assembly and the cutting tool attached to the whirling ring with the rotating speed of 6 000 r/min was 235 N and 902 N respectively. The maximum stress of 0.74 MPa on the base frame is far smaller than the yield strength of 282 MPa. The calculated natural frequency of 148 Hz of the system is far from the frequency of the driving speed of 6 000 r/min. The experimentally obtained maximum cutting force of 792 N is smaller than that of calculated value. And the experimentally obtained natural frequency of 118 Hz is beyond the driving speed of 6 000 r/min. From above results it can be judged that the whirling system is statically and dynamically stable.

Key words: Whirling unit; structural stability estimation; ADAMS software; NASTRAN software; mode shape measurement

1 Introduction

Manufacturing of worm gears is very important in the automobile industries. Recently, whirling processes are overwhelmingly used in the manufacture of worms compared to roll forming processes, because of increasing demands of shape accuracy and good surface finish [1]. To achieve a good cutting practice of worm, the structural stability of whirling unit should be analyzed beforehand [2].

In this study, using ADAMS and NASTRAN softwares the structural stability of whirling unit was estimated. At the same time, the cutting force measuring experiments and vibration tests were carried out to substantiate the simulated results.

2 Cutting in whirling unit

Cutting in the whirling unit is performed in which a series of cutting edges around the whirling ring remove material by turning over the rotating workpiece, as shown in Fig.1.

The cutting geometry in the whirling unit is shown in Fig.2. The maximum depth of cut, shown in the figure as ‘EF’, is calculated from Eq.(1) [3] and the cross section of the chip removed by a cutting insert is shown in the figure as ‘CDE’ [4–6].

$$h_{\max} = a \frac{N_{\sigma}}{N_t} \sqrt{\frac{2dr(R-r)}{R^3}} \quad (1)$$

3 Cutting force simulation

For simulating the cutting forces in whirling process using ADAMS software, the whirling unit is divided into two parts, i.e. cutting edges and spindle assembly. The 1st, 3rd, and 5th cutting edges are rough cutting bites and the 2nd, 4th, and 6th are fine cutting bites. The cutting conditions used are shown in Table 1.

Fig.3 shows that the magnitudes of the estimated cutting forces by rough cutting bites are larger than those by fine cutting bites.

It is observed that the maximum cutting force on the cutting edge is 902 N and the maximum force in the bearing assembly is 235 N. It was known that the

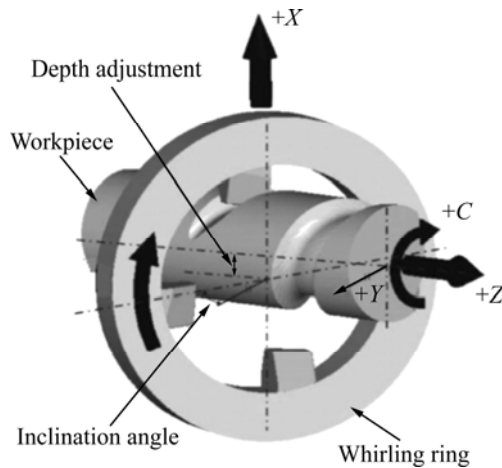


Fig.1 Schematic view of whirling process

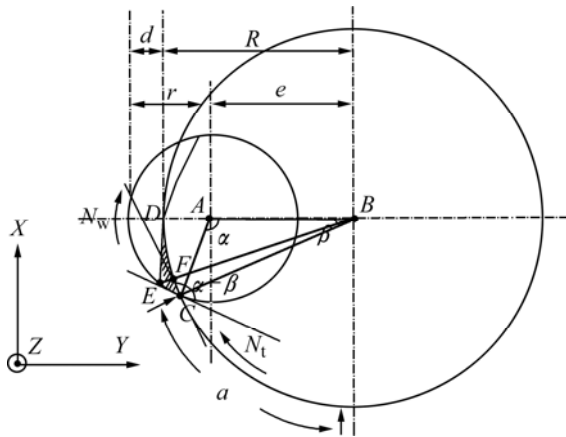


Fig.2 Geometry of cutting in whirling process

Table 1 Cutting input conditions

Workpiece			S45C
Rotation of whirling ring/(r·min ⁻¹)			6 000
Rotation of workpiece/(r·min ⁻¹)			100
Feed/(mm·r ⁻¹)			3.927
Cutting radius/mm			9
Workpiece radius/mm			4
Height of gear tooth/mm			1.95
Maximum depth of cut/mm			0.051
Eccentricity/mm			6.94
Tilting angle/(°)			11.5
Bearing	Bushing	Translational properties	Stiffness-x, y, z=1.8×10 ⁵ Damping-x, y, z=1.8×10 ²
		Impact force parameters	Stiffness-x, y=1.0×10 ⁶ , z=0 Damping-x, y=1.0×10 ⁶ , z=0
Reverse action	Contact force	Rotational properties	Stiffness=1.0×10 ⁵ N/mm Damping=1.0×10 ² N/mm

magnitude of main cutting force F_X is larger than that of the other component forces F_Y and F_Z , as seen in Fig.4 [7–8].

4 Estimation of structural stability

4.1 Maximum stress and deformation

For static structural estimation of the whirling unit using NASTRAN software, the maximum stress and deformation in the unit were obtained.

It is assumed that nodes in the bottom of gear housing have three degree of freedom, and nodes in the center and inner parts of the bearing assembly are constrained in the MPC (Multi Point Constraint) condition, as shown in Fig.5.

The input force in the center of bearing assembly is 235 N which were obtained using ADAMS software. The mechanical properties of the unit are shown in Table 2.

Table 2 Mechanical properties of unit

Part name	Material	Elastic modulus/ GPa	Ultimate tensile strength/MPa	Yield strength/ MPa
Base frame	FCD450	200	440	282
Bearing shaft				
Spindle	SCM415	205	900	800
Worm				
Bearing	—	210	—	—
Motor	—	210	—	—
Cover	SS41	200	415	230
Gear housing	GC30	200	241	—
Motor bracket				
Rear	SM45C	205	569	343
Ring				
Timing				

Fig.6 shows that the maximum stress of 0.74 MPa on the base frame and the maximum deformation at the end of the motor is 1.75 μm [9]. The yield strength of the base frame is 282 MPa and the deformations in the whirling unit are negligible. From the above it can be judged that the structure of the whirling unit is statically stable [10].

4.2 Natural frequencies

For dynamic structural stability estimation of whirling unit, the modal analysis of the vibration with NASTRAN software was carried out.

At the 1st order mode it was found that the displacement of the motor and the whirling body are the largest in the

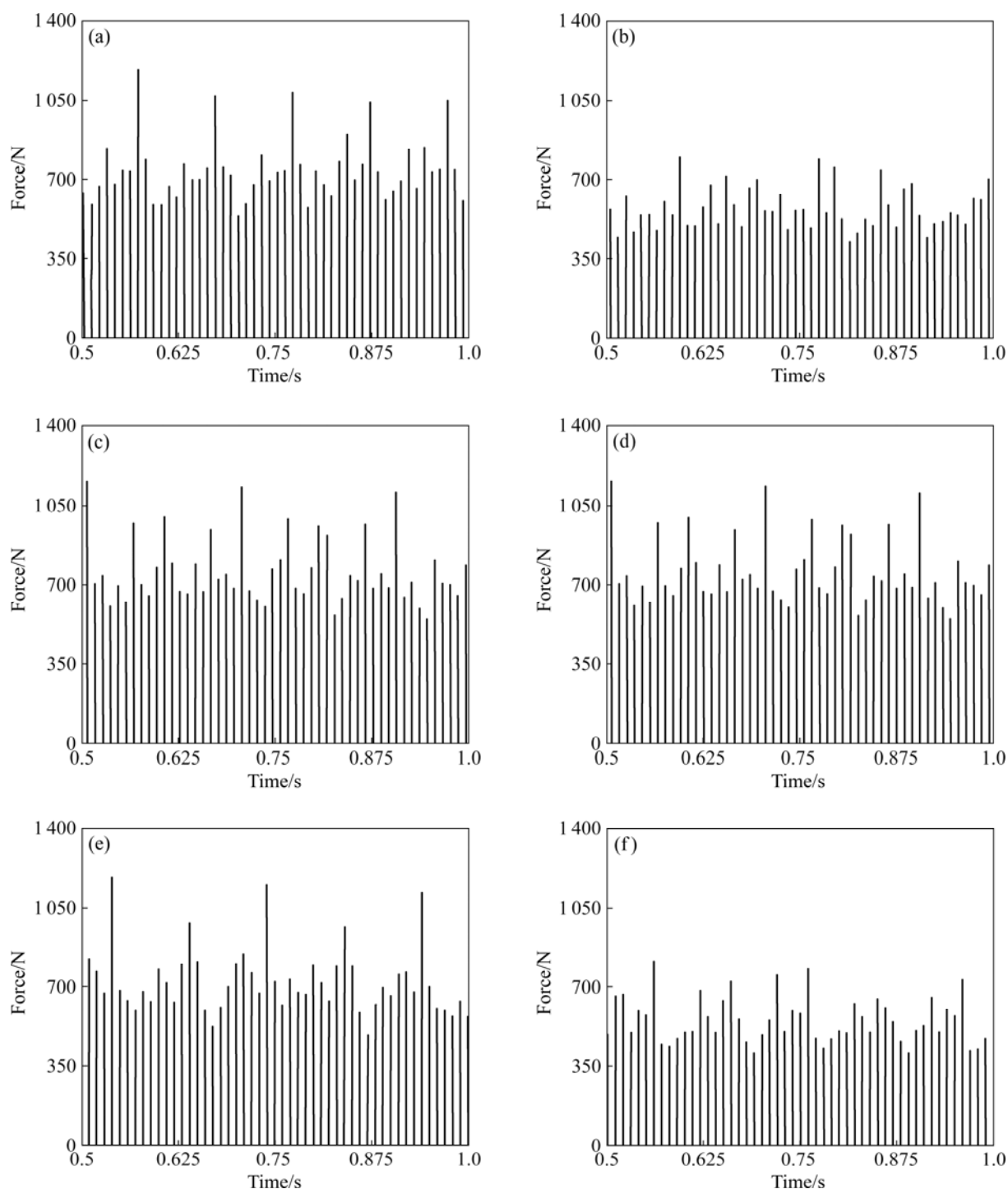


Fig.3 Cutting force of each bite in whirling ring: (a) 1st bite; (b) 2nd bite; (c) 3rd bite; (d) 4th bite; (e) 5th bite; (f) 6th bite

whirling unit, their natural frequency is 148 Hz. At the 2nd order mode it was known that the displacement of the motor is the largest and its natural frequency is 258 Hz.

The driving speed of 6 000 r/min of whirling unit is far below the estimated natural frequencies of 148 Hz (8 800 r/min) and 258 Hz (15 400 r/min) respectively. It can be judged that the structure of whirling unit is dynamically stable.

5 Experiments for determination of cutting force

The non-contact rotating tool dynamometer (Kistler RCD 9123B) was used to measure the cutting forces generated during the whirling process, as shown in Fig.8.

The data of the cutting force components F_x , F_y , and F_z were obtained at the interval of 40 μ s during the

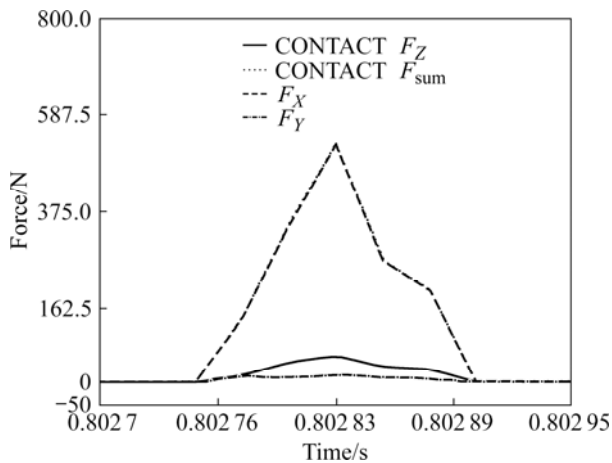


Fig.4 Cutting forces F_x , F_y , F_z and their sum F_{sum}

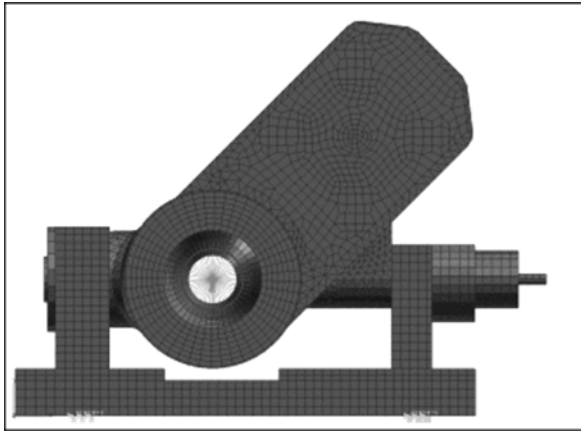


Fig.5 Boundary and load conditions of whirling unit

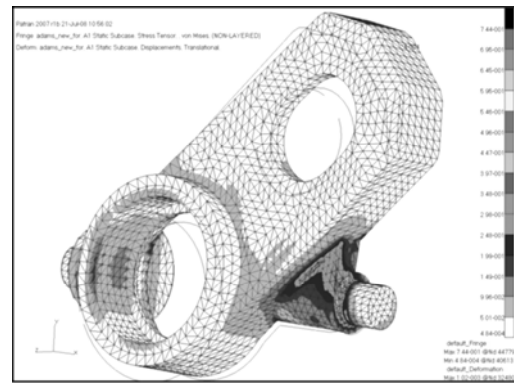
period of 3.4. The sum of cutting force components, F_{sum} could be calculated from [11]

$$F_{sum} = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (2)$$

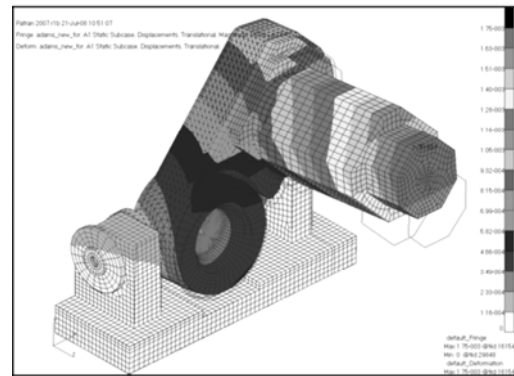
The maximum cutting force on the cutting edge measured in the experiments is 792 N, which is near to the maximum cutting force of 902 N simulated using ADAMS software. The magnitudes of the main cutting force F_x and the passive cutting force F_y are larger than that of the feed force F_z , as shown in the figure. Because the magnitude of the real passive cutting force F_y in the experimental is far larger than that of estimated, the transverse vibration (vibration perpendicular to the axis) of the workpiece takes place[12].

6 Experiments for determination of natural frequency

To measure the natural frequencies of the whirling unit itself, modal test in the stop mode was performed. And to verify whether the resonance takes place at the natural frequencies in the constant speed driving mode

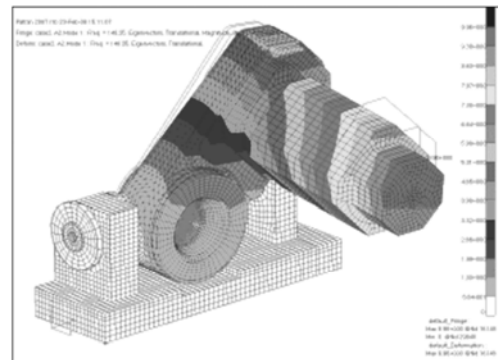


(a)

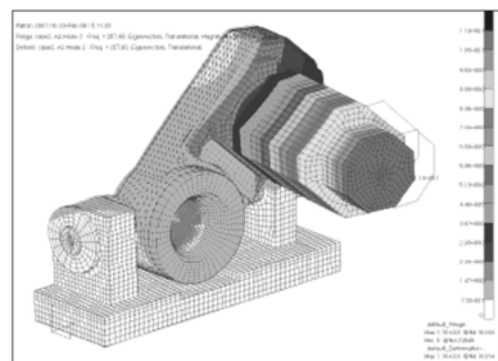


(b)

Fig.6 Von-Mises stress of base frame (a); Deformation of motor in whirling unit (b)



(a)



(b)

Fig.7 1st (a) and 2nd (b) order mode shape

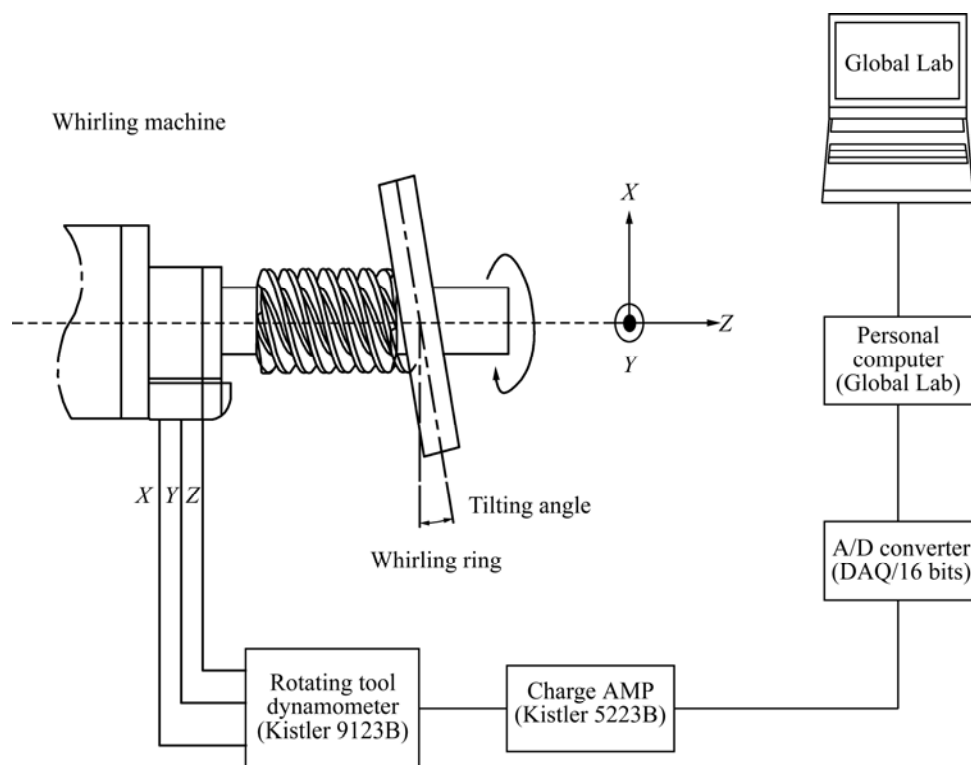


Fig.8 Cutting force measurement system with rotating tool dynamometer

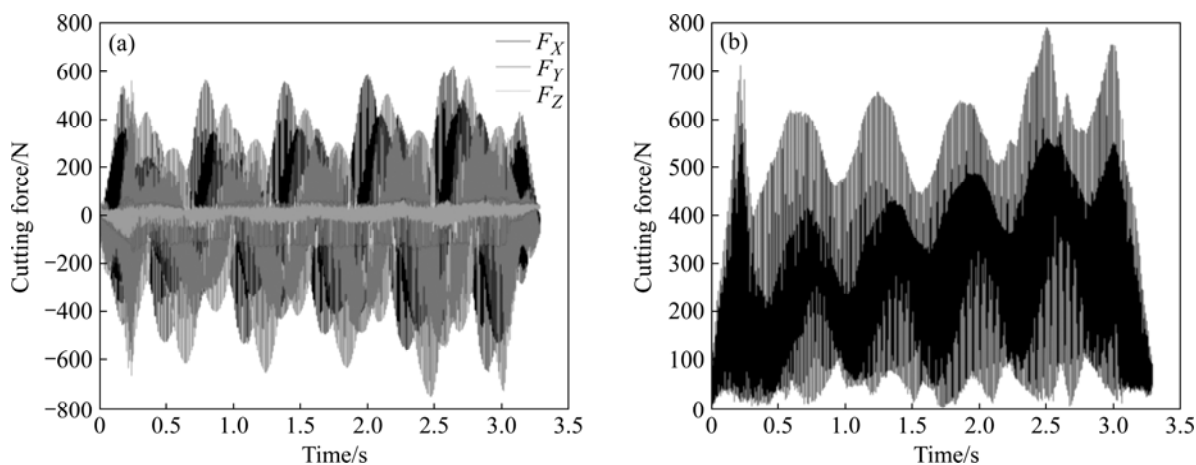


Fig.9 Cutting force components F_x , F_y , and F_z (a) and their sum F_{sum} of cutting force (b)

vibration test with no load at specific rotation speed from 4 000 to 8 000 r/min was performed [13]. Fig.10 shows the natural frequencies measurement system. The test conditions are shown in Table 3.

Accelerometers were set-up at the 5 point as shown in Fig.11, and in Table 4 measuring objects are indicated. Fig.12 shows that several parts of whirling unit vibrate at their natural frequencies between 100 and 270 Hz. But the responses of the 2 and 5 accelerometers in the figure shows that the whirling ring does not vibrate below 500 Hz. On the other hand the responses of No.1, No.3, and No.4 accelerometers show that the motor and whirling

body vibrate at the natural frequencies of 118, 173, 217, and 248 Hz.

The result of 1st order vibration test in the constant speed driving mode shows the larger displacement of the vibration takes place at 118 Hz (7 080 r/min) than any other frequencies, as shown in Fig.13. The reason is that the frequency of the forced vibration is the same with the natural frequency of the free vibration.

And it was verified that the natural frequency of 118 Hz of the motor and whirling body measured in the test was near to that of 148 Hz at the 1st order mode estimated using NASTRAN software.

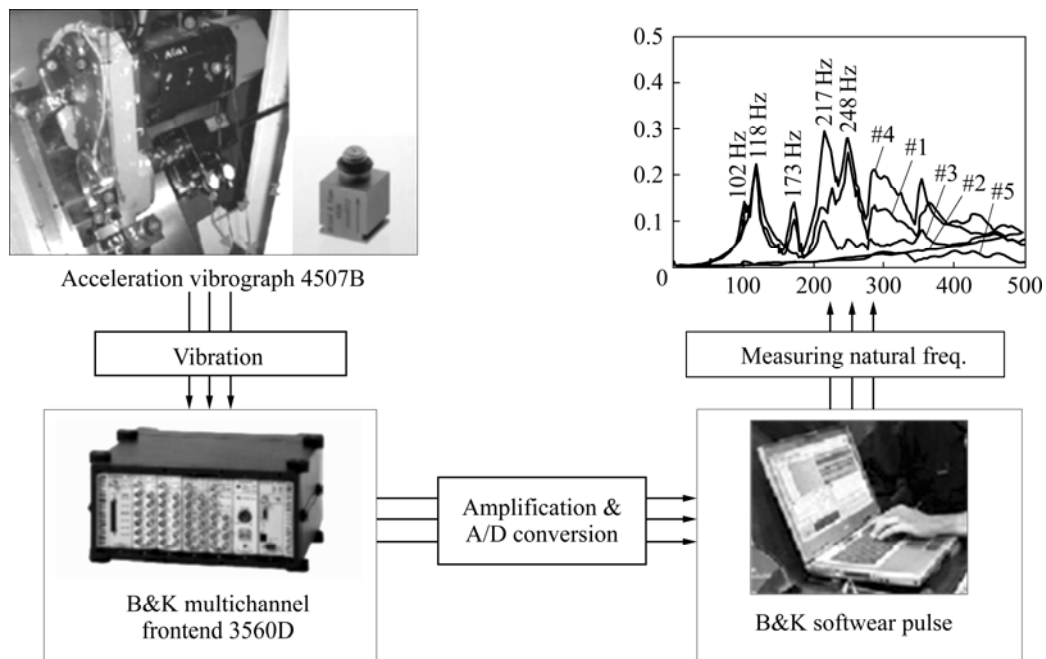


Fig.10 Vibration measurement system with accelerometers

Table 3 Test conditions in modal and vibration test

Item	Specification
Spindle	[Modal] 0 r/min
	[Vibration] 4 000, 5 200, 6 000, 6 100, 6 500, 7 080, 7 500, 8 000 r/min
Instrument	Accelerometer (5 pieces)
FFT Analyzer	B&K Pulse 8.0
Window (Filter)	[Modal] Transient (Force: Impact hammer)
	Exponential (Acceleration: Accelerator)
	[Vibration] Hanning (FFT)
Data averaging	[Modal] 5th
Averaging	[Vibration] 20th
Max. Freq	1.6 kHz
Sampling Freq.	[Modal] 1 Hz
	[Vibration] 0.5 Hz

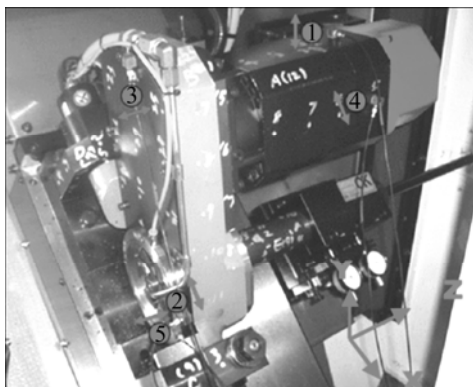


Fig.11 Setting-up positions of accelerometers

Table 4 Vibration measuring objects with accelerometers

No.	Measuring object
1	Motor Y-direction vibration
2	Whirling ring X-direction vibration
3	Whirling body Z-direction vibration
4	Motor X-direction vibration
5	Whirling ring Y-direction vibration

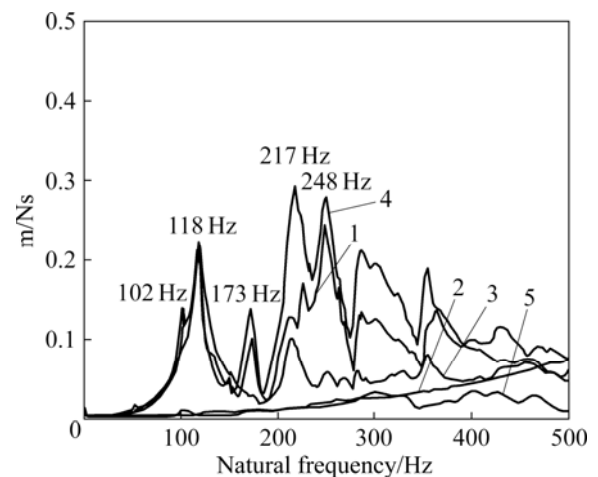


Fig.12 Measurement results of natural frequency in modal test

Fig.14 shows the result of the 2nd order vibration test in the constant speed driving mode. It can be found that the resonance did not take place at 173, 217 and 248 Hz, which were the natural frequencies of the free vibration measured in the modal test [14].

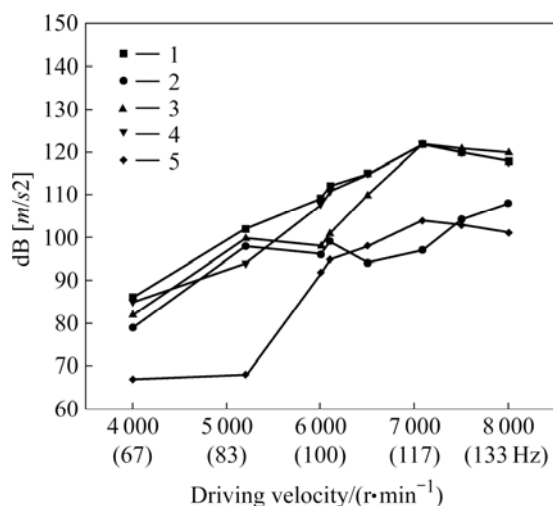


Fig.13 Test result of vibration at 1st order mode

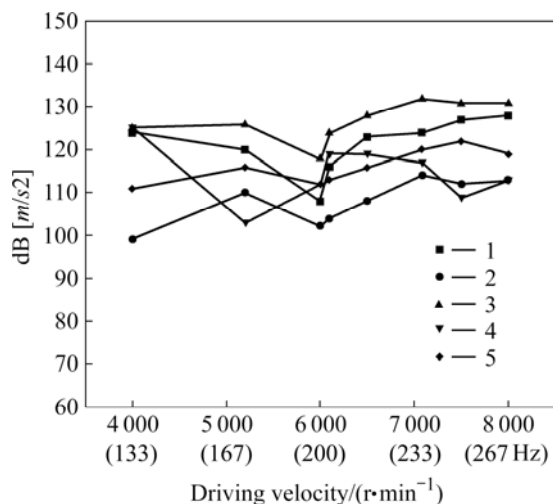


Fig.14 Test result of vibration at 2nd order mode

7 Conclusions

1) With the non-contact rotating tool dynamometer, it was verified that the cutting force of 920 N estimated is effective.

2) The maximum estimated stress and deformation of the whirling unit were 0.74 MPa and 1.75 μm . It can be judged that the structure of the whirling unit is statically stable.

3) The natural frequency of the motor and whirling body measured in the vibration test was 118 Hz, which

was near to that of estimated 158 Hz.

4) The natural frequency of 118 Hz (7 080 r/min) measured in the vibration test was beyond the driving speed of 6 000 r/min of the whirling unit, and it can be judged that the structure of the whirling unit was dynamically stable.

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