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A STUDY ON IDENTIFICATION OF DYNAMIC CHARACTERISTICS OF MACHINE TOOL BY MEANS OF MICRO TREMOR

微動による工作機械の振動特性の同定に関する研究[1]

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1. Introduction

The vibration observed on machine tool should be avoided by change of the operation condition or suppressed by elaborate design as much as possible whichever it may be self-excited vibration or forced vibration. It causes the decrease of productivity, the deterioration of work precision and surface finish.

The dynamic characteristics of machine tool is generally observed by such method as these; 1) frequency response method, 2) impulse response method, 3) random excitation method. These all use some exciting force from outside of machine.

In spite of tremendous efforts for improving the dynamic characteristics of machine tool, usually still there remains vibration with small amplitude, micro tremor, which is caused by gear trains, driving belt and other internal moving parts of machine even under driving condition without cutting.[2),3)] This paper is a study on identification of the dynamic characteristics such as natural frequency, normal mode and damping ratio for the natural frequency by making use of the tremor without giving any particular exciting force from outside of machine. Usually the tremor can be felt by putting our hands on machine. The method of cross-spectrum analysis is applied.[4),5),6)] A lathe machine is used for the analysis.

The wave forms of the tremor which are observed at various points on a machine tend to be random. Thus the method of random vibration analysis such as power spectrum and cross-spectrum analysis is applicable to the identification of the vibration system.

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At first the analysis as for natural frequency is considered. Generally damping ratio of machine tool structure is not so large that the dominant frequency components selecting the natural frequencies appear in the tremor excited by the sources of excitation aforementioned.

Secondly the analysis as for normal mode is presented. The normal mode at each natural frequency can be obtained when the amplitude ratio and the phase relation of various points to a standard one are measured. These relations between each two points are computed applying the method of cross-spectrum analysis for the tremors observed at two points simultaneously.

At last the analysis as for damping ratio is mentioned. A specific method which utilizes phape of phase characteristic is proposed here. If phase relation is obtained between tow points, it shows a shape of change from same phase to reverse or vice versa around a natural frequency. When the characteristic around natural frequency is simulated by one-degree-of-freedom system, the theoretical transfer function of response displacement to exciting displacement $H(s)$ can be represented as

$$H(s)=\frac{2\zeta\omega_0 s+\omega_0^2}{s^2+2\zeta\omega_0 s+\omega_0^2} \quad \cdots\cdots\cdots\cdots\cdots\cdots(1)$$

where s is operator of Laplace transform, ω_0 is natural circular frequency and ζ is damping ratio. ζ is given so that the theoretical phase relation may coincide with the measured one in sense of least square of the error.

2. Experimental Procedure

A 4 shaku (about 4 feet) lathe is used for the experiment. The reason that the lathe is adopted is that the shape of the machine is rather simple and fundamental from the structural view point, and effect of the structural vibration to cutting process is easily understood in terms of relative displacement between work and tool. The measuring points of the tremor are settled on gear box P1 where is considered closest to the source of excitation, on bearing box of the spindle P2, on tool post P3 and on tail stock P4 as shown in Fig. 1. As the standard point for obtaining the normal mode P1 and P2 are adopted.

As the pick up strain gage type accelerometer is used. Direction of rocking mode, front and rear direction from operator stand point, is especially payed attention to. Generally this is direction of the weakest stiffness for lathe and that might give large effect for the machining precision and surface finish.

The tremor during driving without cutting is measured under various driving condition such as the maximum spindle speed 940 rpm and other several low speeds, and disengaging condition of gear coupling of the spindle. This changes the frequency components of excitation source, so that these are distinguished from the natural frequency. On the other hand in order to compare the results of the analysis by the tremor with inherent dynamic characteristic the usual frequency response method is carried out, too. Electro-hydraulic exciter is used, and the natural frequencies and the normal modes for these are identified. In addition to this the excitation using random wave form generated by thermal shot noise also made. The response vibration to this random input is analyzed by means of cross-spectrum method, and the natural frequencies and the normal modes are confirmed.

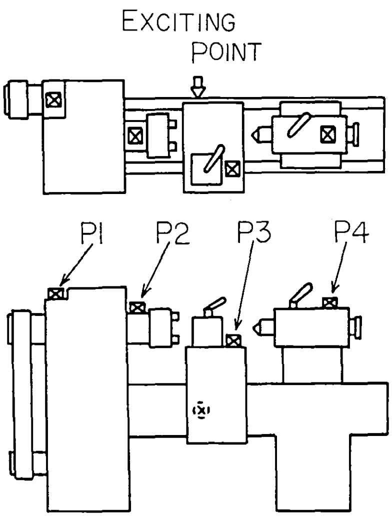

Fig. 1　General scheme of measuring points

The tremor or the vibration observed at P1, P2, P3 and P4 are recorded on 4 channels data recorder with 3 step variable speeds. Thus they are transformed to digitized data on paper tape IBM card through high speed AD converter, the maximum sample speed of which is 6000/s. These are made input to digital computer, and power spectrum, cross-spectrum and transfer function are obtained by performing the numerical computation. The natural frequency is read and the normal mode shape is drawn according to these results. Estimation of the coherency is taken into consideration as an index of reliability of the transfer function through the analysis.

3. Results of the Experiment and the Analysis

(1) Power spectrum and transfer function by the tremor

Fig. 2 and Fig. 3 show the power spectrum. The former is computed from the tremors cut off the higher frequency components and the latter is obtained by using those including higher frequency components. Fig. 5 provides the transfer function P3/P2. The expression of the transfer function P3/P2 means the transfer function regarding P3 and P2 as input and output to the system to be identified respectively.

The numerical computation is made by sampling period $T=2.0\cdot10^{-3}$ s, number of data $n=1000$, length of correlogram $h=100$, resolution of frequency $1/2hT=2.5$ Hz and data length $nT=2.0$ s for Fig. 2 and $T=5.0\cdot10^{-4}$ s, $n=1000$, $h=100$, $1/2hT=10.0$ Hz and $nT=0.5$ s for Fig. 3.

(2) Natural frequency

Tab. 1 (a) shows the frequencies where the

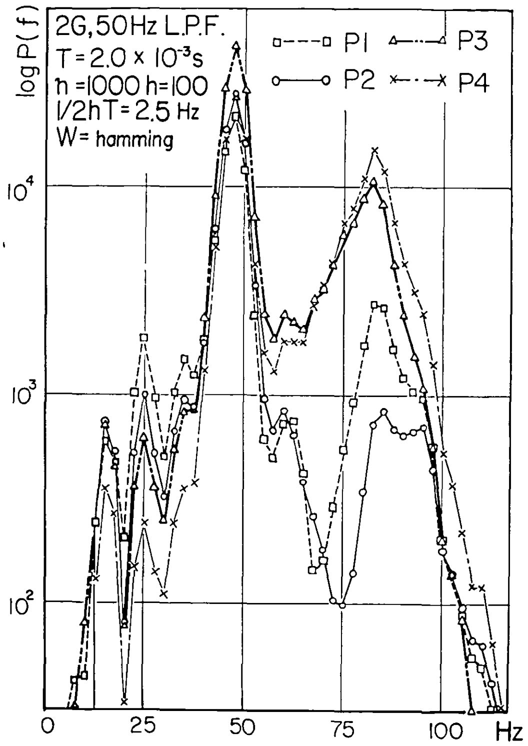

Fig. 2 Power spectra of the tremor in low frequency range

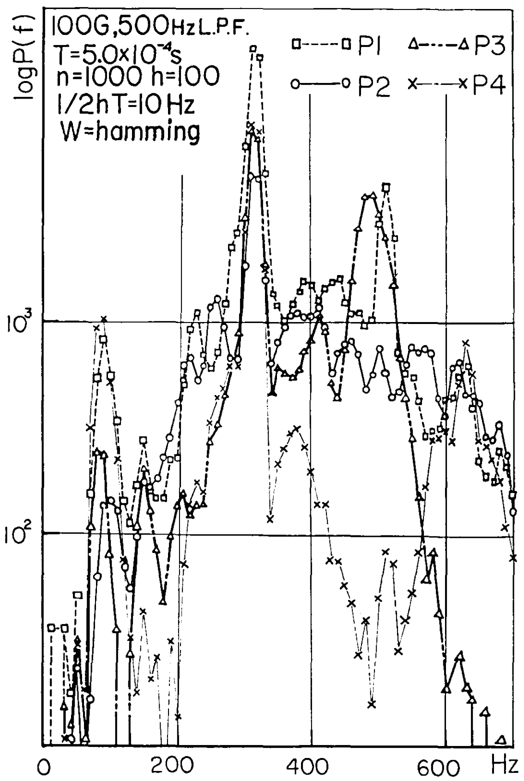

Fig. 3 Power spectra of the tremor up to high frequency

power spectra in Fig. 2 and Fig. 3 stand the extreme. In Tab. 1 (b) the natural frequencies by frequency response method are picked up. As for the latter the excitation is performed up to 530 Hz.

15.0, 25.0 and 31.0 Hz correspond to the rotational speed of the spindle and the motor, and the frequency of gear engaging in unit time. These are not easily found by the direct observation of wave forms, but the expression in frequency domain makes it possible to know the existence of the components. The measured rotational speed of the spindle 940 rpm is equal to 15.7 Hz. 24.7 Hz is similarly identified from the motor speed. The gear coupling has possibility to excite 125 and 313 Hz at the speed taking note of the number of gear tooth. The instrumentation by putting a directional microphone closely to engaging gear teeth makes it possible to assure the existence of 320 Hz. As the resolution of the computation is 20 Hz, the judgement above mentioned is given. Now it can be said that the frequency components shown in Tab. 1 (a) agree well with those in Tab. 1 (b) except the frequency of excitation.

Table 1 Natural frequencies and frequencies at which power spectrum provides extreme (The figures in parenthesis gives frequency resolution.)

(a) Analysis of the tremor	(b) Sinusoidal excitation
15.0 (2.5)	
25.0 (2.5)	
47.5 (2.5)	47.5
80 (10)	80
150 (10)	160
220 (10)	210
260 (10)	250, 280
310 (10)	
380～410 (10)	400
460～480 (10)	450
530 (10)	530

Hz

(3) Normal mode

The approximate shape of the normal modes in terms of the amplitude ratio among P1, P2, P3 and P4 are given in Fig. 6. Those based on the tremor are arranged in Fig. 4 (c). Fig. 4 (a) and (b) display the results by the sinusoidal and the random excitation. The table tells us not only difference of the results, but also feature of the methods themselves. The results in Fig. 4 (c) is worse than that in Fig. 4 (a), (b) from the view point of extent of the mode shape coincidence. However it is interesting to notice that principal modes can be identified by making analysis of the tremor and without using particular excitation from outside of the machine.

In case of the random excitation the data processing which is same as that the tremor is treated is carried out. The time of experiment which is necessary for the excitation of the machine is usually very economized in comparison with that for the sinusoidal excitation. The difference caused between the results of the random excitation and the micro tremor depends on the frequency characteristic of the input. If this is white, the analytically assumed response characteristic are well satisfied and the analysis does not introduce error, and the results ought to coincide with those by the sinusoidal excitation. Fig. 4 (c) suggests that the characteristic of the input which causes the tremor is far from that of white noise. Then it disturbs naturally the transfer function and the difficulty to define the normal mode occurs.

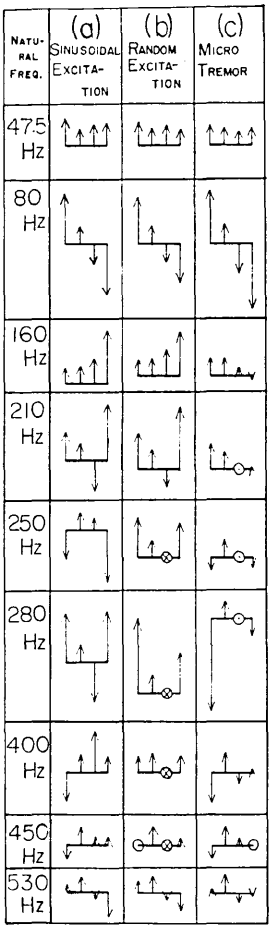

Fig. 4 Comparison of normal mode

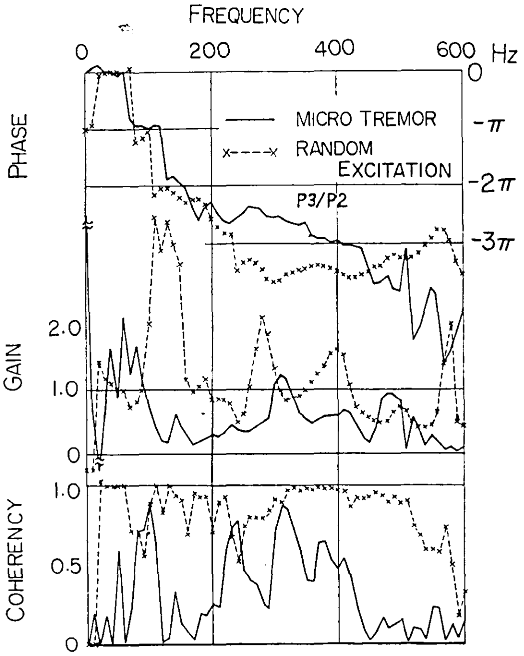

Fig. 5 Comparison of transfer function by the tremor with that by the response to random excitation

Fig. 5 compares the transfer function P3/P2 by the random excitation with that by the micro tremor. The numerical computation for the former is carried out by same parameters as the tremor, $T=5.0\cdot10^{-4}$ s, n=1000, h=100, 1/2hT=10.0 Hz and nT=0.5 s. It is most remarkable that the coherency is higher for the former than for the latter. This is similarly formed for the case of P2/P1 and P4/P2. The reason why the coherency is so high for the random excitation is that the machine is excited at a point and the excitation has power spectrum close to the theoretical one, that is, band limited white. On the contrary the source of the excitation for the tremor is rather distributed in addition to the existence of frequency components with dominant power.

(4) Damping ratio

Fig. 6 shows the transfer function P4/P2 and P3/P2. Behaviour of lower frequency range is seen in details. The computation is made as T=

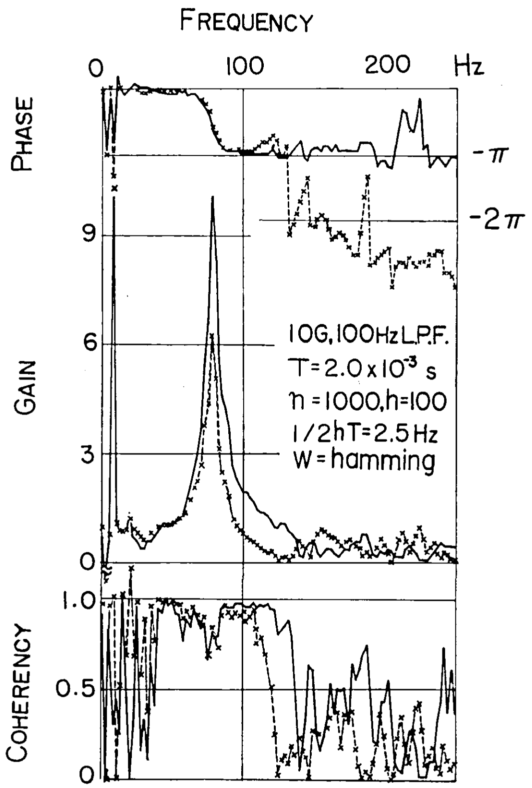

Fig. 6 Transfer function obtained for low frequency range

$2.0 \cdot 10^{-3}$s, n=1000, h=100, 1/2hT=2.5Hz and nT=2.0s. The phase relation provides reverse at about 80Hz. The coherency at 80Hz in Fig. 6 is higher than others, so the estimation can be reliable. The phase relation is not so changeable as the height of peak of power spectrum around 80Hz in spite of the parameter change of the numerical analysis.

Assuming one-degree-of-freedom system in neighbour of the natural frequency 80Hz, the damping ratio is obtained so as to fit the phase characteristic of the transfer function (1) to the phase relation of Fig. 6 in sense of the least square of the error. As the result it is given as $\zeta=0.023$. For the higher order natural frequency at which the reverse of phase can be seen the same analysis can be applicable.

4. Conclusions and Acknowledgement

It is made evident as for a lathe that the natural frequencies, the principal normal mode and the damping ratio are obtained by means of the micro tremor applying the cross-spectrum analysis. The sinusoidal and the random excitation is made at the same time. This shows that when appropriate random excitation is adopted, the normal mode is identified up to higher order natural frequency than the case the tremor is utilized. However, the advantage that the tremor is made use of is the machine is exposed to such circumstance that the tremor occurs even under operation. Although the tremor may affect the machining precision and the surface finish, quantitative estimation will be left in future.

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