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PRELIMINARY EVALUATION FOR APPLICATION OF MACHINE VIBRATION DETECTION USING WI-FI SENSING TO MACHINE FAILURE PREDICTION SYSTEM

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Abstract. *This paper describes the detection of machine tool vibration using CSI as a preliminary evaluation for developing a prediction system for machine tool failure using Wi-Fi sensing. The machine failure prediction system using Wi-Fi sensing detects machine tool vibration using changes in Wi-Fi radio waves caused by machine tool vibration. It predicts failures based on past vibration information when the machine tool vibrates differently than usual. Therefore, we will evaluate whether Wi-Fi sensing can detect machine vibration by evaluating how CSI information differs depending on whether the machine tool is operating, using a drilling machine or a milling machine. Experimental results show that it was possible to detect whether the machine tool was cutting metal or not. However, detecting whether the machine was stopped or in operation was impossible. On the other hand, while working on the milling machine, we showed the possibility of distinguishing who was working on the metal.*

Keywords: Wi-Fi sensing, Channel state information, CSI, Detection of machine tool vibration, Prediction system for machine tool failure

1. Introduction.

In recent years, there has been a demand for more sophisticated factory equipment due to the shortage of workers, reduction of labor costs, more sophisticated industrial activities, and higher factory utilization rates. It calls for not only the automation of industrial machinery but also the advancement of methods for predicting factory equipment failures and maintenance. However, manual methods of predicting failures are costly and labor-intensive. Moreover, when sensors and cameras are built into industrial machinery or attached to objects, they require installation costs and additional construction work, which does not offer the advantages of cost reduction and labor elimination. To improve these problems, we focused on Wi-Fi sensing.

Wi-Fi sensing is a sensing technology that uses changes in Wi-Fi radio wave Channel State Information (CSI). Wi-Fi sensing can observe changes in the state of space through changes in CSI and can be used as a non-contact sensor because radio waves are sensitive to changes in the area. In recent years, Wi-Fi sensing has been used in a wide range of research, including indoor positioning with an accuracy of several tens of centimeters, detection of human breathing and falls, and sensing of sounds in neighboring rooms [1,2]. In addition, due to the expansion of applications associated with the recent progress of research on Artificial Intelligence (AI) and Internet of Things (IoT) technologies, automatic

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measurement systems have been proposed to detect machine tool failures by analyzing sensor values that measure machine tool vibration through machine learning [8,9].

In the past, while detecting mechanical machine tool failures and defects relied on machine stoppages or experienced engineers' intuition, AI, IoT, and machine learning technologies have made fault detection more accessible than ever. However, in such automatic measurement systems, the mounting position of the sensor is critical for accurately detecting faults. Therefore, in-depth knowledge of the equipment and empirical understanding of the machine are required when installing the sensors. On the other hand, WiFi-based vibration sensing can sense equipment vibration based on changes in the propagation path of Wi-Fi communication, thus making it possible to measure machine operation without directly installing sensors on the machine tool [3].

Therefore, we are studying the possibility of using Wi-Fi sensing to realize a machine failure prediction system. The system then predicts failures based on past vibration information when the machine vibrates differently than usual. Currently, a method is used to construct a system that measures machine vibration by attaching a sensor with a built-in accelerometer and temperature sensor to the machine [6,7]. However, these sensors must have a power source, such as a battery, to measure their readings. Another method that has been proposed is to measure changes in CS by attaching a patch antenna to the machine without attaching a sensor or other measurement device [3]. On the other hand, our research investigates the possibility of measuring machine vibration only by changes in CSI without attaching additional parts such as sensors or antennas to the machine.

As a preliminary evaluation for the development of this system, this study will evaluate whether Wi-Fi sensing can be used to detect machine vibration in machine tools. When a machine vibrates unusually, the system predicts failures based on past vibration information. Therefore, as a preliminary evaluation for the development of this system, this study will evaluate whether Wi-Fi sensing can be used to detect machine vibration in machine tools. In detecting machine vibration, we will use a drilling machine and a milling machine to detect machine vibration and evaluate whether the machine condition can be determined.

This paper first describes Wi-Fi sensing using CSI. Section 3 describes the experimental environment used in this experiment, followed by an evaluation of the investigation on detecting machine vibration using CSI, which was conducted as a preliminary evaluation. Finally, Section 4 presents the conclusion of this paper.

2. Channel State Information (CSI).

In this study, the object under test is placed between the transmitter and receiver of Wi-Fi communication, and Wi-Fi sensing is performed using CSI. The object under test causes changes in Wi-Fi communication radio waves in diffraction, reflection, and attenuation due to multipath, and these changes are measured using CSI. CSI represents the state of the propagation path between transmitting and receiving devices extracted at the physical layer in Wi-Fi communications as specified in 802.11n. CSI can be calculated from the signal information for each subcarrier in Orthogonal Frequency Division Multiplexing (OFDM). Furthermore, CSI has information on amplitude and phase changes due to propagation loss of transmitted radio waves and multipath effects such as reflections and diffractions, so it is possible to observe and infer oscillations and variations in the observed objects from the measured CSI values. A complex multidimensional matrix represents CSI with amplitude and phase information. This study obtains CSI using the CSI Tool [4,5].

In OFDM, which is adopted in IEEE 802.11, data transmission is performed on multiple subcarriers, so CSI of multiple subcarriers can be obtained from a single communication. When the number of antennas on the transmitting and receiving sides is n respectively, the propagation path H of the radio wave differs for each combination of transmitting and receiving antennas, as shown in Figure 1.

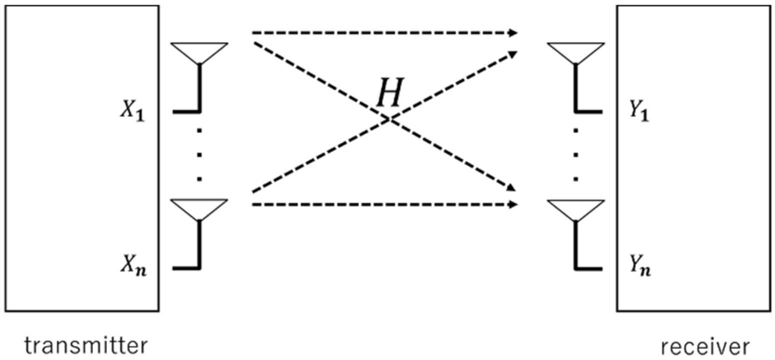


Figure 1. Transmission path information

Equation (1) shows the formula for the transmission path and between transmission and reception when X_n is the data transmitted by the nth transmit antenna, Y_n is the data received by the nth receive antenna, and N_n is the noise.

$$Y_n = HX_n + N_n \tag{1}$$

Since the transmission path H of radio waves is different for each subcarrier (k) by using OFDM, CSI can be calculated for each subcarrier of each receiving antenna (Y_n) and expressed as a multidimensional matrix as in Equation (2). This multidimensional matrix contains information on the transmission path. The CSI Tool is used to obtain the amplitude and phase deviation.

$$H = \begin{bmatrix} h_{X_1Y_1} & \cdots & h_{X_1Y_n} \\ \vdots & \ddots & \vdots \\ h_{X_nY_1} & \cdots & h_{X_nY_n} \end{bmatrix} \tag{2}$$

3. Experiment.

3.1. Experimental environment. Figure 2 and Figure 3 show the experimental environment in this experiment. First, a machine tool used to measure the vibration, a drilling machine or a milling machine, is placed between two laptop PCs; one is a transmitter PC, and the other is a receiver PC. Then, using the CSI Tool, packets are sent from the transmitting PC and received by the receiving PC to obtain CSI on the transmission path between the transmitting and receiving PCs. In the experiment, the transmitting PC is a Let's note CF-S9 with an Intel Wi-Fi Link 5300 NIC installed as a wireless LAN card, and the receiving PC is a ThinkPad X301 with an Intel Wi-Fi Link 5300 NIC installed as a wireless LAN card.

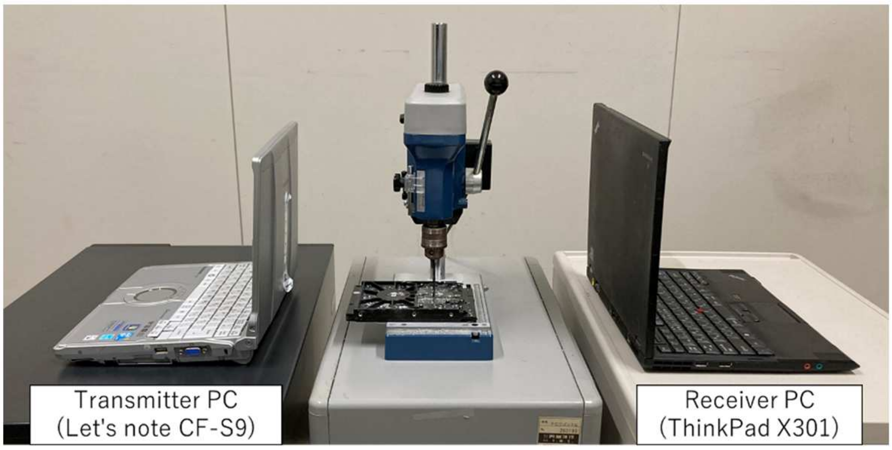


Figure 2. Experimental environment of the drilling machine

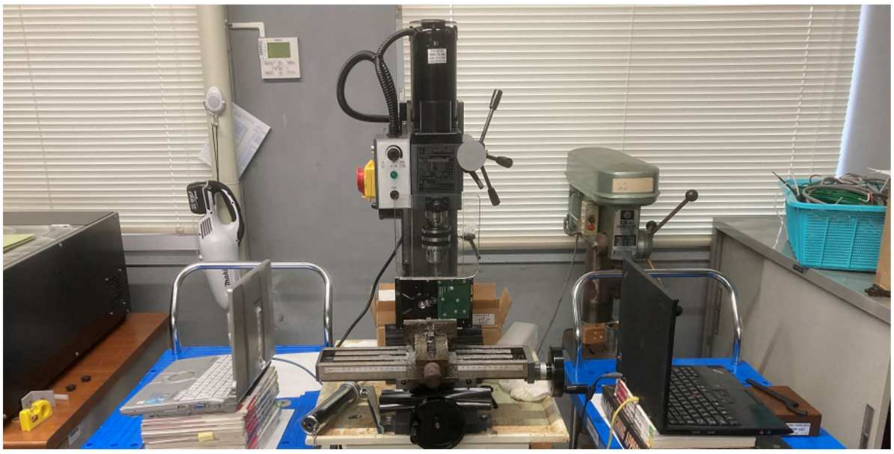


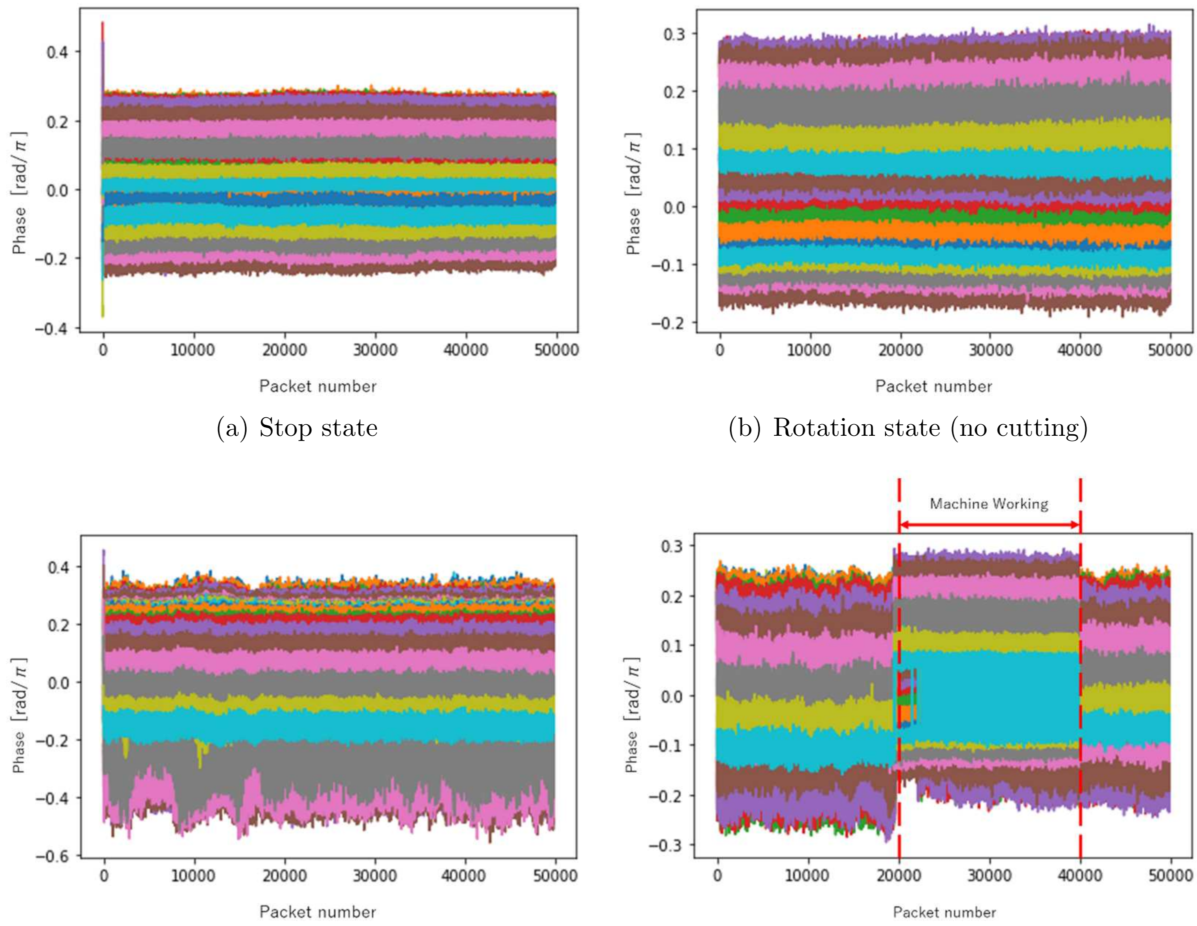
Figure 3. Experimental environment of the milling machine

In the experiment, we will verify whether it is possible to detect a machine tool's operation status (in operation and stop) and machining status using a drilling machine or a milling machine. In addition, we will verify the difference produced by the difference in the person who performs the operation (a student who has used a milling machine before and a student who has not). For the drilling machine experiment, the transmission distance is 40 cm, the packet transmission rate is 50,000 packets, and the transmission interval is 1 ms. For the milling machine experiment, the transmission distance is 73 cm, the packet transmission rate is 10,000 packets, and the transmission interval is 1 ms. The data from the drilling machine and the milling machine were compared when these were stopped when they were in operation (when no object was being cut) and when they were cut an object. The thing to be metal processing is a hard disk frame.

3.2. **Experimental results.** Figures 4, 5, and 6 show the results of the experiment. Figures 4 and 5 show the results of the verification of detecting the machine tool operation status (operation/stop) and machining status for the drilling machine and the milling machine. Figure 6 shows the results of an experiment to see how the phase of CSI is affected by whether the milling machine has machining experience or not.

In each graph, the phase information is calculated from the experimental data measured with the CSI Tool. All subcarriers are plotted packet by packet for the CSI phase information obtained from a single receiving antenna. The graph's horizontal axis is the packets since the measurement starts, meaning the experiment's time. On the other hand, the vertical axis is the phase of CSI obtained and plotted in radian notation. The graph is color-coded for each subcarrier, so if the subcarrier's phase does not change over time, the color band of the graph will be constant. However, if the phase of each subcarrier varies with time, the color band of the graph will be disturbed. As mentioned above, the transmission interval of a packet is 1 ms, meaning it takes 10 seconds to transmit 10,000 packets.

First, Figure 4 shows the experiment's results using a drilling machine. The graph when the drilling machine is stopped is shown in Figure 4(a), and when the drilling machine is running but not processing metal is shown in Figure 4(b). These graphs show almost no change between the stopping and operating conditions. Therefore, it can be said that the presence or absence of the rotating motion of the drilling machine cannot be detected. Next, Figure 4(c) shows the result when a hard disk is being shaved. The graph shows that the negative phase is significant from the 0th packet to the 20,000th. From these results, it can be said that the presence or absence of drilling machine rotation cannot be detected using CSI, but the presence or absence of cutting can be detected.



(a) Stop state (b) Rotation state (no cutting)

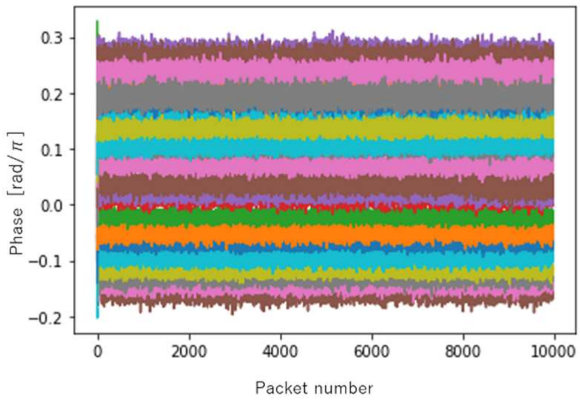
(c) Rotation state (cutting) (d) Drilling machine is processing

Figure 4. (color online) Experimental results of drilling machine

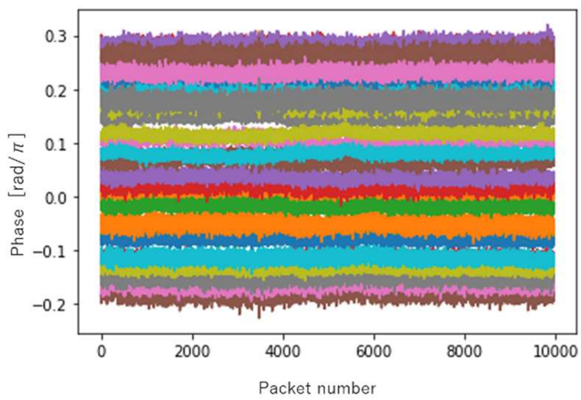
To evaluate whether it is possible to detect whether the drilling machine is moving, we started the operation of the drilling machine at 20,000 packets (20 seconds) and stopped at 40,000 packets (40 seconds). Figure 4(d) showed the experimental results of a phase change at the 20,000th packet (20 seconds) when the operation started and the 40,000th packet (40 seconds) when the operation stopped. From this result, it can be said that CSI can detect the vibration of the start and stop of the drilling machine operation.

Next, the experiment's results using a milling machine are shown in Figure 5. Figure 5(a) shows the graph when the milling machine stops, and Figure 5(b) shows when the machine is operating but not cutting metal. As with the graph of the drilling machine, there was almost no change in phase. On the other hand, Figure 5(c) shows the results for the case where the hard disk is being processed. The graph shows that the phase changed significantly from the 0th packet to the 10,000th. Therefore, it can be said that the presence or absence of machining can be detected, although the presence or absence of machine operation cannot be detected.

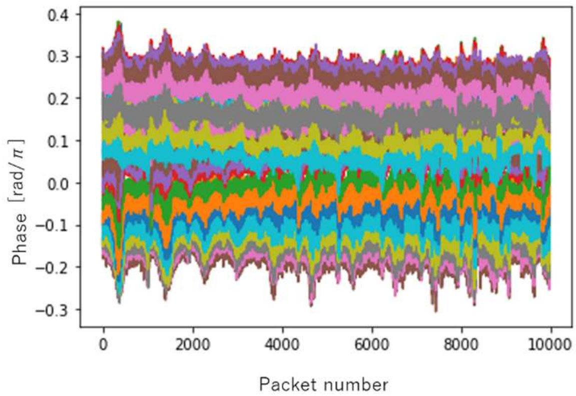
Figure 5(d) shows the results of the experiment in which the milling machine started machining at 20,000 packets (20 seconds) and stopped at 40,000 packets (40 seconds) in order to evaluate whether it is possible to detect the machining status of the milling machine. The experimental results show that the graph shows a phase change at the 20,000th packet (20 seconds) when the operation started and also at the 40,000th packet (40 seconds) when the process stopped. From this result, it can be said that CSI can detect oscillations at the start and stop of milling machine operation.



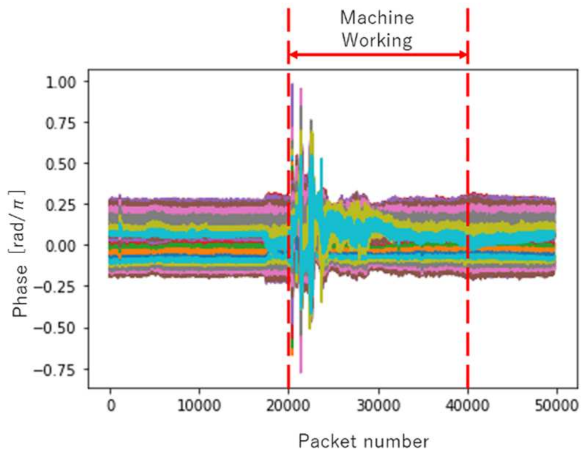
(a) Stop state



(b) Operation state (no cutting)

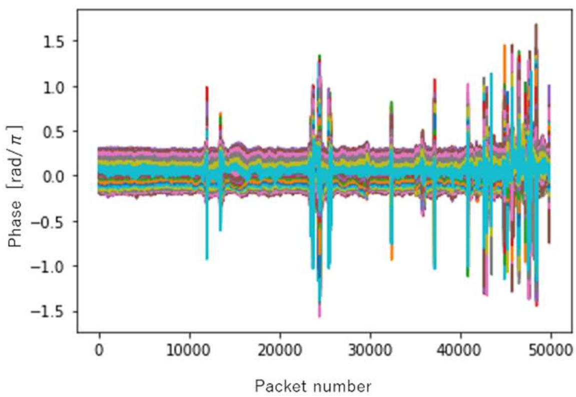


(c) Operation state (cutting)

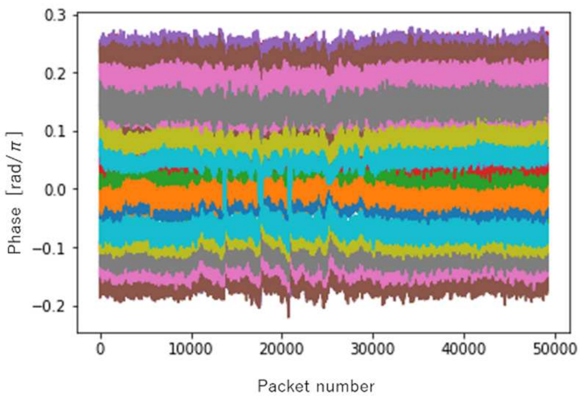


(d) Milling machine is processing

FIGURE 5. (color online) Experimental results of milling machine



(a) Inexperienced milling machine



(b) Experienced milling machine

FIGURE 6. (color online) CSI phase whether experience with milling machines or not

Finally, we will evaluate how the phase of CSI changes with the presence or absence of machining experience on a milling machine. The presence or absence of machining experience with a milling machine significantly impacts accuracy during machining. In addition, the cutting speed and feed rate during machining are essential, and the vibration and noise during machining also change depending on the presence or absence of experience. Therefore, we evaluate whether the machining conditions of a milling machine can be determined by measuring the phase of CSI. Figure 6(a) shows a case in which a student who has never worked with a milling machine before processes metal, and Figure 6(b) shows a case in which an experienced student processes metal.

The phase in the case of the beginner student (Figure 6(a)) is a maximum of 1.5 (rad/π), which is larger than the phase of about 0.3 (rad/π) in the case of the student with experience (Figure 6(b)). Therefore, in the case of no machining experience, the vibration and sound of the milling machine during machining are significant, indicating that the phase observation of CSI can detect the change in the vibration of the milling machine depending on whether the operator has experience in work or not. From this, it can be said that there is a possibility that the CSI can measure changes in the vibration situation of a machine tool, especially during machining.

4. **Conclusions.** In this study, as a preliminary evaluation for developing a machine failure prediction system using Wi-Fi sensing, we evaluated whether machine vibration could be detected using CSI. In assessing whether machine vibration could be detected using a drilling machine and a milling machine, it was possible to detect when the machine was cutting and when it was not cutting, but not when it was otherwise stationary or in motion. On the other hand, we could confirm that the phase change of CSI differed depending on the operator during metal processing on the milling machine.

However, since this study was a preliminary evaluation, the phase change was evaluated by reading the graph. Therefore, the graph shape alone cannot assess how much vibration was detected.

In future work, to conduct a detailed evaluation of machine vibration detection, we are considering comparing the difference with the average value of the phase data. In addition, we are considering conducting experiments on NC machine tools to compare changes in CSI with cutting parameters during metal machining.

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