Analysis and Control over Noises in Main Driving System of XK-736-type NC Miller

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Abstract: *Some concrete methods are suggested in the article to control noises in main driving system of XK-736-type NC miller by analyzing working conditions of gears in the main driving system and bearings in the spindle gearshift system. Without changing the original design, noises are reduced ideally by modifying gear top, and by controlling the profile error; the central distance of meshing gear, the quality of the inner and outer rings of bearings; and the fit accuracy among bearing, hole and axis. The results may provide a reference for diagnosing and maintaining in future use.*

Key words: NC miller; main driving system; noises

1 Introduction

CN millers will inevitably produce noises and vibration, friction, and impact since the spindle gearshift system employs shafts, gears and bearings. More continuous and representative noises are produced in the CNC miller where the speed of the main driving system is controlled by computer than that in the normal miller [1].

Noise pollution is a major environmental issue which is paid much attention by the present society. Analysis and control over noise relates not only to environmental protection, but also to people's life quality and health, product's competition, reliability and accuracy of top products. Many countries have been investing a large amount of manpower, material and financial resources to study it [2]. It is well known that noises' source play a key role in considerations related to noise and vibration. So the resolution lies in studying the acoustic mechanism of the running miller, diagnosing and controlling the main source.

With the development of science and technology and the improvement of people's living standards, noise pollution draws more and more attention. As a by-product of industry, mechanical noises not only hinder the progress of mechanical technology, but also affect humans' physical and mental health. Medical tests have shown that a noise over 70 dB results in not only damages to hearing, nervous system, cardiovascular system, digestive system, but also diverting humans' attention, reducing people's efficiency, and even causing accidents. Therefore, some measures must be taken to control mechanical noises.

2 Noise phenomena

XK-736-type CNC miller is a domestic product in 1970s. When first put into use, it has a big noise that comes mainly from the main driving system. After be-

Received 14 May 2012

This paper is supported by the University Research Projects of the Education Department of Zhejiang Province in 2011 under Grant No. Y20111926

ing used for years, it produces a even bigger noise. When measured at a speed of 2 000 r/min of the spindle with a sound level meter, it has a noise up to 85. 2 dB.

3 Diagnosis and analysis of noise

It´s known to all when excited by any forces, the mechanical system will generate a vibration. The vibration energy will spread throughout the system. When it goes to the radiation surface, the energy will be converted into a pressure wave that will then spread out through air, that´s just the sound radiation. Therefore, these three steps (excitation response, transmission within the system, and radiation) are corresponding to the formation of vibration noise, friction noise and impact noise as shown in Figure 1.

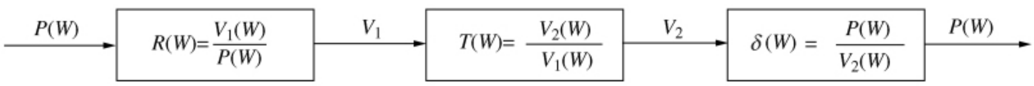

Figure 1 Formation of spindle noise

Where, $P(W)$ is the exciting force. When being responded, the mechanical system $R(W)$ was stirred a vibration velocity $V_1(W)$. Then a kinetic energy with the transfer function of $T(W)$ transfers in the system. When this energy goes to the radiation surface, a vibration velocity $V_2(W)$ emerges. The air that contacts with the surface is disturbed and converted into a pressure wave. Then, a radiation efficiency $\delta(W)$ shows that the vibration energy is converted into a sound energy that causes a sound pressure $P(W)$.

$R(W)$ depends not only on the structure´s stiffness, damping and mass, but also on the exciting force, its frequency and acting point. $T(W)$ relies on materials, shapes, combinations of parts in the propagation path. $\delta(W)$ depends on parameters such as material, size, shape, thickness and support conditions [3].

Because of the excitation and response of gears, bearings and other components in the main driving system, noise emerges along with the transmission and radiation in the system. These abnormal parts increase the exciting power and hence noises are generated.

1) Analysis of gear noises

In XK-736-type CNC miller, the main driving system depends mainly on gears to fulfill transmission and shifting. Therefore, the meshing gear is one of the main noise sources.

Let´s first look at a pair of meshing gears, shown in Figure 2, where AC represents a meshing interval.

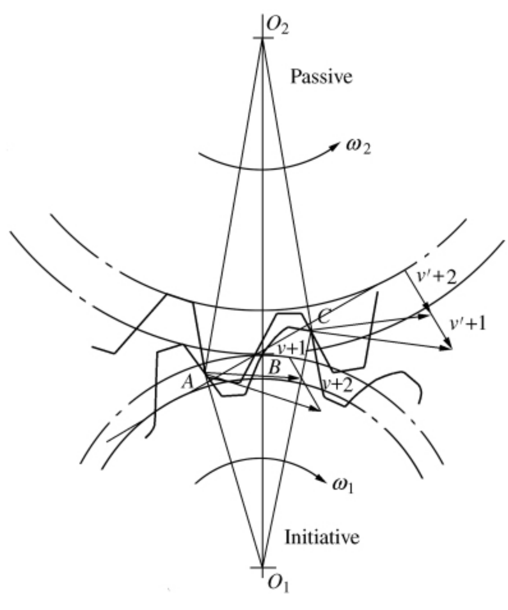

Figure 2 Diagram of gear meshing

When the meshing pair goes into the asymptote meshing interval (between node A and node B), the junction point moves along the meshing line, and there is a gradual decrease in the relative sliding velocity of each node. An exciting force is formed because the change in the relative sliding velocity in node B. This exciting force will be intensified with increased errors, load fluctuations and components influence, transmission resonance, and poor lubrication. While it goes far away from the meshing interval (between node B to node C), the relative sliding velocity is proportional to the gear's rotary speed and increases with the distance from the junction point to node B.

So, there are mainly 4 kinds of noises generated by the running gears in the main driving system:

1) Impact noises generated by the forced vibration (at the meshing frequency) which is caused by the continuous impact among gears.

2) Noise brought by the transient vibration (at the natural frequency) which is caused by the external exiting force on gears.

3) Resonance noise (one per rotation) caused by a low-frequency vibration (being consistent with the rotational speed) which is induced by an unbalanced rotation due to the eccentric combination of gears, shafts, and bearings.

4) Friction noise emerges with the self-oscillation which is induced by frictions among gears. It has been found that an uneven surface results in a periodical impact noise.

Figure 3 shows noises emerging in the miller.

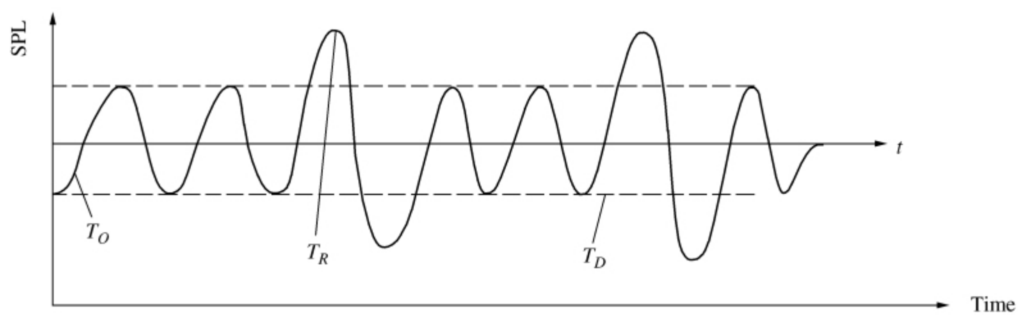

Figure 3 Oscillogram of gear noise

T_O—Starting time, T_R—Time of peak, T_D—Time for envelope curve to under-peak.

In order to find out accurately the gear pairs with big noises from the driving gears in the main driving system, it is necessary to analyze the meshing frequency for each gear.

The meshing frequency can be computed by

$$f_n = \frac{zn}{60} z f_c \tag{1}$$

Where, z is the teeth number, n is the rotational speed, and f_c is the driving frequency.

The higher the speed, the greater the frequency. And noise increases proportionally with the meshing frequency.

The maximum noise is obtained at the speed of 2 000 r/min, and all these five transmission shafts are at the highest speed. The transmission route is shown below:

$$1450 \times \frac{40}{40} \times \frac{36}{33} \times \frac{49}{31} \times \frac{45}{56} \tag{2}$$

At the rotation speed, the meshing frequencies of gears in each transmission shaft are shown in Table 1.

Table 1 Meshing frequencies of gears in each transmission shaft

Axis number	Rotation speed	Rotation frequency/Hz	Teeth ratio	Meshing frequency/Hz
Ⅰ	1 450	24.2		
Ⅱ	1 450	24.2	40/40	968.0
Ⅲ	1 582	26.4	36/33	950.4
Ⅳ	2 500	41.7	49/31	2 043.3
Ⅴ	2 000	33.3	45/56(oblique)	1 498.5

Comparing the frequencies in Table 1 with the conversed frequencies of the other 17 speeds, we find that the highest frequency is concentrated on the gears that are switched on at the maximum spindle speed regardless of teeth number. The meshing frequency keeps invariant when the shifted gears mesh with others, so noises are mainly from these pairs of gears.

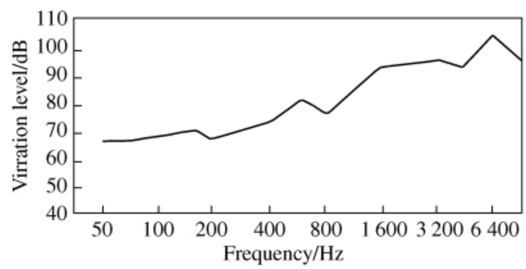

Figure 4 Vibration spectrogram of shaft

2) Analysis of bearing noise

In the spindle gearshift system, there are 38 rolling bearings among which the largest bearing has an outer diameter of 200 mm. Noise is influenced greatly by the combination of bearing, axis and hole, pre-tightening force, concentricity, lubrication conditions, load on bearing, and radial clearance. Besides, there is corresponding tolerance range for parts of rolling bearings in the National Standards[4]. Therefore, the bearing noise depends, to a great extent, on the manufacture deviation of bearing itself.

The bearing noise can be regarded as another major noise source for the spindle gearshift system, especially for those who have high rotation speeds. Take bearing 46 113 in shaft Ⅳ for instance, the vibration frequency is as shown in Figure 4 when the speed is 1 500 r/min.

The inner and outer rings of the rolling bearing are deformed easily. Under the influence of external factors of rings and the accuracies of their own, the rolling bearing is more likely to have rocking vibration, axial vibration, radial vibration, and axial bending vibration.

The basic rotary frequency caused by an unbalanced rotation is computed by:

$$f_r = \frac{n}{60} \tag{3}$$

Where, n is the rotational speed of ring, f_r is the rotational frequency of gear. Similarly to gears, the higher the speed, the greater the frequency, the more the noise generated.

In the main driving system, it has been observed that there are some bruised depressions in the roller or in the inner and outer rings of bearing. The depressions will contact the roller or the rings respectively one time when the bearing rotates a circle. The noise frequency can be computed by

$$f_B = 2f_s \tag{4}$$

The bearing noises will increase directly due to a poor accuracy of the inner and outer rings. The rotation frequency can be computed by the following equation.

$$f_s = \frac{E}{2d} f_t \left[1 - \left(\frac{d}{E} \right)^2 \cos^2 \beta \right] \tag{5}$$

Where, E is the diameter of bearing, d is the diameter of roller, β is the contact angle.

The depressions in the roller and the ring result in a high frequency harmonic and an increased noise.

4 Noises processing

1) Controlling of gear noises

The gear noises are caused by many factors, some of which relies on its design parameters. Aiming at the noises' characteristics, we make some modification and improvement without changing the original design of the gears.

(1) Gear top modification. Under the influence of the profile error and the normal circular pitch, an instantaneous impact is caused by the elastic deformation of tooth load when the gears mesh. Therefore, in order to reduce the meshing impact, gear top modification is employed to correct the bending deformation and to compensate gears' error. The modification amount depends on the error of the normal circular pitch, and the bending deformation and direction of the loaded gear. The gear top modification is mainly aiming at those gear pairs which have the highest meshing frequency. Different modification amount will be used for those gears whose modulus is 3, 4, and 5, see Figure 5.

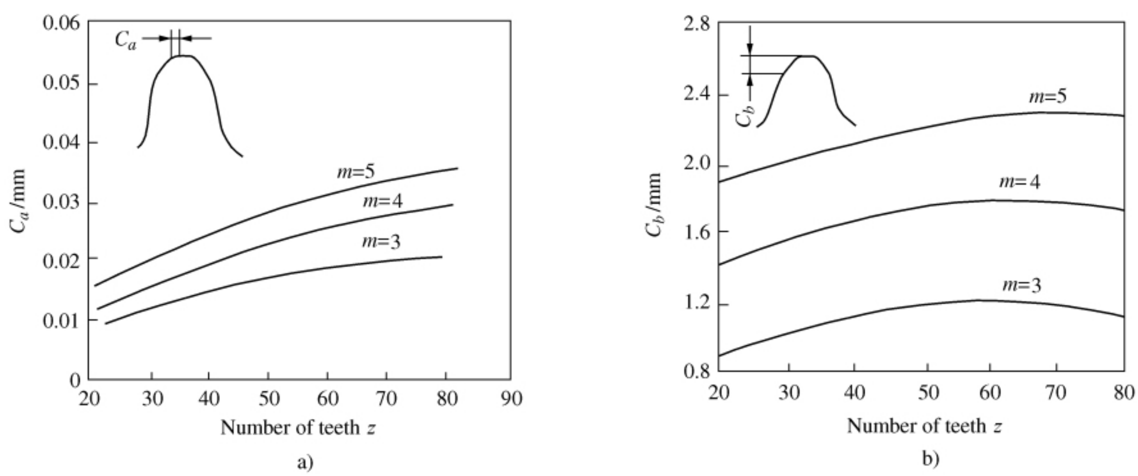

Figure 5 Gear top modification amount

The optimal modification of C_a and C_b in Figure 5 results in a good effect. It shows that the modification compensates the bending deformation and the normal circular pitch error. Much attention should be paid to the modification amount and repeated tests should be employed lest that the modification is too big to damage the effective profile, or is too small to modify the gear top. In view of concrete conditions of gears, only the dedendum or the addendum needs modifying. An unsatisfied effort of the above modification calls for modifying both the dedendum and the addendum. C_a and C_b can be assigned to one or two gears according to concrete conditions.

(2) Controlling of profile error. The profile error dues mainly to poor processing conditions. It is a significant noise source that emerges with the meshing gears.

In general, the bigger the error, the more the noise generated. When tested at a speed of 1 000 r/min, its profile error is reduced from 0.017 mm to 0.005 mm. Noise of a pair of gears can be cut down to 8 dB or so, shown in Figure 6. As for concrete conditions of the main driving system, many researches have been done to determine the profile error and proper modification has been carried out on several pairs of gears which have bigger profile error.

The profile error should not simply be considered to be proportional to noise. In some cases, noise depends not only on the profile error, but also on the gear shape.

Figure 7 compares noise emerging when the standard gear meshes with three sorts of gears which has the same profile error but different profile shapes.

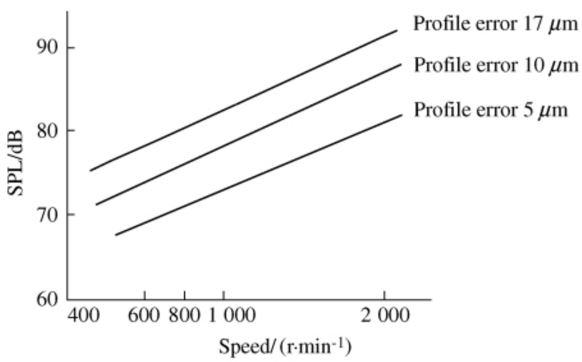

Figure 6 Relationship between noise and profile errors

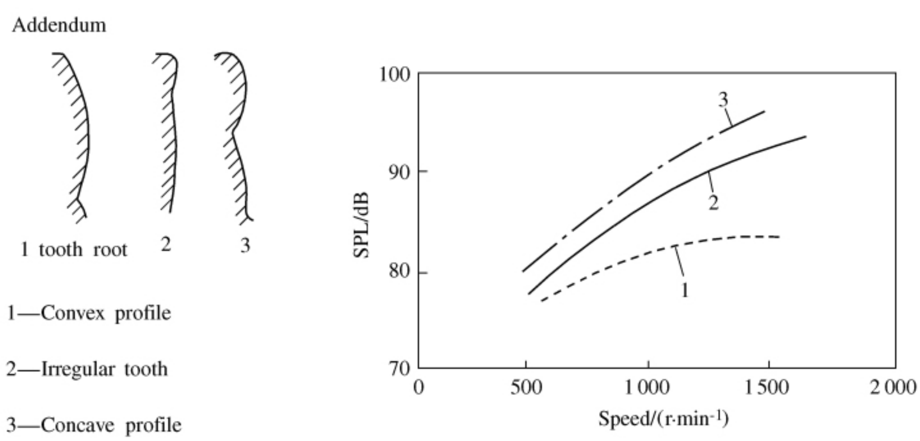

Figure 7 Comparison diagram of noises with the same profile error but different profile shapes

Figure 7 indicates that teeth with concave profile are impacted twice in one meshing, and the more concave the profile, the more the noise generated. Therefore, in order to cut down noises, the teeth should be modified to be convex.

(3) Controlling of center distance of meshing gears. The actual center distance changes with the pressure angle. The center distance changes periodically, so does the pressure angle and the noise. Analysis reveals that the noise isn't affected significantly when the distance is too large and the noise increases dramatically when the distance is too small. Noise caused by the changing distance can be eliminated by keep the following in an ideal state: outer diameter of the gear, bending and deformation of shaft, combining of draft, gear and bearing.

2) Controlling of bearing noise

(1) Controlling of quality of inner and outer rings. For all the bearings in the main driving system of XK-736-type CNC miller, the inner ring rotates while the outer ring is fixed. A vibration noise emerges due to the unbalance rotation when the inner ring vibrates radically. If there is a poor tolerance in form and position of the outer ring and the mating holes, then there will be a radial swing in the outer ring, and the bearing's concentricity is destroyed. If there is a great beating in the sides of the rings' end face, there will be a deflection of the inner ring from the outer ring. The higher the bearing's precision, the less the deflection, the less the noise. Besides the bearing's geometry deflection, we should also control the waviness of the bearing's rollway, lower the surface's roughness, and protect the rollway's surface from injuring or scratching during the combining process. It has been tested and observed that vibration frequencies are obviously different for density or sparse waviness.

(2) Controlling of accuracy of combining hole, shaft and bearing. When combining bearing with axis and hole, a radial clearance should be ensured for the bearing. The optimal radial clearance depends not only on the combinations of inner ring with axis, the combination of outer ring with hole, but also on the temperature difference produced by the inner and outer rings during operation. How to choose the original clearance plays an important role in controlling bearing's noise. Too big a radial clearance leads to noises with low frequency, while too small a clearance leads to noises with high frequency. Figure 8 shows the relationship between the bearing noise and the radial clearance for the 204-type bearing. From this figure, we can draw a conclusion that the optimal clearance is 0.01 mm.

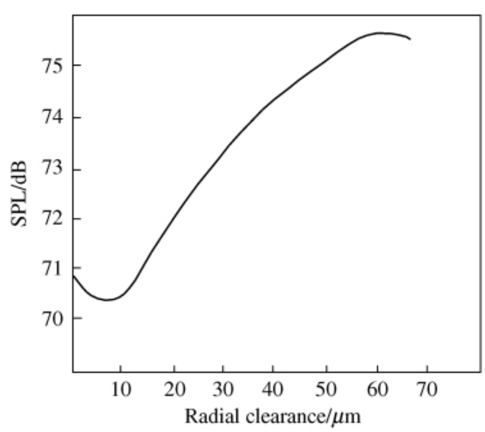

Figure 8 Relationship between noise and radial clearance

The noise propagation will be affected by the form of combining the hole with the outer ring. A tight combination would enhance acoustic conductivity and enlarge noise. Too tight a combination will force the rollway deform, increase the shape error of the rollway, cut down the radial clearance, and increase noise. While too loose a combination will lead to an excessive noise. Only a proper combination will enable the oil-film that locates on the junction point of bearing and hole to produce a damp to lower noise.

The form tolerance and the surface toughness should meet the precision demand of the selected bearing. If the bearing is fixed tightly on the indefinably-processed axis, then the axis error will transmit to the rollway of the inner ring, which leads to a high waviness and an increased noise.

5 Conclusion

A good result is achieved by analyzing and testing the main driving system in the XK-736-type miller. The modified noise is cut down to and kept 74 dB (11.2 dB less than before) when measured by sound level meter after the miller has been operated for years. The proposed noise control technique may find its wide use in other CNC millers as well.

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Brief Biographies

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