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INVESTIGATE THE NOISE PROBLEMS OF BALL SCREWS WITH AND WITHOUT CAGE

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Abstract

The noise problems of ball screws with and without cage were investigated experimentally in this work. The noise sources of three types of ball screws without cage were first identified. The results show that the high frequency noise comes mainly from the friction between elements while the low frequency noise is mainly caused by the impact between balls and nut or screw. The noise sources of ball screws with cage were then identified. The results show that the cage can reduce the high frequency noise effectively only in some rotational speeds. Besides, the amount of reduction of noise by using the cage is different for different designs of ball screws.

1. INTRODUCTION

Electric motor and combustion engine are the most important power sources in our daily life. Both of these power sources are rotary type. In order to converter the rotary type of power sources into a linear type, ball screws are the most important machine element. Nowadays, the trend of most machines is to have higher speed, but also to have lower noise level. As a result, the demand for a ball screw with higher speed, but with lower noise level has increased recently.

The noise problem in screw-nut transmissions has been investigated by Olofsson[1]. Because there are no rotating elements between the screw and nut, the friction induced noise is the most important noise source in screw-nut transmissions. Tokunaga found that the high frequency noise of a ball screw came from the impact between the circulating ball and the return tube [2] while the low frequency noise came from the ball passing frequency and its harmonics [3]. The conclusion that the high frequency noise was caused by the collision between the balls and the return tube [2] was based only on the experiment that the noise could be reduced when the return tube was covered with a lead plate. It will be proved in this work that the high frequency noise mainly comes from the friction between the elements in the ball screw. Because the noise level of a ball screw generally is proportional to the rotational speed of the screw, a longer lead was proposed by Ninomiya [4] to reduce the rotational speed with the same feed rate. Another method to reduce the noise is the use of cage to prevent the contact between balls [5, 6]. However, the caged ball screws may induce another noise problem. This will be discussed in this work.

Most of the reports mentioned above investigated the noise problem by using only one type of ball screw. In order to classify the noise generation mechanisms, the noise characteristics of different types of ball screws with different operation conditions were investigated in this work. The results show that the main generation mechanisms of noise are different for different types of ball screws with different operation conditions.

2. EXPERIMENTAL SET-UP AND PROCEDURE

A ball screw testing system was developed in this work, as shown in Fig. 1. The screw shaft (1) is supported by journal bearings (7) at both ends. To take the axial force, two trust plated (11) are used. The shaft is driven by a servo motor (9) through a flexible coupling (8) to reduce the possible misalignments and vibration from the motor. To keep the nut in a linear motion, the nut (2) is supported by two linear sliding guides (3) through a bracket (5). A flange (6) is used in the testing machine so that one an change the ball screw quickly without re-adjusting the linear sliding bearing (3)(4). The reciprocation stroke of the nut is controlled by two limit switches (12).

The measurement instruments include the microphone, accelerometer and the data acquisition system. The microphone was placed in the middle of the stroke of the reciprocation nut, but with 4cm above the center line of the screw and with 12cm away from the central line of the screw. An accelerometer was attached to the top of the nut to measure the vibration of the nut. The signals from the microphone and accelerometer were recorded by digital data recorder for off-line analysis. However, a spectrum analyzer was also used to check the measurement results at real time. All the experiments were carried out in an anechoic chamber, as shown in Fig. 1. The experimental procedure can be summarized as follows:

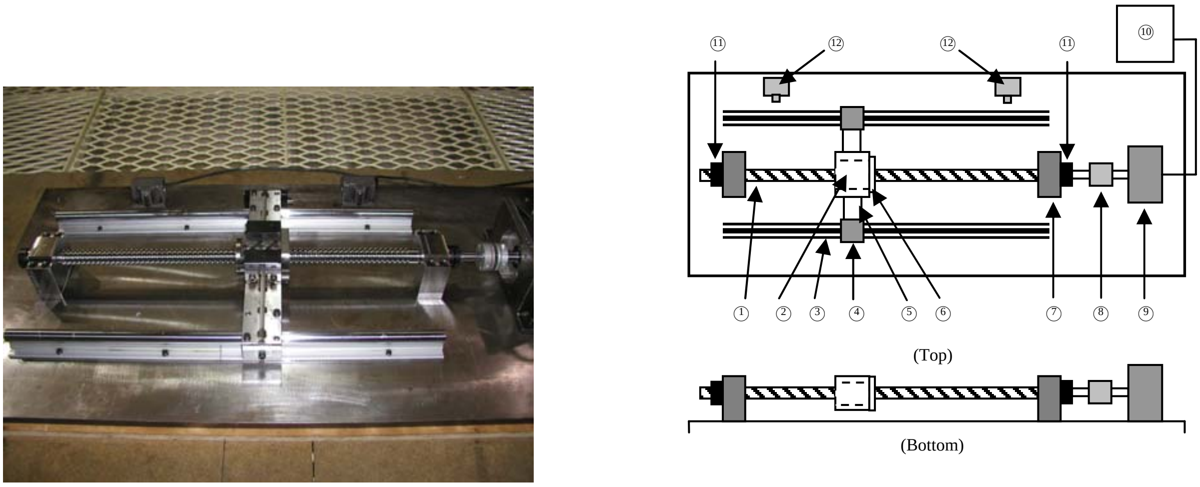
(1) Install the ball screw and measurement instruments properly on the testing machine.
(2) Measure the background noise when controller of the servo-motor is in stand-by state.
(3) Set the reciprocation velocity of the nut (strokes per minute).
(4) Start measurement for 3 minutes.
(5) Change the reciprocation velocity of the nut, and repeat the steps (4) and (5).

As mentioned, several different types of ball screw were tested in this work, the measurement procedure for each type of ball screw is the same as above.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Although the final objective of this work is to identify the noise sources of ball screws, the vibration and noise characteristics of each type of ball screw shall be discussed first. Table 1 shows the types of ball screws tested in this work. Basically, there are three types of circulation, i.e., recirculation with external return tube, recirculation with internal return cap, and recirculation with end cap. Each type of circulation is further divided into two types of configurations, i.e., ball with cage and ball without cage. Therefore, one may say there are total six types of ball screws tested in this work. Table 1 also shows the symbols of each type of ball screws.

The difference between the three types of circulation is shown schematically in Fig. 2. The characteristic of ball screws with external return tube is that there are two and half turns of balls (shown as dashed line in Fig. 2(a)) and a return tube (shown as solid line) in each circulation. There are two ball circulations in each ball screw. In other words, there are five



(a) (b)

Figure 1. (a) Photo of the testing system
(b) Components of the testing system

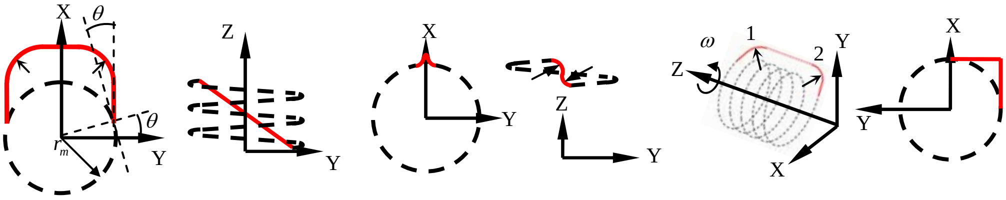


Figure 2. Three types of recirculation

turns of active (or loaded) balls in each ball screw. The characteristic of ball screws with internal return tube is that there is nearly only one turn of ball and a very short return tube in each circulation (as shown in Fig. 2(b)). There are five circulations in each ball screw. As a result, there are also about five turns of active balls in each ball screw. The characteristic of ball screws with end cap circulation is that there are about five turns of balls and a long return tube in each circulation, as shown in Fig. 2(c). There is only one ball circulation in each ball screw.

3.1 Ball Screws Without Cage

As mentioned, the main objectives of this work are to investigate the effect of cage on the noise characteristics of three different types of ball screws. Therefore, the noise characteristics of ball screws without cage should be discussed first. The noise spectra of three types of bass screws without cage are shown in Figs. 3 to 5, respectively. Qualitatively, the spectra of the three types of ball screws have the following same characteristics:

(1) The spectra can roughly be divided into two ranges, according to the variation of forms with respect to the speed, one is the frequencies between 0-2KHz, the other is 2 to 20KHz.

(2) The spectra in the low frequency range (i.e., 0-2KHz) change their forms with respect to the speed while the spectra in the high frequency range (i.e., 2-20KHz) keep their form, but only the amplitudes increase with the speed. Note that the peaks around 9KHz and 18KHz come from the noise of the controller of the servo motor.

To show the spectra change their forms with the speed in the low frequency range, the spectra in the low frequency range are enlarged, as shown in Fig.6 for type A1. One can find that not only the amplitudes of the spectra change with the speed, the frequencies of peaks also change with the speed. As to the question why the spectra change their forms with speed in the low frequency range while the spectra keep their form in the high frequency range will be discussed later.

Although qualitatively the spectra of the three types of ball screws have the same characteristics; quantitatively, the noise levels are different for the three types of ball screws. Fig. 7 shows the noise levels with respect to the speed. If the speed (the horizontal axis) is expressed in log scale, the noise levels in dB(A) increase almost linearly with the speed. Roughly speaking, the ball screw with external return tube (type A1) has the highest noise level while the ball screw with end cap has the lowest noise level. However, as mentioned, the noise distribution can be separated into low and high frequency ranges. It is more reasonable to compare the noise levels in the low and high frequency ranges separately. Figs. 8 and 9 show the comparison of noise levels in the low and high frequency ranges, respectively. One can find that the difference of the noise levels in the high frequency range is very significant. On the contrary, the difference between types A1 and B1 in the low frequency range is not so significant.

From the above experimental results, the following questions are worth investigating:

(1) What are the basic mechanisms for generating the low (0-2KHz) and high (2-20KHz) frequency noise?

(2) What is the reason for that the overall noise level of type C1 is the lowest among the three types of ball screws?

Because there is no significant peak in the spectra (Figs. 3-5) in the high frequency range, the noise of the ball screws in the high frequency range can be regarded as a broad band noise. It is well known that stable frictional force generally generates broad band noise. Besides, the amplitude of frictional force in a ball screw is very closely related to the rotational speed [7]. Based on this reasoning, it was believed that the high frequency noise was induced by frictional force. In other words, the generation mechanism of the high frequency noise is the friction between ball and ball, ball and nut, also ball and screw. To prove this point, the lubricant on the ball screw was washed out by alcohol, and the noise behaviors of the ball screws were measured again at different speeds. Fig. 10 shows a typical result of this experiment. One can find clearly that the noise level of the ball screw without lubricant is sharply increased in the high frequency range in comparison with that of the ball screw properly lubricated. However, the noise level in the low frequency range is not affected by the lubricant. The above result indicates clearly that the noise in the high frequency range is induced by friction and the noise in the low frequency range is induced by another mechanism. What is the another mechanism will be discussed in the following. As mentioned, the basic characteristic of the noise in the low frequency range is that the peak frequencies in the spectra vary with the speed. One knows that the ball passing frequency (BPF) is proportional to the speed of the ball screw. A calculation shows that most of the peak frequencies in the low frequency range are almost coincident with the BPF and its harmonics. One knows that when the balls are not caged, the value of BPF may vary somewhat because the clearance between balls can’t be hold constant. That is why some of the peak frequencies are not coincident with the BPF and its harmonics. As will be shown later, if the balls are caged, then all the peak frequencies are coincident with the BPF and its harmonics. If the balls impact with other components with constant frequency, then the vibration frequencies shall the BPF and its harmonics. This result indicates that the noise in the low frequency range is caused by the ball impact with the nut or the screw shaft. A theoretical simulation with ADAMS [8] shows that there is a serious collision between the balls and the return tube at the entrance of the tube. In other words, the noise in the low frequency range is caused by the collision between the balls and the return tube.

As to the question why the overall noise level of type C1 is the lowest among the three types of ball screws, the answer is that there is only one ball recirculation in type C1 so that the total impact force between the balls and the return tube is minimum among the three types of

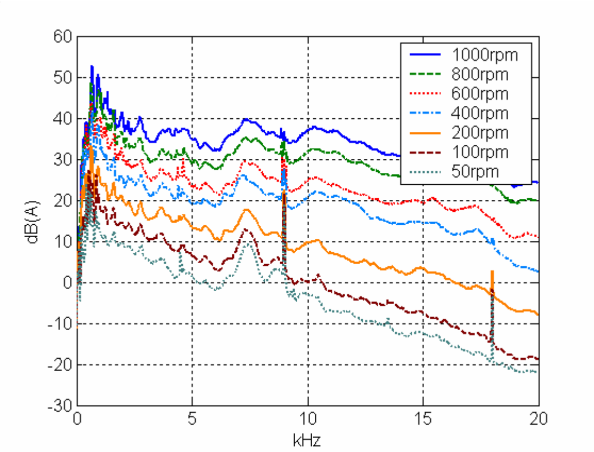


Figure 3. Noise spectra of ball screw with different speeds, type A1

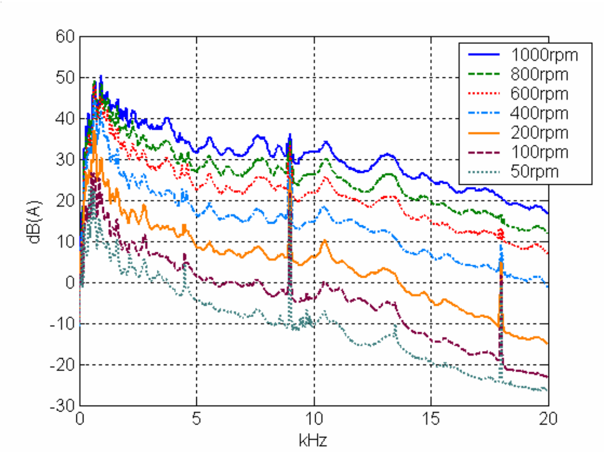


Figure 4. Noise spectra of ball screw with different speeds, type B1

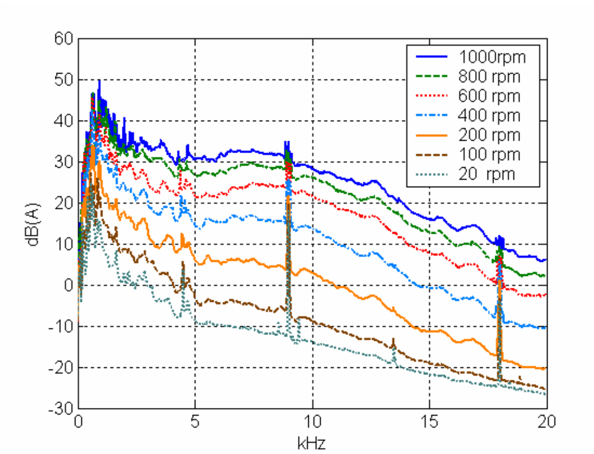


Figure 5. Noise spectra of ball screw with different speeds, type C1

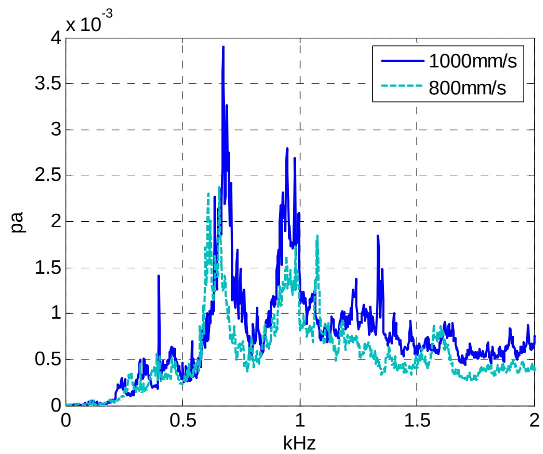


Figure 6. Spectra change with speeds in low frequency range, type A1

ball screws. Although there are five ball recirculation in type B1.while there are only two ball recirculation in type A1, the return tube in type A1 is exposed to the air without any noise barrier. That is why the difference of the noise levels between types A1 and B1 is not very significant.

From the above results, the main mechanisms of noise generation are identified for three types of ball screws without cage. In what follows, the effect of the cage on the noise characteristics of three types of ball screws will be discussed.

3.2 The Effect of Ball Cage

As discussed in the previous section, the high frequency noise mainly comes from the frictional force between the balls or between the ball and nut. Besides, the impact between the balls is also a possible noise source. Therefore, it is meaningful to cage the balls with soft material in order to reduce the noise. The cage used to separate the balls is also called the spacer-ring. Fig. 11 shows the comparison of noise levels of ball screws type A1 (without cage) and type A2 (with cage). One can find that the cage (or spacer) can effectively reduce the noise level at low rotating speeds. In other words, the noise caused by the friction between balls is very significant in type A1 at low rotating speeds. However, the effect of cage on the noise level at high rotating speeds is not significant. As mentioned, the mechanisms of noise generation are different for high and low frequency ranges. In order to know the actual reason for the

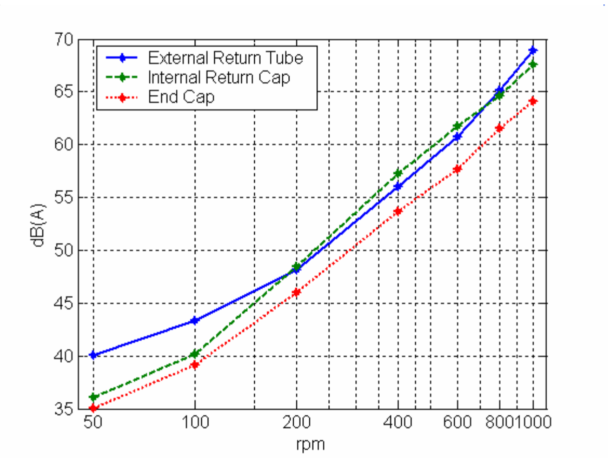


Figure 7. Noise levels with the speeds

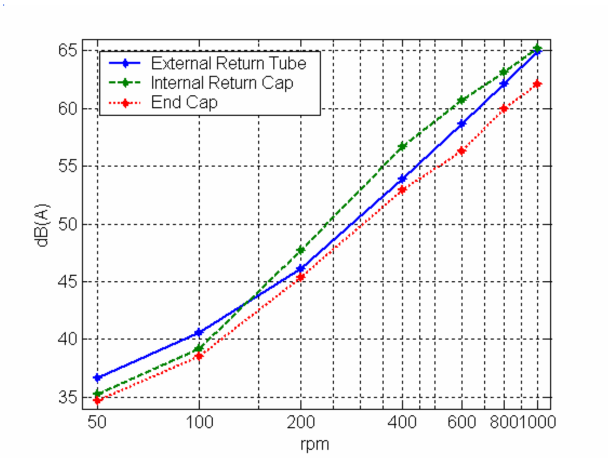


Figure 8. Comparison of noise levels in low frequency range(0~2KHz)

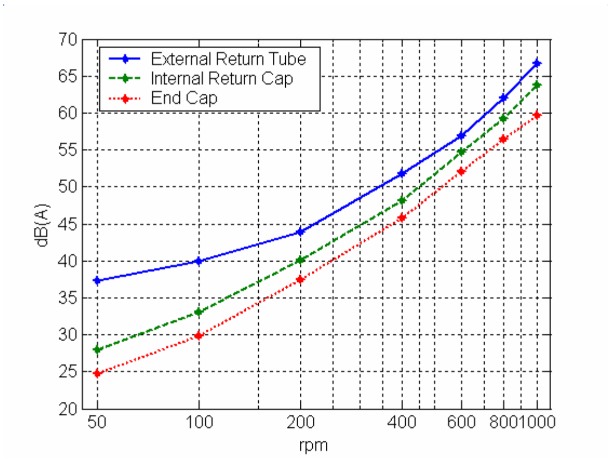


Figure 9. Comparison of noise levels in high frequency range(2~20KHz)

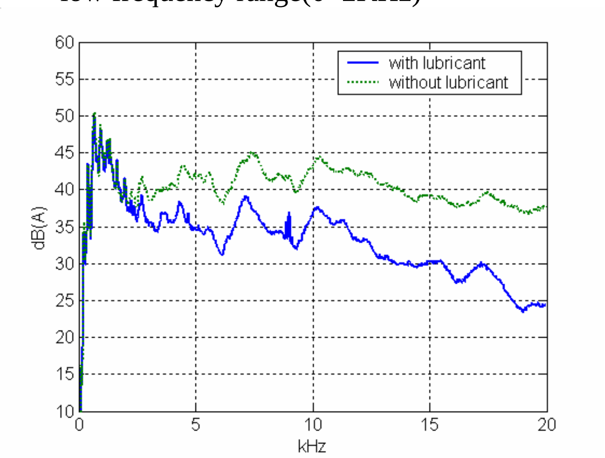


Figure 10. Effect of friction on noise, type A1,1000 rpm

reduction of noise by using the cage, the noise levels are separated into high and low frequency ranges, as shown in Figs. 12 and 15. One can find that the cage can effectively reduce the noise in the high frequency range, especially in the low velocity range. However, the noise level of type A2 in the low frequency range is higher than that of type A1. This is due to the fact that the noise in the low frequency range is mainly induced by the impact of the balls on the entrance of the return tube. If the balls are not caged, the impact frequency is not constant because the clearances between the balls are not constant. On the contrary, if the balls are caged, the impact frequency is content. If the impact frequency is constant, then the vibration excited by the impact force contains only the frequency of impact and its harmonics that locate on the low frequency range. On the contrary, if the impact frequency is not constant, then the vibration excited by the impact force will be quasi-random. Consequently, the frequency of the vibration can extend to the high frequency range, and the components in the low frequency range will be reduced. That is why the noise level of type A2 in the low frequency range becomes higher than that of type A1 in high velocity. The result of Fig. 13 also indicated that the friction force between the ball and the cage increases sharply with the rotating speed. In other words, the cage can improve the friction between ball and balls, but it will induce an additional friction between ball and cage when the rotating speed is increased. It is also suspected that the frictional noise could partially come from the contact between the cage and the nut or screw when the rotating speed is very high. The above results show that one should consider the kinematic and kinetic behaviors of the cage in high rotating speed. Otherwise, one can’t get any advantage from the use of cage.

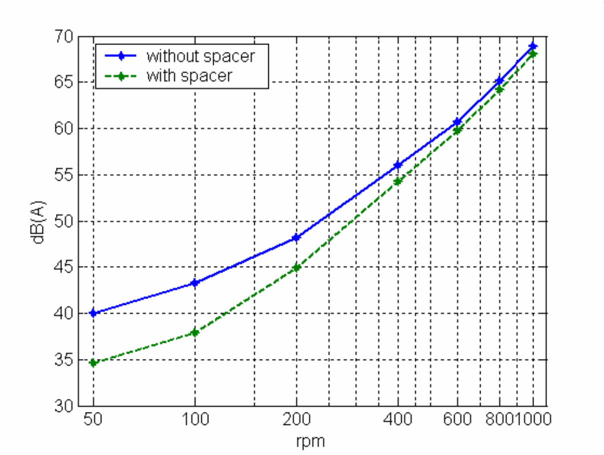


Figure 11. Comparison of the noise levels between types A1 and A2

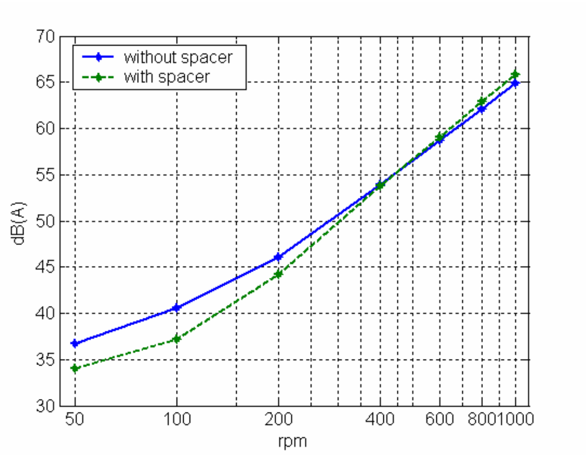


Figure 12. Comparison of noise levels in the low frequency range (0~2KHz), type A

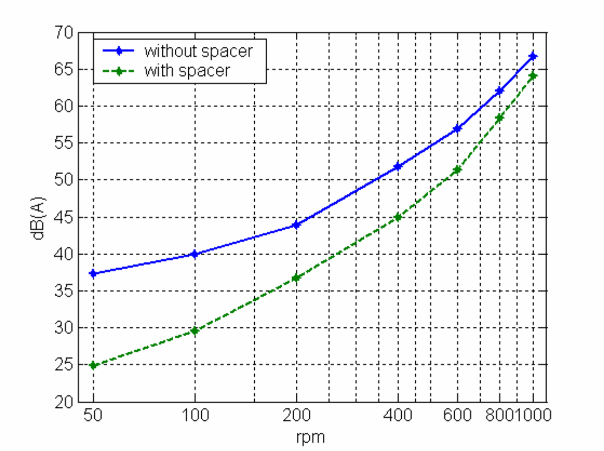


Figure 13. Comparison of noise levels in the high frequency range (2~20KHz),type A

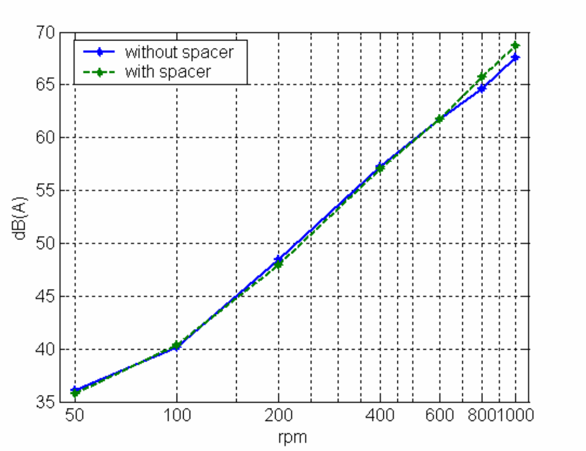


Figure 14. Comparison of noise levels (0~20KHz), type B

Table 1. Types and symbols of ball screws tested in this work.

Symbols	Types of ball screws
A1	Recirculation with external return tube,without cage
A2	Recirculation with external return tube,with cage
B1	Recirculation with internal return cap, without cage
B2	Recirculation with internal return cap, with cage
C1	Recirculation with end cap, without cage
C2	Recirculation with end cap, with cage

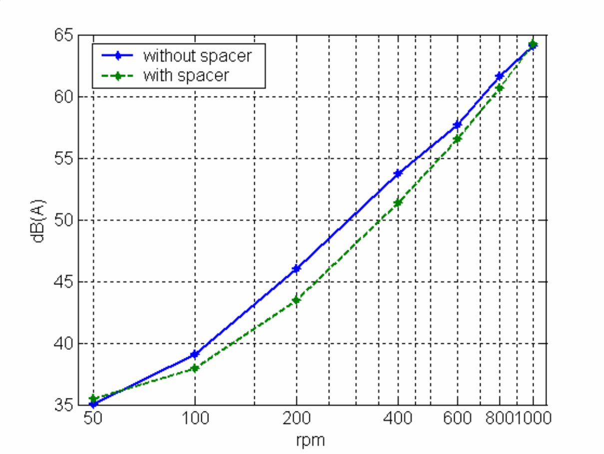


Figure 15. Comparison of noise levels (0~20KHz), type C

The effect of the cage on type B is shown in Fig. 14. In contrast to type A, there is no difference between types B1 and B2 even in low rotating speed. The function of cage is to prevent the contact or impact between balls. The result of Fig. 14 indicates that the noise induced by the contact or impact between balls in type B1 is negligible. This is due to that the noise induced by the impact between ball and the return tube is more important for the B than type A. Consequently, the noise caused by the friction between balls is unimportant for type B. One can also find in Fig. 14 that the cage may induce extra noise in high rotating speed, the same as type A.

Fig. 15 shows the comparison of noise levels of types C1 and C2. One can find that there is no advantage by applying cage to the ball screw type C in very low and very high speeds. Only a little benefit can be found in the middle rotating speed. This is due to the fact that the noise in the high frequency range is effectively damped because the re-circulation tube is located inside the nut. The reason for the increase of noise level in high rotating speed is the same for types A, B and C, as discussed before.

4. CONCLUSIONS

The noise characteristics of three types of ball screws with and without cage were investigated in this work. The main mechanisms of noise generation of the three types of ball screws without cage were first identified. The noise in the high frequency range (2-20KHz) comes mainly from the frictional force between elements. The noise in the low frequency range (0-2KHz) comes mainly from the BPF and its harmonics which are caused by the periodic impact between the ball and the return tube. The cage can effectively reduce the noise due to the frictional mechanism (high frequency noise), but it can’t reduce the impact force between the ball and the return tube (low frequency noise).

Because the weighting (or percentage) of the noise in the low and high frequency ranges are different for the three types of ball screws, only the noise of the ball screw type A can effectively be reduced by the use of the cage. One can’t get significant advantage from the use of cage for the ball screw types B and C. This is a very important conclusion found in this work. The reason for this important conclusion is also discussed in detailed in this work.

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