Discussion

N. H. Cook. The authors are to be commended on their use of optical measurements as applied to machine-tool vibrations. They have been employing these methods skillfully for many years and have been able to obtain accurate phase relationships. Their general experimental excellence can be verified by the amazingly close match of available and dissipating energies as shown in Figs. 7 and 8 of the paper. However, it is not at all clear why the authors feel that the vibration is caused solely by the force lag in the horizontal direction. Indeed, the magnitude of available energy in the vertical direction is larger by an order of magnitude than that in the horizontal direction. The particular vibration investigated by the authors has two degrees of freedom and the problem must be considered in its entirety as there is very strong cross-coupling between motion in the horizontal and vertical directions. It is readily shown that if a linear two-degree-of-freedom system is considered there are several possible types of instability. Of these only two generally develop in practice. One is basically due to variation of force with velocity. This is the same general type as investigated by Arnold and Chisholm on a single-degree-of-freedom system. The other type of vibration is due primarily to the strong cross-coupling between the horizontal and vertical directions. It is this type that the authors have investigated. A theoretical investigation of the two-degree system shows that the time lag observed by the authors is an effect rather than a cause. However, there are no critical experimental data to show whether this lag is a cause or an effect.

Based upon the disputable assumption that the vertical motion is unimportant, the authors have obtained a solution for the single-degree-of-freedom nonlinear case involving horizontal vibrations which are larger than the undeformed chip thickness. The authors feel that vibrations of amplitude less than the chip thickness will not be self-sustaining. It is the experience of the writer and of others that the horizontal vibrations can be of any size up to the chip thickness but seldom become appreciably greater than this amount (as indicated by the authors' limit cycle).

It would be of interest to obtain a solution for the two-degree-of-freedom system based upon the horizontal-time-lag theory. The writer also would like to hear the authors' comments on vibration of tools which are extremely stiff in the horizontal direction compared to the vertical direction. Such tools (as investigated by Arnold, Chisholm, Salžič, and Doi) do vibrate with large vertical amplitude and insignificant horizontal amplitude.

R. S. Hahn. The authors have presented some very interesting data derived through the use of an ingenious method for measuring lathe vibrations. There are some interesting questions to consider in connection with these tests.

In studying the stability of a system it is usually best to confine oneself to small oscillations about the equilibrium position, thereby avoiding nonlinearities. The data of Fig. 5 show the chatter after it has attained considerable magnitude. It is not purely sinusoidal. Have the authors similar data pertaining to small oscillations that do not allow the tool and work to separate? According to Fig. 5 of the paper there is a very slight and hardly discernable phase lag between the vibration and the force. To the casual glance they would seem in phase. In reality the displacement of the tool is being measured and it is tacitly assumed that the force on the tool is in phase with the motion of the tool. Actually one is dealing with a two-degree vibrational system in which one oscillator (a mass on a spring), the workpiece system is coupled by a spring (the tool-work contact) to another oscillator (the tool system). The workpiece oscillator has an uncoupled natural frequency of 77 eps. The tool oscillator has a natural uncoupled frequency of 2900 eps. When the two systems are coupled together it is possible for the 77-eps system to "drive" the 2900-eps system and to do so with a very small phase lag.

In other words one can be sure that the phase lag observed is entirely due to cutting phenomena and not partially due to the vibratory system?

The writer, on the other hand, is inclined to agree with the authors that some sort of lag takes place. For example, the writer has evidence which indicates that appreciable time is required for the establishment of stress-thermal-strength conditions on and in the vicinity of the shear plane as evidenced by

BIBLIOGRAPHY

the time required for the chip curvature to reach equilibrium.

It should be pointed out that the data of Fig. 5 deal with conditions where “feedback” is occurring whereas those of Fig. 11 apparently deal with very low speed and are not subject to feedback.

The authors’ Equation [1] is essentially identical to the writer’s equation for feedback in grinding chatter.9 The Nyquist stability criteria could equally well be applied to this equation also.

A. O. Schmidt,10 B. F. Turkovich,11 and J. R. Roubik,12 An interesting extension of the authors’ previous investigations is presented. This report is certainly based on painstaking and well-devised experiments. If these tests were extended or repeated with higher cutting speeds it would be most helpful to those concerned with practical metal-cutting applications. Some of the results of the reported experiments serve to confirm certain conclusions of metal cutting at low speeds. The explanation as given for the horizontal deflection of tool and workpiece can aid us in understanding how, at slow cutting speeds, a cutting fluid has a chance to exert a lubricating effect between the chip and tool face.

We look forward to another report from these investigators and hope they can direct their attention to conditions more closely resembling those encountered in production shops.

E. Salje,13 Doi and Kato’s work in the field of self-excited vibration is evidently significant. It is likely to result in drastic innovations in the treatment of self-excited vibrations attendant on machining operations. The authors are to be congratulated on their distinguished contribution.

Optical measurement of forces and deflections, while simple, is reliable and precise. The authors may be assumed to have made sure that the work and the tool were the only elements capable of motion in the system. Had this not been the case, it would be uncertain whether it was possible to measure a static cutting force— but one varying with time— by the deflection of the cutting tool. The actual magnitude of the force would have been distorted owing to inertia and damping forces. There could also have been phase displacement. Specifically, however, the phase of the force relative to the deflection is to be ascertained with great precision. Indeed, the chief developments that follow are based essentially on this quantity $h$.

Another point: The ratio of observed tool displacements to work deflections must be small; otherwise the results will again be falsified.

Finally, it may be noted that sources of error may arise in reproduction of diagrams, as when graphs are constructed from oscillograms. The writer is thinking particularly of Figs. 2, 3, 5, and 6.

A salient point is the authors’ simultaneous measurement of deflections and forces, the energies being determined from the result. This technique opens up new possibilities in the study of self-excited oscillations. Tendencies in the same direction are to be found in the Russian literature. All of the data indicates that Arnold’s declining force-speed characteristic does not afford a complete explanation of self-excited oscillation.

The lag measured by the authors between the peaks for deflection and force may be regarded as the most important feature of the article. The lag $h$ makes possible an unstable condition such as the authors have demonstrated for one degree of freedom. Besides, the lag is dependent on cutting conditions (chip breakers, cutting angle) and we can at last anticipate exact explanations for certain vibration phenomena.

In future work, the relationship between lag and external cutting conditions is particularly in need of clarification. In this connection, special importance would seem to attach to the range of higher cutting speeds from 80 to 120 m/min, or about 240 to 360 fpm, and greater chip thicknesses (with continuous chip).

AUTHORS’ CLOSURE

The authors greatly appreciate the most interesting discussions of Dr. Cook, Dr. Hahn, Dr. Schmidt, Dr. Turkovich, Dr. Roubik, and Dr. Salje.

1. Dr. Hahn and Dr. Salje, in connection with the measuring method of cutting force, remark that the displacement of cutting edge lags behind the cutting force due to the inertia of cutting tool and the damping force. It is indeed a fact that the lag of cutting force shown in Fig. 5 is partially due to the tool inertia. But the amount of the lag is considered to be less than $\frac{1}{1000}$ sec, because the natural frequency of tool is 3000 cps.

2. Dr. Hahn’s remark as to small oscillations that do not allow the tool and work to separate is most interesting. One record of such vibrations has been reported in (5), Figs. 70 and 72. The authors intend to carry out further investigations on this problem.

In connection with “feedback,” the experimental result of chatter not subject to feedback was reported in (5), Fig. 79. According to that report, the lag of horizontal cutting force was ascertained similarly to that of Fig. 5 of this paper; but the variation mode of the horizontal cutting force in Fig. 79 differed somewhat from that of Fig. 5, and the amount of available energy was less than that of Fig. 6 of the paper.

3. Dr. Cook asks why the authors feel that the chatter is caused solely by the lag in the horizontal direction. The authors consider that the cause of chatter is due to the horizontal vibration of work. If the horizontal vibration is initiated in workpiece at its own natural frequency, the area of cut, and thus the vertical cutting force, will fluctuate with that frequency setting up the vertical vibration of work. According to the authors’ experiences, it was ascertained that when the chatter was excited the horizontal amplitude of work was enlarged faster than that of vertical; on the other hand, when the chatter died out the horizontal amplitude was decreased faster than that of vertical. According to the experiments on prevention of chatter, chatter can be effectively avoided by preventing both the horizontal vibration of work and of cutting edge. It was observed that when the natural frequency of work differed in vertical and horizontal directions, the vertical vibration of work having its horizontal natural frequency was caused.

Dr. Cook remarks that two types of chatter develop in practice, one due to variation of cutting force with velocity, the other the same as studied in the paper. However, the authors believe that in practical cutting operation there is no self-excited chatter caused solely by the variation of vertical cutting force with velocity. In other words, there is no chatter which is not accompanied by variation of area of cut and which does not produce chatter marks on cut surface.