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A Fundamental Study on Frictional Noise*

(2nd Report, The generating mechanism
of squeal noise of higher modes)

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In this paper, we investigated a frictional noise produced when a long steel cantilever was pressed in the radial direction on a rotating thick disk. The results obtained are summarized as follows:

- (1) With a longer rod, both fundamental and higher mode squeal noises occur. These squeal frequencies are coincident with the lateral natural frequencies of the rod. The squeal frequencies of higher modes are equal to the lateral natural frequency near the longitudinal natural frequency of the rod.
- (2) Squeal noise of higher modes occurs in two cases. The first case is when contact surface between the rod and the disk is relatively large and the longitudinal vibration increases after a squeal noise of the fundamental mode damps. The second one is when the longitudinal vibration increases in rubbing noise.
- (3) However, a complete squeal noise of higher modes does not occur without damping of a squeal noise of fundamental mode, even if longitudinal vibration of the rod increases.

1. Introduction

In the first report⁽¹⁾ we investigated a frictional noise produced when a steel cantilever (we call it " rod ") was pressed in the radial direction on a rotating thick disk without lubrication. From these results, it was found that frictional noise can be classified into " rubbing noise " and " squeal noise ". Rubbing noise has a low sound pressure level and its frequencies are composed of the lateral natural frequencies of the rod and the low frequencies caused by surface roughness. On the other hand, squeal noise has a high sound pressure level and its waveform is almost sinusoidal. Also, its frequency is a lateral fundamental natural frequency of the rod when the rod is short. However, in the case of longer rods, squeal noises occur at both fundamental and higher lateral natural frequencies. Furthermore, it was observed that squeal noise changes from the fundamental to a higher mode or from a higher to the fundamental one.

Baglin et al.⁽²⁾ and Klepp⁽³⁾ studied the frictional vibration of higher modes. Baglin et al. rubbed a slender mild steel rod supported by two leaf springs against a non-steel plate such as brass or epoxy resin. They showed that the frequency of the rod reached the second lateral natural frequency when the rod was rubbed against the brass plate. But, they did not describe the generating mechanism of higher mode vibration. Klepp concluded from ex-

perimental and theoretical results that the frictional vibrations of higher modes occur more frequently than that of the fundamental mode at high sliding velocity. However, he studied the vibration equivalent to rubbing noise. Thus, it seems that the generating mechanism of squeal noise of higher modes has not been analyzed sufficiently.

In this paper, we study the squeal noise of higher modes on the rods with different lengths and diameters experimentally and theoretically.

2. Experimental apparatus and methods

The experimental apparatus is illustrated in Fig. 1. A rod is pressed in the radial direction on a thick steel disk rotating at a constant speed and squeal noise is generated without lubrication. The parts of the rod and the disk except the driving parts are placed in a simple anechoic chamber. Frictional noise is

Fig.1 Experimental apparatus

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measured by a condenser microphone at a height of about 100 mm from the contact point between the rod and the disk. The accelerations in the lateral and longitudinal directions of the rod were measured by two light accelerometers (0.4 gr.). One was attached to the rod at a distance of 5 mm from the tip of the rod for measuring the lateral acceleration and the other to the steel plate for measuring the longitudinal acceleration. Measured data are all recorded on magnetic tape. The frequencies of acceleration are analyzed by a real-time spectrum analyzer. The waveforms are reproduced by an electro-magnetic oscillograph. Table 1 shows the specifications of the rod and the disk. The tip of the rod has a hemispherical shape. The circumferential velocity of the disk is 70 cm/s. The applied load on the disk is 2 kg and the angle of the rod against the center of the disk is zero.

3. Experimental results

With a short rod, squeal noise which has a frequency almost coincident with the lateral fundamental natural frequency of the rod was generated. With a longer rod, the lateral natural frequency of higher modes becomes lower and it is predictable that squeal noise of a higher mode occurs. So the squeal noise behaviour was examined separately over a range of rod lengths, from 50 to 100 mm, the rods being 7 mm in diameter.

Before discussing the squeal noise, we investigated the rubbing noise on a

Fig.2 The frequency spectrum of sound pressure and lateral acceleration in rubbing noise

long rod. Figure 2 shows the frequency spectrum of both the rubbing noise and the lateral acceleration of the rod (75 mm in length). The waveform of rubbing noise is also shown, and the acceleration level is given as dB level (80 dB = 1000 cm/s²). Rubbing noise is composed of low frequencies caused by the surface roughness and the eccentricity of the disk, lateral natural frequencies of the fundamental, second and third modes and 18000-19000 Hz, which is considered a longitudinal fundamental natural frequency of the rod. Its sound pressure level is very low. Such a frequency composition did not change with the variation of rod lengths in the experiments on rubbing noise.

The squeal noises of the fundamental and 3rd modes occur with a rod length of 75 mm. Waveforms of the sound pressure, lateral and longitudinal accelerations are represented in Figs. 3 and 4. In many cases, the tip of the rod is worn away

Fig.3 The waveforms of sound pressure and accelerations of the rod in fundamental squeal noise (Rod length = 75 mm)

Fig.4 The waveforms of sound pressure and accelerations of the rod in squeal noise of the 3rd mode (Rod length = 75 mm)

Table 1 Specifications of the disk and the rod

Disk		Rod	
Material	S45C	Material	S45C
Diameter mm	200	Diameter mm	5, 5.5, 6, 6.5 7, 7.5, 8
Thickness mm	40	Length mm	75
Hardness Hv	400	Hardness Hv	150

within a few minutes after beginning the experiment. When the diameter of the contact surface between the rod and the disk becomes 1-2 mm, rubbing noise changes to squeal noise of 770 Hz, which is equal to the fundamental lateral natural frequency (see Fig. 3). When the diameter of the contact surface becomes about 3 mm, squeal noise of the fundamental mode damps, and the squeal frequency changes to 13900 Hz corresponding to the 3rd lateral natural frequency of the rod (see Fig.4). Even if no squeal noise of the fundamental mode occurs, however, rubbing noise changes often directly to squeal noise of the 3rd mode because of the worn rod and larger contact surface. Figure 5 shows the tip of the rod in squeal noise of the 3rd mode. From this figure, it is seen that the rod is worn away, and the contact surface becomes 2-3 mm in diameter.

From Figs. 3 and 4, it is also found that the longitudinal acceleration level increases in squeal noise of higher modes. The lateral acceleration level in squeal noise of the 3rd mode is two times as high as that of the fundamental mode. But the longitudinal acceleration level is about 10 times as high as that of the fundamental mode.

Squeal noise sometimes changes from the fundamental to a higher mode and to the fundamental mode again during one revolution of the disk. This is very interesting fact in order to know the

Fig.5 The tip of the rod

Fig.6 The waveforms of sound pressure and accelerations when squeal noise changes from the fundamental to higher modes (Rod length = 100 mm)

generating mechanism of squeal noise of higher mode. Figure 6 shows these waveforms of sound pressure and accelerations of the rod of 100 mm in length. In this figure, to make the vibration of the higher mode clear, time scales of waveforms are expanded about 20 times, only in the case of the higher modes. At first, the lateral vibration of the rod vibrates at 430 Hz, the fundamental natural frequency, and the sound pressure level is low because of low frequency. However the vibration of the fundamental mode damps with a lapse of time and after squeal noise changes to rubbing noise, squeal noise of 15700 Hz (the 4th lateral natural frequency) occurs. From this figure, it is seen that longitudinal acceleration is at a very low level in the squeal noise of the fundamental mode, but it increases as squeal noise changes to a higher mode. When the squeal noise of the fundamental mode does not damp in spite of a high longitudinal acceleration level, rubbing noise does not change to a complete squeal noise of a higher mode. Figure 7 shows this experimental result with a rod 100 mm in length. When the lateral vibration of the fundamental mode does not damp and the longitudinal acceleration level becomes high, the vibration of a higher mode is added to that of the fundamental one. But it does not change to a complete higher mode vibration as shown in Fig. 6. When the longitudinal acceleration level be-

Fig.7 The waveforms of sound pressure and accelerations in the squeal noise (Rod length = 100 mm)

Table 2 Squeal frequencies and lateral vibration modes for various rod lengths

Length of the rod mm	Squeal frequency Hz	Vibrating mode of the rod
50	1660	1
	29200	3
65	1000	1
	20500	3
75	770	1
	13900	3
85	600	1
	20400	4
90	550	1
	18800	4
100	430	1
	15700	4

comes low again, only the vibration of the fundamental mode is generated. Sound pressure also has the same tendency as lateral vibration.

Our experimental results suggest that squeal noise of higher modes occurs in two cases. One is when squeal noise of the fundamental mode damps and the longitudinal acceleration level increases. The other is when the longitudinal acceleration level becomes high with rubbing noise. But in each case, it is necessary that real contact surface between the rod and the disk be comparatively large. Table 2 shows squeal frequency and the lateral vibration modes for various rod lengths. When the rods are 50, 65 and 85 mm in length, 29200, 20500 and 20400 Hz are shown in this table as a squeal, but their sound pressure levels are very low because their frequencies exceed the audible frequency range. However, we consider them squeal noise because the lateral and longitudinal acceleration level are high and these waveforms are sinusoidal. In this table, squeal of the lateral fundamental mode occurs with all rods. When the rods are 50, 65 and 75 mm in length, squeals of the 3rd mode are generated. And when the rods are 85, 90 and 100 mm in length, squeals of the 4th mode occur. No squeal noise of the 2nd mode occurs with rods of any length.

Fig.8 The experimental and theoretical results of squeal frequencies with various rod lengths

Fig.9 The experimental and theoretical results of squeal frequencies with various rod diameters

As described above, rubbing noise contains all natural frequencies of lateral vibration, and squeal noise contains only the natural frequency of a specific mode and its higher mode varies according to the rod length. From Figs. 3, 4, 6 and 7, we can see that the longitudinal vibration of the rod has a great effect on the generation of squeal noise of higher modes and the order of the vibration mode is closely related to the longitudinal natural frequency.

Figure 8 shows the relation between squeal frequency and longitudinal natural frequency obtained from the frequency spectrum of rubbing noise. (As we can not analyze the frequencies over 20 kHz, we can not measure longitudinal natural frequencies over 20 kHz.) In this figure, lateral natural frequency calculated under the boundary condition (clamped-free) and squeal frequency in the first report⁽¹⁾ (the rod length of 32 mm) are also shown. Squeal noise occurs at the lateral natural frequency near the longitudinal natural frequency. Therefore, when the rods are 85, 90 and 100 mm in length, the mode of squeal noise is the 4th near the longitudinal natural frequency. And when rods are 50, 65 and 75 mm in length, the mode of squeal noise is the 3rd. Squeal frequencies of the fundamental mode are almost coincident with the calculated values, but squeal frequencies of higher modes are lower than calculated values. This is because the rod is not completely clamped. From experiments with various rod lengths, it is clear that the squeal frequency of higher modes depends on the longitudinal natural frequency of the rod. To confirm this fact further, we investigated squeal frequency and the vibration of modes with rods of various diameters and a constant length. In this experiment, longitudinal natural frequencies are almost constant.

Figure 9 shows the relation between squeal frequencies and longitudinal natural frequencies, when the rods are 75 mm in length and vary from 5 to 8 mm in diameter. When the rods are 5, 5.5, 6 and 6.5 mm in diameter, squeal frequencies are 20200, 21700, 22000 and 25000 Hz (the 4th lateral natural frequencies). When the rods are 7, 7.5 and 8 mm in diameter, squeal frequencies are 13900, 15500 and 17200 Hz (the 3rd lateral natural frequencies). But squeal noise of the 2nd mode does not occur. From this figure, it is also obvious that squeal noise of higher modes occurs at the lateral natural frequency near the longitudinal natural frequency.

4. Theoretical analysis

From experimental results, it is obvious that longitudinal vibration has a great effect on the generation of squeal noise of higher modes. So we must consider not only the lateral vibration of the rod but also the longitudinal one, and derive differential equations under the assump-

Fig. 10 Schematic figure of the rod and the disk

tion that the vibration of the disk can be neglected. Figure 10 shows a schematic figure when the contact load P acts on the tip of the rod, length l . Assuming that the influence of shear and rotating inertia can be neglected, the end of the rod is clamped and the rod makes contact with the disk elastically, we get the following differential equations for the lateral and longitudinal vibrations of the rod.

$$EI \frac{\partial^4 u}{\partial x^4} + \frac{\gamma A}{g} \frac{\partial^2 u}{\partial t^2} + C \frac{\partial u}{\partial t} = P[\mu(V_r) \cos \varphi + \sin \varphi] \delta(x-l) \quad (1)$$

$$EA \frac{\partial^2 v}{\partial x^2} - \frac{\gamma A}{g} \frac{\partial^2 v}{\partial t^2} - C^* \frac{\partial v}{\partial t} = P[-\mu(V_r) \sin \varphi + \cos \varphi] \delta(x-l) \quad (2)$$

where u, v : lateral and longitudinal deflections of the rod; E : Young's modulus; A : sectional area; I : moment of inertia; γ : specific weight; g : acceleration of gravity; C, C^* : damping coefficients of lateral and longitudinal vibrations; $\mu(V_r)$: coefficient of friction expressed as a function of relative sliding velocity V_r ; V_r : relative sliding velocity between the disk and the rod; $V_r = V - \dot{u} \cos \varphi - \dot{v} \sin \varphi$; V : rotational velocity of the disk; φ : an angle of inclination of the tip of the rod, which is the sum of initial angle of inclination φ_0 and deflection of the tip of the rod $(\partial u / \partial x)_{x=l}$; and δ : Delac's delta function.

u and v are expressed as follows:

$$u = \sum_{i=1}^{\infty} X_i(x) T_i(t) \quad (3)$$

$$v = \sum_{j=1}^{\infty} X_j^*(x) T_j^*(t) \quad (4)$$

where $T_i(t), T_j^*(t)$ are functions of time and $X_i(x)$ is the i th lateral eigenfunction of the rod under the boundary condition ($x=0$; clamped, $x=l$; free). $X_j^*(x)$ is the j th longitudinal eigenfunction of the rod under the boundary condition ($x=0$; clamped, $x=l$; supported by an equivalent spring), and it is expressed as follows:

$$X_j^*(x) = \sin\left(\frac{\lambda_j^*}{l} x\right)$$

where λ_j^* is derived from the following equation.

$$\frac{k_d l}{EA} + \lambda_j^* \cot \lambda_j^* = 0$$

where $\bar{k}_c$ is equivalent spring constant calculated from Hertzian theory of elastic contact and it is obtained by regarding the contact between the tip of the rod and the disk as that between a ball and a

plane, namely

$$k_c = \left\{ \frac{4Pr_0 E^2}{9(1-\nu^2)} \right\}^{1/3} \quad (5)$$

where r_0 : radius of the tip of the rod; and ν : Poisson's ratio

Substituting Eqs. (3) and (4) into Eqs. (1) and (2), multiplying both sides of the resulting two equations by $X_i(x)$ and $X_j^*(x)$ respectively and integrating from 0 to l , we obtain the following non-linear differential equations:

$$\begin{aligned} \ddot{T}_i + \frac{g}{\gamma A} C \dot{T}_i + \omega_i^2 T_i &= X_i(l) \frac{g}{\gamma A l} \\ &\times P[\mu(V_r) \cos \varphi + \sin \varphi] \quad (i=1, 2, \dots, \infty) \end{aligned} \quad (6)$$

$$\begin{aligned} \ddot{T}_j^* + \frac{g}{\gamma A} C^* \dot{T}_j^* + \omega_j^{*2} T_j^* &= -\frac{X_j^*(l)}{X_j^*} \frac{g}{\gamma A} \\ &\times P[-\mu(V_r) \sin \varphi + \cos \varphi] \quad (j=1, 2, \dots, \infty) \end{aligned} \quad (7)$$

ω_i : i th lateral natural circular frequency; and ω_j^* : j th longitudinal natural circular frequency,

$$X_j^* : \frac{l}{2} (1 - \sin 2\lambda_j^* / 2\lambda_j^*)$$

Moving the origin to equilibrium position of the rod and denoting the deflections of the rod from the origin by $\bar{u}$ and $\bar{v}$,

$$\bar{u} = \sum_{i=1}^{\infty} X_i(x) \bar{T}_i(t), \quad \bar{v} = \sum_{j=1}^{\infty} X_j^*(x) \bar{T}_j^*(t)$$

and an angle of inclination at equilibrium position and initial load by $\bar{\varphi}$ and P respectively, Eqs. (6) and (7) then become:

$$\begin{aligned} \ddot{\bar{T}}_i + \frac{g}{\gamma A} C \dot{\bar{T}}_i + \omega_i^2 \bar{T}_i &= X_i(l) \frac{g}{\gamma A l} \\ &\times [P(\mu(V_r) \cos \bar{\varphi} + \sin \bar{\varphi}) \\ &- P_0(\mu(V) \cos \bar{\varphi} + \sin \bar{\varphi})] \end{aligned} \quad (9)$$

$$\begin{aligned} \ddot{\bar{T}}_j^* + \frac{g}{\gamma A} C^* \dot{\bar{T}}_j^* + \omega_j^{*2} \bar{T}_j^* &= -\frac{X_j^*(l)}{X_j^*} \frac{g}{\gamma A} \\ &\times [P(-\mu(V_r) \sin \bar{\varphi} + \cos \bar{\varphi}) \\ &- P_0(-\mu(V) \sin \bar{\varphi} + \cos \bar{\varphi})] \end{aligned} \quad (10)$$

By Hertzian theory the relation between the load P and the vertical displacement at the contact point $\bar{v} \cos \bar{\varphi} - \bar{u} \sin \bar{\varphi}$ is obtained as follows:

$$P = k(\bar{v} \cos \bar{\varphi} - \bar{u} \sin \bar{\varphi})^{2/3} \quad (11)$$

where $k = \frac{2}{3} \frac{E \sqrt{r_0}}{(1-\nu^2)}$

δ_0 : initial vertical displacement at equilibrium position

Substituting Eq. (11) into P in Eqs. (9) and (10), we can solve the m equations (9) and n equations (10) under the initial condition $\bar{T}_i(0), \bar{T}_i'(0)$ ($i=1, m$), $\bar{T}_j^*(0), \bar{T}_j^{*'}(0)$ ($j=1, n$). But since it is very difficult to solve these non-linear differential equations analytically, we solve them numerically by the Runge-Kutta-Gill method. In this report, we calculate amplitudes of the rod by varying the length and diameter of the rod, considering lateral vibration modes from the fundamental to the 4th ($i=1, 4$), longitudinal fundamental vibration mode ($j=1$) and angle of inclination $\varphi_0 = 0$.

Figure 11 shows the values of the coefficient of friction curves used for the calculation. In the former report⁽¹⁾, it was stated that squeal noise depended on the gradient of a loop formed by the

coefficient of friction and the relative sliding velocity during one period of vibration. For the calculation, we use the curves A, B and C which indicate the gradient of the loop. Curve B shows the gradient of the loop obtained from experimental results on the squeal noise of the fundamental mode. But in squeal noise of higher modes, the friction force can not be measured by a strain gauge owing to high frequency. Therefore, the gradient of the loop can not be obtained. Squeal noise of higher modes occurs only when the real contact surface between the rod and the disk is large. With an increasing contact surface, the negative slope of the coefficient of friction increases. Therefore, curve A which has a larger slope than curve B is used in the calculation of squeal noise of higher modes. By using curve C, the vibration will be damped.

We calculate lateral acceleration when the rod is 75 mm in length and 7 mm in diameter. As an initial condition, we use the static deflection of the rod of each vibration mode when friction force μP_0 acts on the tip of the rod. And as the coefficient of friction, we use curve B with a small slope shown in Fig. 11. For the calculation of $\bar{k}$ and $\bar{k}_c$, the radius of curvature at the tip of the rod, $r_s = 40$ mm, is used in squeal noise of higher modes because the tip of the rod is worn as shown in Fig. 5. In squeal noise of the fundamental mode, $r_s = 10$ mm is used because the wear of the rod is less than that in higher modes. The calculated waveform of lateral acceleration of the rod is shown in Fig. 12(a). This waveform contains both the fundamental and the 3rd lateral natural frequency components, 800 Hz, 15500 Hz. As the level of the 3rd natural frequency component is low, the waveform seems almost sinusoidal. Therefore, we could consider it a squeal noise of the fundamental mode.

Experimental results suggest that squeal noise of higher modes will occur in the following two cases. One is when the real area of contact between the rod and the disk is relatively large and squeal noise of the fundamental mode damps and longitudinal vibration increases. The other is when the longitudinal vibration increases in the rubbing noise. At first, squeal noise of the fundamental mode is

Fig. 11 The coefficient of friction curves used for the calculation

damped by curve C with a small slope. And then we calculate lateral acceleration using $\bar{T}i_0$ and $\bar{T}i_0$ (obtained after damping of the fundamental mode) and $\bar{T}j_0^* = 10^{-5}$ (in which a slightly larger value is added to the initial value after damping). Curve A with a large slope is used as a coefficient of friction. The calculated waveform is shown in Fig. 12(b). The squeal noise of the 3rd mode occurs at 15500 Hz, which has a waveform which is completely sinusoidal. The calculated lateral acceleration level does not agree completely with the experimental result shown in Fig. 4, although it has the same tendency. Using a small initial value corresponding to rubbing noise for lateral vibration and the same initial value as shown in Fig. 12(b) for longitudinal vibration, we calculated the lateral acceleration. The same waveform of the lateral acceleration as that in Fig. 12(b) was obtained. It is theoretically proved that squeal noise of higher modes occurs also when the longitudinal vibration increases in rubbing noise.

Furthermore, we use the calculated initial value on the squeal noise of the fundamental mode for lateral vibration, a slightly larger initial value for longitudinal vibration and curve A with large slope as a coefficient of friction. The calculated lateral acceleration with the lapse of time is shown in Fig. 12(c). In the fundamental mode vibration, when the gradient of the coefficient of friction and initial values of longitudinal vibration increases, the vibration of the 3rd mode increases. But the vibration of the fundamental mode does not change to a complete vibration of the 3rd mode as shown in Fig. 12(b). This has the same tendency as the experimental results as shown in Fig. 7. Therefore, the following results are theoretically revealed; even if the contact surface between the rod and the disk increases and the gradient of the coefficient of friction and the longitudinal vibration become large, the vibration of higher modes occurs slightly without damping of fundamental mode squeal,

Fig. 12 The calculated waveforms of the lateral acceleration of the rod with several initial values

but it does not change to a complete squeal noise of a higher mode.

The calculated vibrations of higher modes with various rod lengths and diameters are shown in Figs. 8 and 9. And longitudinal natural frequencies calculated by Eq. (8) are also shown in these figures. From these theoretical results, it is also clear that squeal noises of higher modes occur at the lateral natural frequency near the longitudinal natural frequency of the rod. In Fig. 8, squeal noises of the 3rd mode occur when the rod is shorter than 80 mm and the 4th modes occur when the rod is longer than 85 mm. In Fig. 9, squeal noises of the 4th mode occur when the rod diameter is smaller than 6 mm and when the rod is larger than 6.5 mm, squeal noise occurs at the 3rd mode frequency near the longitudinal natural frequency.

Fig.13 The calculated waveforms of the lateral acceleration of the rods ($l=80$, $\phi 7$ and $l=75$, $\phi 6.5$)

However when the rod is 80 mm in length (Fig. 8) and the rod is 6.5 mm in diameter (Fig. 9), acceleration waveforms are not sinusoidal as shown in Fig. 12(b). Figure 13 shows these waveforms. In each case, the frequencies of 3rd and 4th modes are included, but the amplitude of the 3rd mode is predominant. These theoretical results on squeal frequency agree with experimental results except with the rod 6.5 mm in diameter (Fig. 9). This difference in the squeal frequency is caused because squeal frequency of the 4th mode is lower than the calculated lateral natural frequency and approaches the longitudinal natural frequency.

5. Conclusions

The results obtained from experimental and theoretical studies on squeal noise of higher modes over various rod lengths and diameters are summarized as follows:

(1) When the rod is longer, both fundamental and higher mode squeal noises occur. These squeal frequencies are coincident with the lateral natural frequencies of the rod. Especially the squeal frequencies of higher modes change according to the rod length and diameter and they are equal to the lateral natural frequency near the longitudinal natural frequency of the rod.

(2) Squeal noise of higher modes occurs in the following two cases. The first case is when real area of contact between the rod and the disk is relatively large (the gradient of the coefficient of friction to sliding velocity is large) and the longitudinal vibration increases after squeal noise of the fundamental mode damps. The second one is when the longitudinal vibration increases in rubbing noise.

(3) However, a complete squeal noise of higher modes does not occur without damping of squeal noise of the fundamental mode, even if longitudinal vibration of the rod increases.

(4) When the non-linear differential equations of the vibration derived from the lateral and the longitudinal vibration of the rod under several initial conditions are solved, the results almost agree with experimental results and the generating mechanism of squeal noise of higher modes is revealed.

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