APPLICATION NOTE 140-6

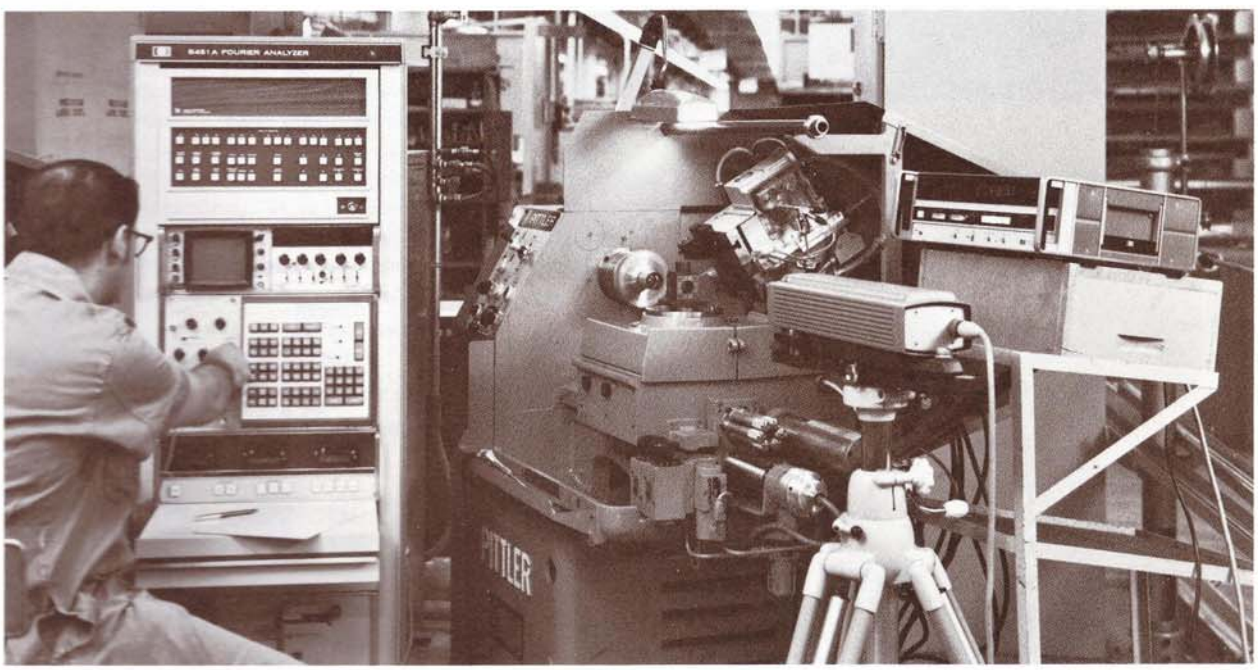
Measurement Of Machine Tool Vibration

SUMMARY OF THIS NOTE

Vibrations in machine tools, commonly known as chatter, can be the cause of poor machining operations resulting in lost time and profit, especially in a high production environment. In such situations, it is essential to rapidly determine the cause of these vibrations and then take steps to alleviate them.

This note describes how the HP Fourier Analyzer was used to determine the cause of chatter in a high production automatic lathe. An HP Laser Interferometer was used as a displacement transducer for detecting the vibrations of the spindle relative to the carriage.

A discussion of the use of transfer function and coherence function measurements in this application is also included.



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MEASUREMENT OF MACHINE TOOL VIBRATION

The HP Fourier Analyzer, used in conjunction with a suitable transducer such as the HP 5526A Laser Interferometer makes an ideal instrument for measuring vibrations in various machine tools. One example was that of a Pittler Automatic Chucker--a high production finish lathe at the Manufacturing Division of the Hewlett-Packard Company. Noticeable chatter marks in the end cuts made by the chucker were attributed to axial vibrations of the spindle. To measure this vibration, the laser interferometer offered a non-contacting method of measuring displacement with a basic resolution of ±0.6 microinches over the range from 0 to 120,000 rpm. The Fourier Analyzer could then be used to show the vibration frequency spectrum, and to extend the resolution to 0.01 microinches or beyond.

Figures 1 and 2 show the setup for making axial vibration measurements using a remote interferometer mounted on the carriage, and a cube corner reflector chucked in the spindle (Figure 3). Figure 4 shows some typical data obtained from the Pittler Automatic Chucker. The strong line at 3720 rpm is caused by the spindle rotating at that velocity. The lines at 7440 rpm and 11,160 rpm are the second and third harmonics of this rotation rate. These components are probably caused by some imbalance in the spindle pulley. The spindle drive motor contribution is shown at 1800 rpm. The component at 3420 rpm has a source determined later. This graph has units of inches^2/rpm and is called a displacement power spectrum. It is plotted on a logarithmic vertical scale. Twice the area under this graph gives the mean square displacement power in inches^2. In this case, the rms (root-mean-square) axial vibration amplitude is 280 microinches.

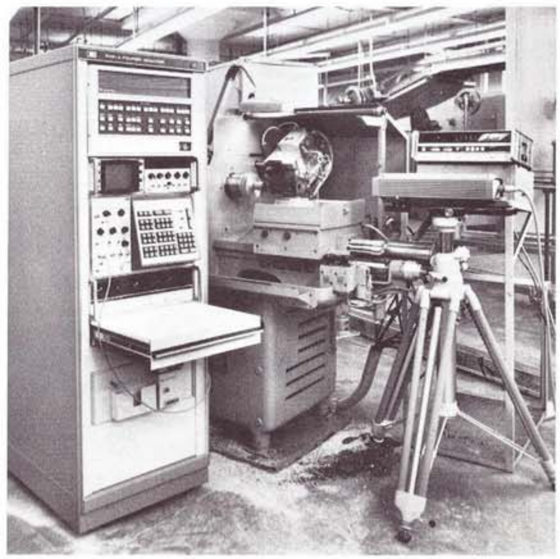

FIGURE 1

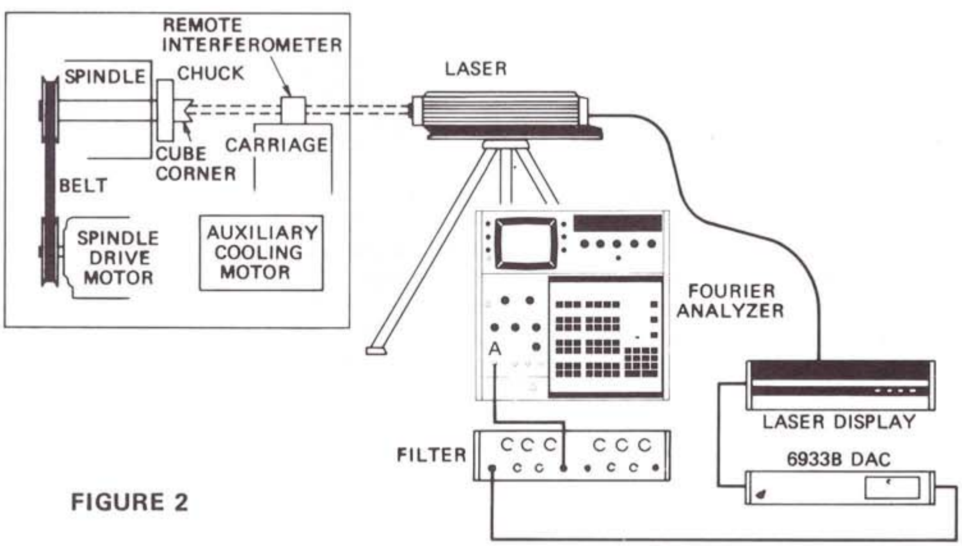

FIGURE 2

FIGURE 3

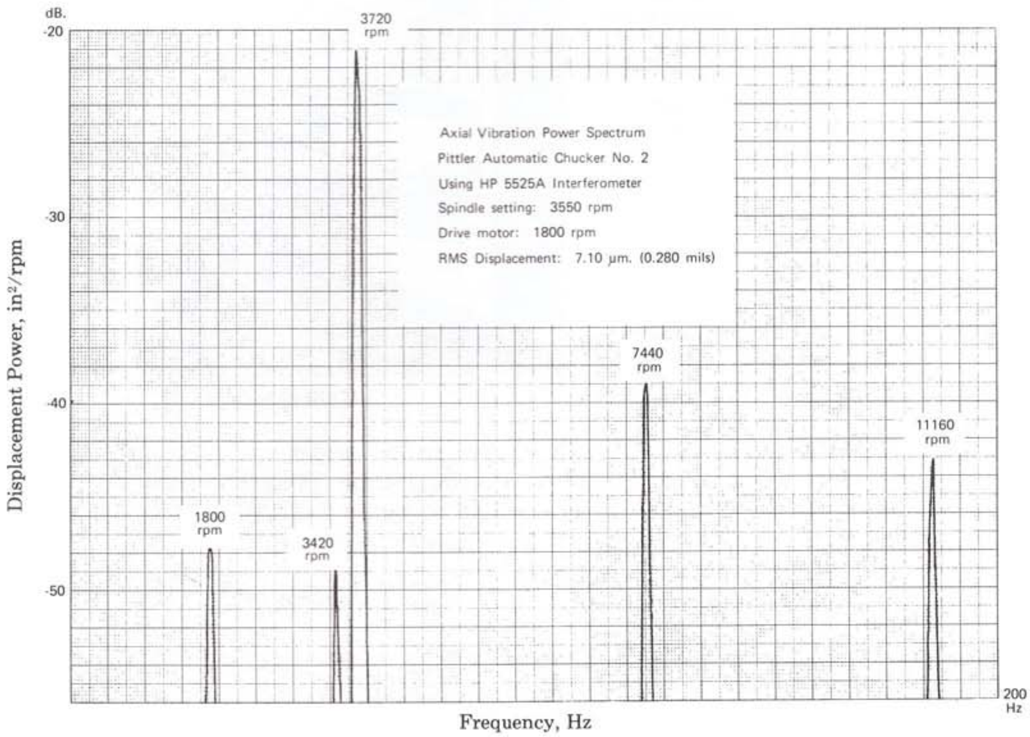

FIGURE 4

Figure 5 shows some time waveforms of displacement for various spindle speeds. Note the large amount of vibration at the highest speed (3720 rpm) compared to the lower speeds. The peak displacement is about 410 microinches which is considerably out of tolerance for a machine of this type. The effect of various harmonics is also apparent from these time waveforms.

By changing motor speeds and belt ratios, it is often possible to directly determine the sources of vibration. The objective was to determine the source of the 3420 rpm component in order to know the source of each of the five components shown in Figure 4. The first step taken was to turn the spindle motor off and leave

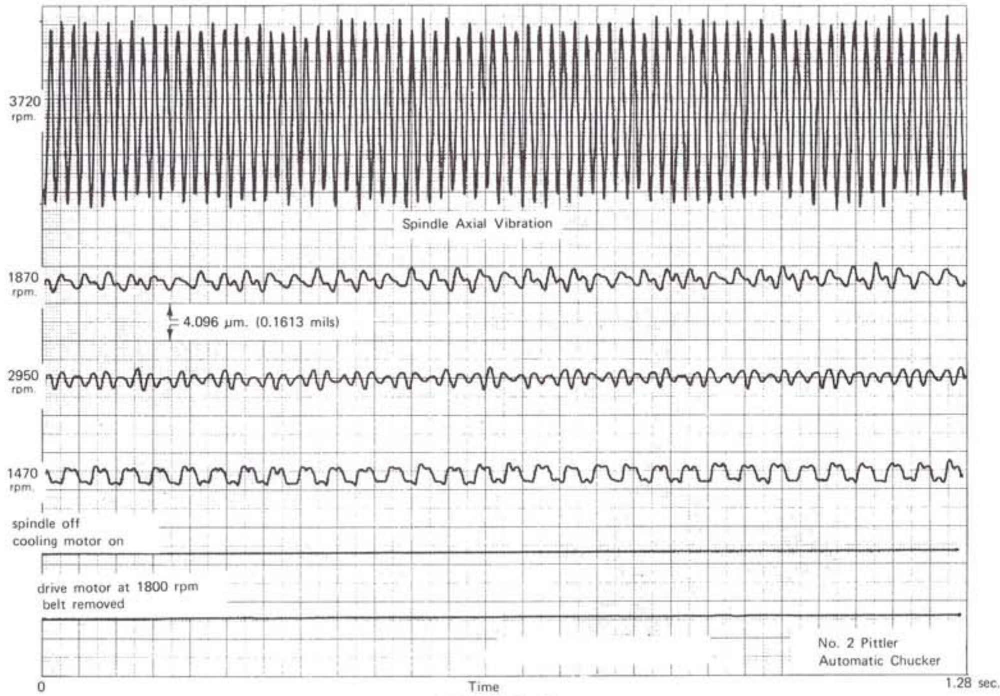

FIGURE 5

the auxiliary cooling motor on. Figure 6 shows a 3420 rpm component caused by the cooling motor with some other rather small components. The next step was to remove the spindle drive belt and allow both the spindle drive motor and auxiliary cooling motor to run. Notice in Figure 7 that the spindle drive motor has components at approximately 1800, 3600, and 7200 rpm. Vibrations caused by the auxiliary cooling motor at 3420 rpm are hardly transmitted to the spindle.

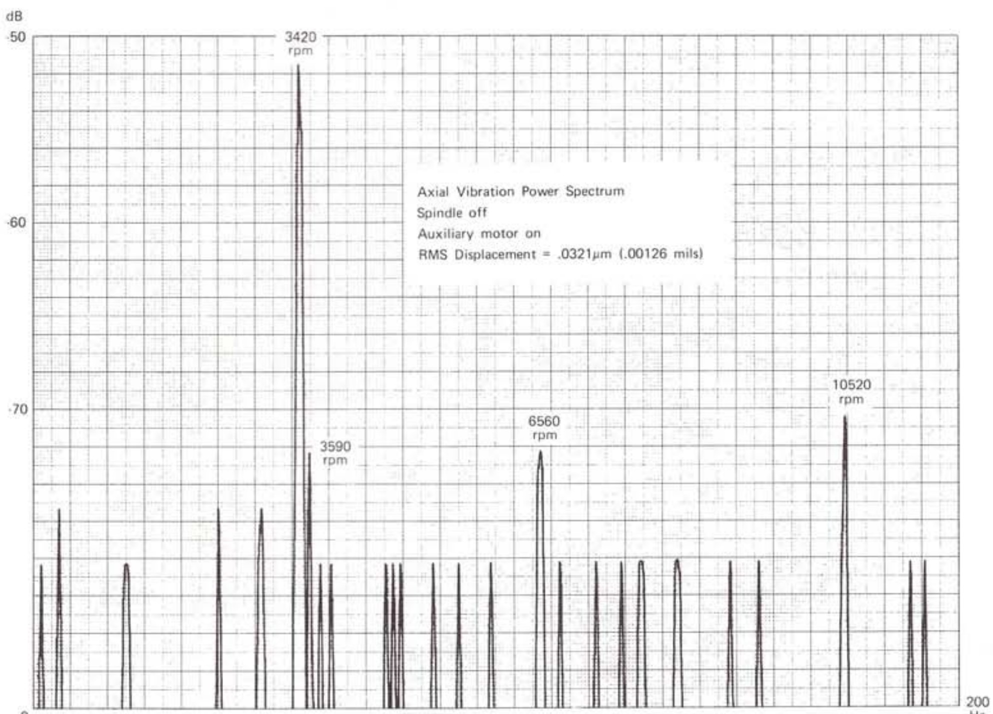

FIGURE 6

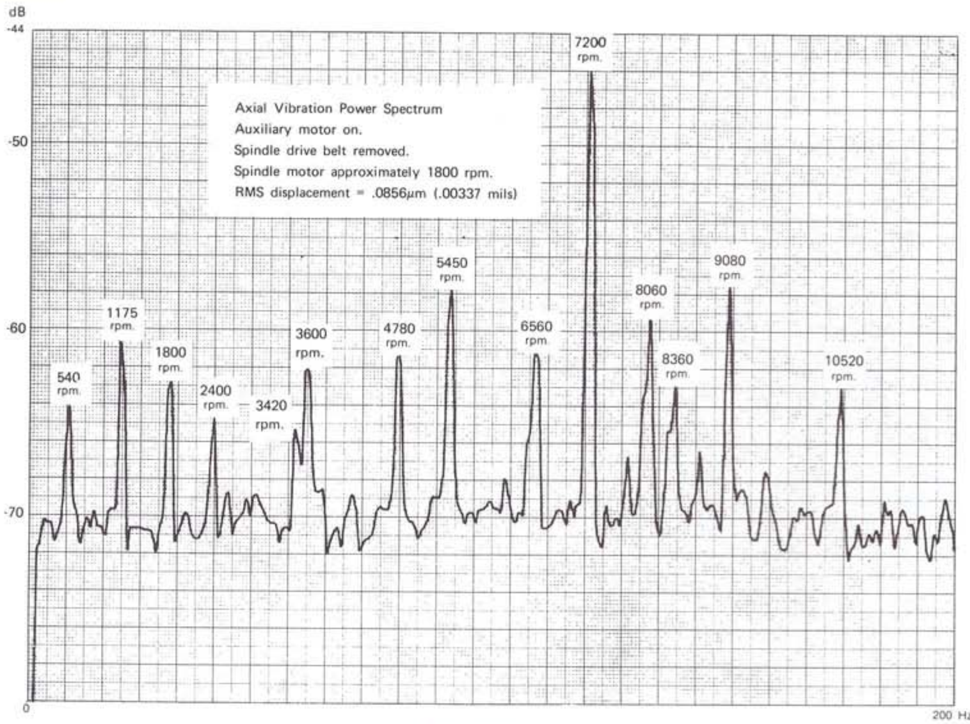

FIGURE 7

The results of this investigation would indicate that the spindle and pulley should be balanced and perhaps the thrust bearings checked. Vibrations caused by the spindle drive motor and the auxiliary cooling motor, although detectable, are minuscule.

Additional information concerning sources of vibration, as well as resonances in the machine tool structure can be obtained by mounting accelerometers at various points, and using the Fourier Analyzer to measure the vibration spectrum at these points.

It is also possible to measure the path transmission characteristics between a vibration source and the spindle. The Fourier Analyzer has two input channels, so two transducers can be monitored simultaneously. Figure 8 illustrates the block diagram of this measurement setup. The transfer characteristic between the vibration source (measured by the accelerometer), and the spindle (measured by the interferometer) is calculated in the Fourier Analyzer by dividing ensemble averages of the cross-spectrum $\overline{G_{yx}} = \overline{S_y S_x{}^*}$, and the auto-spectrum $\overline{G_{xx}} = \overline{S_x S_x{}^*}$, where S_x and S_y are the Fourier transforms of the source and spindle vibration waveforms respectively. The * denotes the complex conjugate, and the bar denotes ensemble averaging. The transfer function is defined as follows:

$$H(f) = \frac{\overline{G_{yx}(f)}}{\overline{G_{xx}(f)}}$$

Thus, the path attenuation at each frequency can be measured, as well as any transmission resonances caused by the machine tool structure which might tend to amplify some components of the vibration spectrum.

Another valuable two channel measurement is the coherence function. This measurement determines the relative vibration power at the spindle that is correlated with the vibration from some source. If the coherence is unity at a

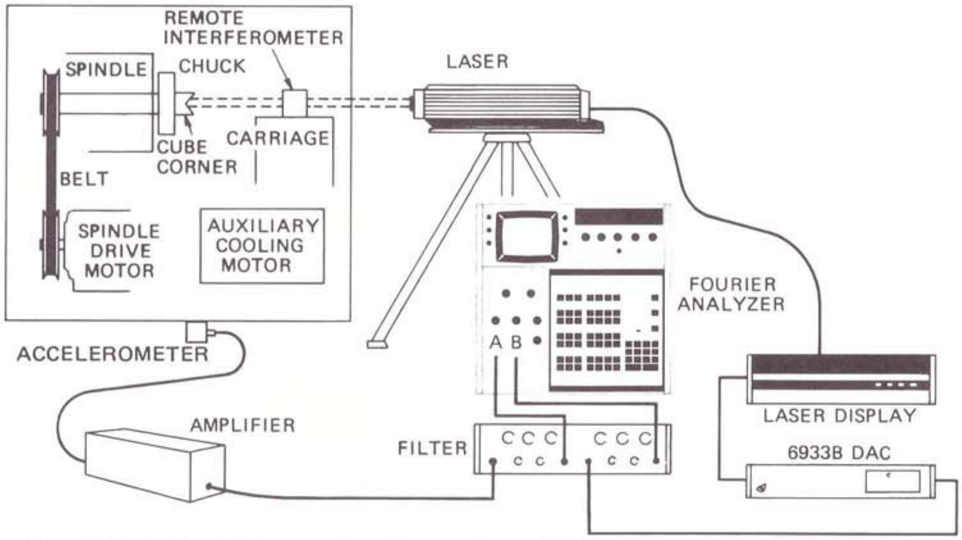

FIGURE 8. Block Diagram for Measurement of Transfer and Coherence Functions

particular frequency, then all of the vibration power at that frequency is caused either by the source being monitored, or by other sources that are coherent with the one being monitored. If the coherence is zero, then the spindle vibration is being caused by other sources. The coherence function is defined as:

$$\gamma^2 = \frac{|\overline{G_{yx}(f)}|^2}{\overline{G_{xx}(f)}\ \overline{G_{yy}(f)}}$$

Where $0 \leq \gamma^2 \leq 1$

and $\overline{G_{yy}} = \overline{S_y S_y}^*$,

all other symbols being the same as before.

The power spectrum of bearing noise can be a useful measure of bearing wear or roughness. If this quantity is measured periodically from the time a machine is installed, an indication of potential trouble can often be spotted before it becomes serious. Dry, rough, or loose bearings will produce excess noise in certain frequency bands that may not be audible, but can often be easily measured with the Fourier Analyzer. This technique can be used to monitor drive and cooling motors as well as the spindle bearings.

It should be emphasized that the interferometer allows a direct measure of relative displacement between the rotating spindle and the tool carriage. This is much more realistic than mounting accelerometers on the carriage or on the frame near the spindle. It should even be possible to mount the cube corner on a piece that is actually being cut, to see the effect of the cutting tool on the part, as well as the effect of loading on the spindle bearings and drive system.

It is also possible to use other types of transducers to indicate displacement. These techniques generally require that the carriage be positioned very close to the spindle. Care must be taken to insure that the transducer is operating in a linear region, and that extraneous noise is not significant. Capacitive or inductive pick-ups are quite useful for making measurements of radial vibration where the carriage is normally very close to the spindle. In any case, the HP Fourier Analyzer is used to show the frequency spectrum, and to improve resolution.

The Laser Interferometer is extremely useful for making spindle growth measurements caused by heating effects, either in the spindle and bearings, or in the carriage and frame of the machine tool. These displacements occur very slowly, requiring the ability of the interferometer to make slow drift measurements. Distortions caused by heating effects from the cutting tool can be measured in a similar way.

In summary, the HP Fourier Analyzer, used in conjunction with various types of transducers, is a very useful instrument for making measurements of machine tool vibrations. The Fourier Analyzer can measure the vibration spectrum, and can calculate path transfer characteristics between a particular vibration source, and the machine spindle. The Analyzer can also measure amplitude histograms, and can calculate the relative coherence between vibrations at two different points. The Interferometer is a very useful input transducer in many situations where very high resolution measurements must be made over some distance, or where very slow drift measurements are desired. It is also extremely linear, and has a very low effective noise level.

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