On-Line Estimation of Groove Wear in the Minor Cutting Edge for Finish Machining

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SUMMARY

The paper investigates the effective detection and estimation of groove wear at the minor cutting edge, which has a vital influence on surface quality in finish-machining. During bar-turning experiments with different cutting conditions, a miniature 3-D accelerometer, mounted in close vicinity to the tool tip, was used to measure the multivariate vibration signal produced by the turning process. The stochastic signal was modelled as autoregressive vector difference equations, and multiple dispersion analysis was used to quantify the complex interactions among various variables. It was found that the characteristic ingredient of vibration in the thrust direction, complemented by that in the main cutting direction, signifies effectively the critical point at which grooves are being "chiseled out", surface roughness is deteriorating rapidly, and subsequently the finishing-tool needs to be replaced. The results are interpreted on a physically sound basis. The results also show that the algorithm developed is a feasible approach to on-line monitoring of minor cutting edge groove wear in finish-machining.

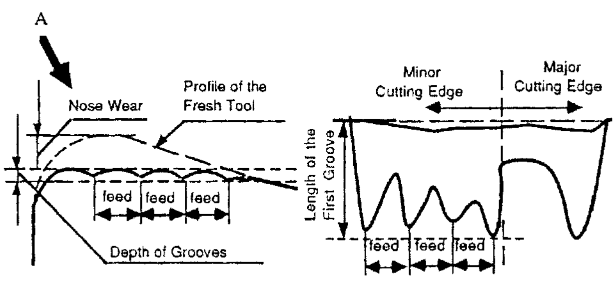
KEY WORDS : Tool Wear, Cutting Edges, Statistical Analysis.

1. INTRODUCTION

On-line tool wear estimation has been recognized as playing an essential role in automated machining systems [1-5]. Much work has been reported, most of which is concerned with **major flank** wear and crater wear estimation. In finish-machining, however, tool wear in the **minor flank** and nose area has proven to be crucial to surface quality and dimensional accuracy. In our previous work [6], the development pattern of the minor flank wear was investigated and its on-line estimation method was developed based on multivariate time series analysis. It was concluded that the critical point at which the finishing tool is to be replaced should be based on the wear status at the minor cutting edge instead of that at the major one.

It was observed long ago [7-10] that grooves will form at the minor cutting edge under certain cutting conditions (Fig.1). It was realised that these grooves affect the surface roughness and dimensional accuracy adversely in finish machining. Most investigations on groove formation and its underlying mechanism were done at Technical University, Delft, by Professor Pekelharing and his colleagues in the 60's and 70's [12-14, 16-18], while work by other researchers was also published in the same period [11,15,19].

Well explained in [20] is the definition of groove wear at the minor cutting edge, which does not actually participate in cutting directly, as shown in Fig. 2. It was observed that rapid formation of the grooves, spaced at a distance equal to the feed, almost always occurs under certain cutting conditions, while not strongly dependent on workpiece and tool materials [13]. It was observed that when enough grooves have been formed, more severe vibration often occurs. As a result, the groove wear pattern is disturbed and the grooves are "wiped out." Theoretically, the groove-less edge should give a better surface. In practice, however, the vibration causes such an increase of the surface roughness that the tool should be replaced [13-14]. In other words, the tool wear reaches its critical point when the grooves are disappearing instead of forming. Suggestions to improve the situation were made by choosing cutting conditions more carefully and by superposing a small vibration in the feed direction to hinder the groove formation [13,16].



(a) View from Tool Top Face (b) View from A

Fig. 1 The Groove Wear in the Minor Cutting Edge

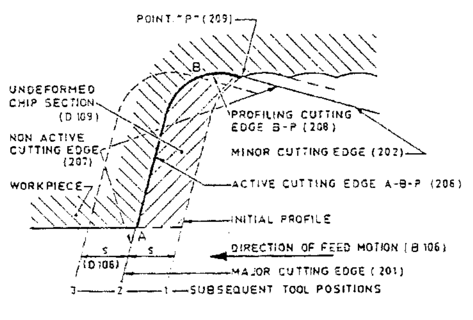


Fig. 2 Definition of the Tool Minor Cutting Edge [20]

There have been many investigations concerning the mechanism of groove formation in the minor cutting edge. Some attributed it primarily to mechancially-based causes, others to thermally-based causes, or a combination of both. The purpose of this paper is to present the results of an experimental investigation concerning detecting the critical point at which vibration disturbs the groove wear as mentioned above, and the finishing tool thus needs to be replaced. Due to the fact that the vibration occurring in the neighbourhood of that point of time is extremely complicated and very little is known about it, a miniature 3-D accelerometer, mounted in close vicinity to the tool tip, was used to capture multi-dimensional vibration signals. The stochastic signal was modelled as an autoregressvie vector difference equation, on the basis of which a parametric investigation was made possible by using multiple dispersion analysis.

2. TOOL WEAR EXPERIMENTS

2.1 Tool Wear Experiments under Finish-Machining Condition

A miniature 3-D accelerometer (PCB Model 306A06), mounted at the close vicinity of the tool tip, was used to measure the multivariate vibration signal produced in the machining process. The tool wear experiments were conducted on a high-precision CNC lathe. The machining conditions used in the experiments are shown in Table 1. All the cutting conditions are within the range recommended by the tool maker company.

Table 1 Machining Conditions Used in Tool Wear Experiments

Machine Tool	HITEC-20SII CNC Lathe (18 KW)
Tool Insert Type	TNMG160408 (Carbide P10, Grooved Chip Former)
Tool Geometry	0°, 5°, -6°, 90°, 60°, 0.8
Work Material	AISI4140 (HNB=320)
Cutting Conditions	Group A : V=160m/min f=0.08 mm/rev d=0.25mm Group B : V=160m/min f=0.04 mm/rev d=0.25mm Group C : V=125m/min f=0.08 mm/rev d=0.25mm Group D : V=190m/min f=0.08 mm/rev d=0.25mm Group E : V=190m/min f=0.04 mm/rev d=0.25mm

The machining process was interrupted periodically in order to measure tool wear and surface roughness. Two sets of 524 data points each, one with a sample interval equal to 30μs and the other with 3.13ms, were taken for the vibration signal in each of the three orthogonal directions, just before each interruption. An extra two sets of data were also recorded between consecutive interruptions to provide more information for signal processing.

Scanning electron microscopy (SEM) was used as a major means to determine the groove wear. Surface roughness (R_a) was measured by using a surfcom - surface measurement instrument.

2.2. The Patterns of Groove Wear and Roughness Changes

Fig. 3 gives a set of photographs taken by SEM, showing the groove wear development for cutting condition B as a representative for the lower feed groups (0.04 mm/rev). The grooves formed in the minor cutting edge can be easily seen and the number of grooves decreases after cutting for about 17 minutes. The change in the number of grooves is further plotted in Fig. 4, while the surface roughness measured is shown in Fig. 5.

Comparing Figs. 4 and 5, it is evident that when the grooves were being wiped out, the surface roughness was deteriorating sharply. Therefore, it is clear that the finishing tool should be replaced when the grooves are disappearing instead of forming. It is also seen that at the initial machining stage, roughness value has a rapid increase before it reaches a stable level due to the normal running-in.

Another set of SEM photographs of the groove wear development for cutting condition A is shown in Fig. 6, as a representative for the higher feed groups (0.08 mm/rev). Figs. 7 and 8 show its groove wear pattern and surface roughness development. It is seen that even after in cutting for more than 50 minutes, no such decrease in the number of grooves or rapid increase in roughness occurred. This perhaps is due to the fact that the higher feed results in wider ridges between adjacent grooves thus better wear-resistance.

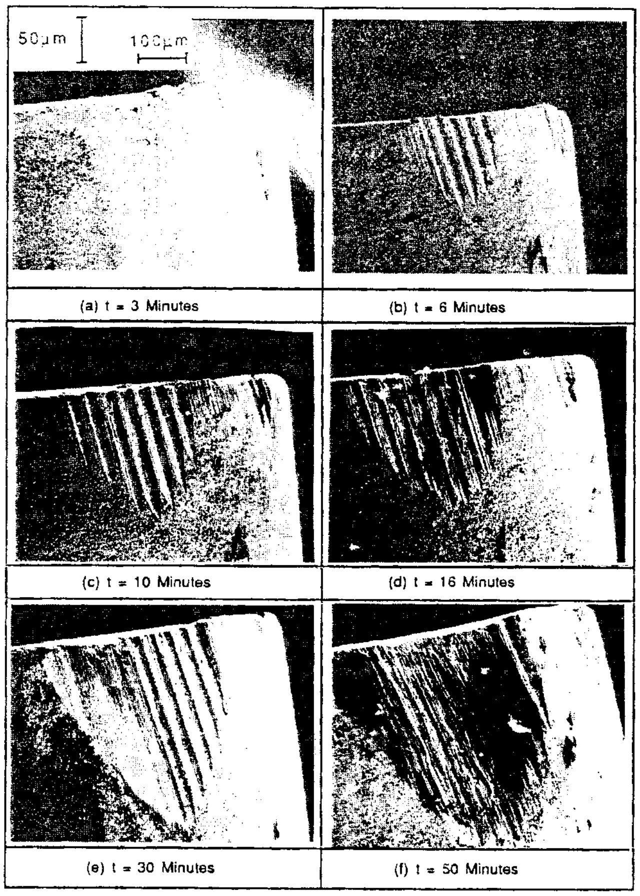


Fig. 3 Groove Wear in the Minor Cutting Edge for Group B
(V = 500 rpm, f = 0.04 mm/rev, d = 0.25 mm)

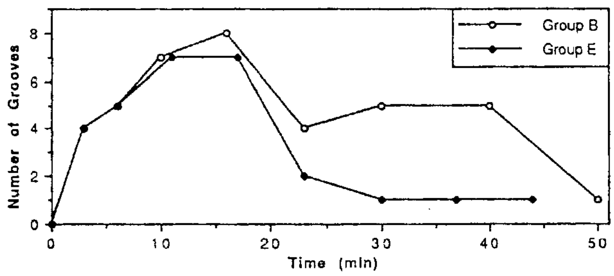


Fig. 4 The Number of Grooves (feed = 0.04 mm/rev)

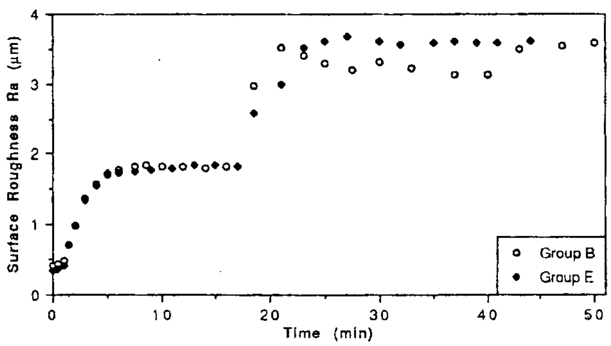


Fig. 5 The Development of Surface Roughness (feed = 0.04 mm/rev)

3. MULTIVARIATE TIME SERIES MODELLING

3.1 Establishment of Autoregressive Vector Model

Multivariate time series models were developed as a way of quantifying the dynamic interaclations among the vibration data recorded in three orthogonal directions. The advantage of employing such a technique is that it provides a model decomposition of the system dynamics convolved in the data. The resulting discrete series of the 3-D vibration signals, sampled at uniform intervals, can be represented either in the form of vector difference equations, i.e., an ARMAV model (n,m) with autoregressive order n and moving average order m (Eq. 1), or the explicit Green function with process residuals (Eq. 2).

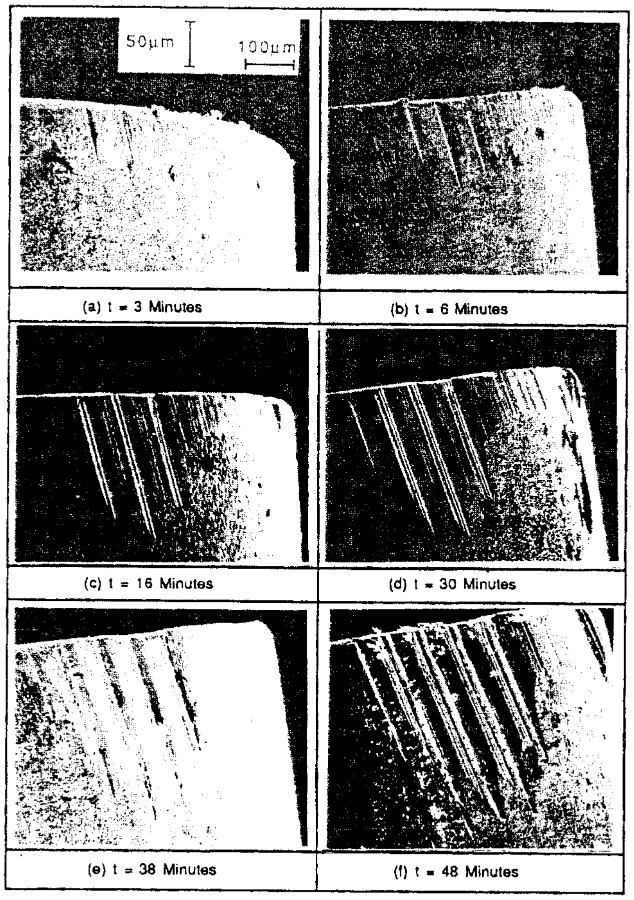


Fig. 6 Groove Wear in the Minor Cutting Edge for Group A
(V = 500 rpm, f = 0.08 mm/rev, d = 0.25 mm)

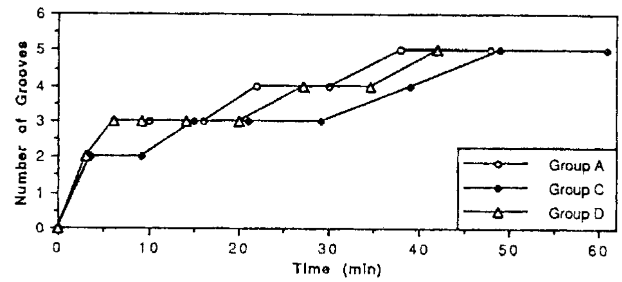


Fig. 7 The Number of Grooves (feed = 0.08 mm/rev)

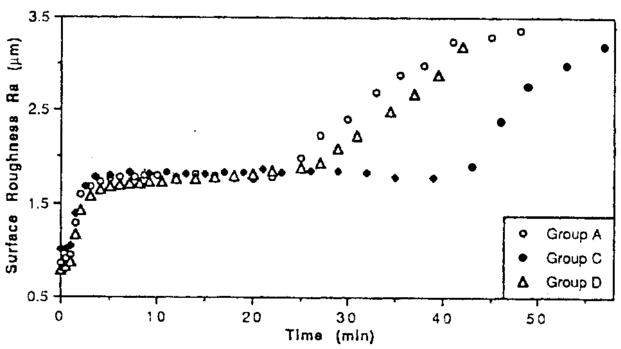


Fig. 8 The Development of Surface Roughness (feed = 0.08 mm/rev)

$$X_t = \sum_{k=1}^{n} \Phi_k X_{t-k} + a_t - \sum_{k=1}^{m} \theta_k a_{t-k} \tag{1}$$

$$X_t = \sum_{k=0}^{\infty} G_k a_{t-k} \tag{2}$$

It can be shown that an ARMAV(n,m) model can be approximated by an ARV(n) model if the order is selected sufficiently high [21]. An ARV(n) model requires much less computationally, and is thus more suitable for on-line purposes. A trivariate ARV(n) model takes the following form.

$$X_t = \sum_{k=1}^{n} \Phi_k X_{t-k} + a_t \tag{3}$$

where $X_t = \left(X_{1t}, X_{2t}, X_{3t} \right)^T$,

$$\Phi_k = \begin{pmatrix} \Phi_{11k} & \Phi_{12k} & \Phi_{13k} \\ \Phi_{21k} & \Phi_{22k} & \Phi_{23k} \\ \Phi_{31k} & \Phi_{32k} & \Phi_{33k} \end{pmatrix}, \text{ and } a_t = \left(a_{1t}, a_{2t}, a_{3t} \right)^T .$$

Such a model expresses the observed trivariate series, $X_{1t} = V_{xt}$ = vibration in the feed direction, $X_{2t} = V_{yt}$ = vibration in the thrust direction, and $X_{3t} = V_{zt}$ = vibration in the main cutting direction, as linear combinations of past observation vectors X_{t-k} (k=1, 2, ..., n) plus an independent random vector a_t and therefore describes the instantaneous dynamics of the cutting process.

3.2 Multiple Dispersion Analysis

Dispersion analysis has been shown to be an effective means to single out particular ingredients of interest from a signal, such as identifying chatter and estimate more than one type of tool wear, i.e., major flank, crater and minor wear [6, 23, 24]. However, the formation of groove wear is much more complicated, involving the mechanism of complex interactions among all three dimensional vibrations. Therefore, multiple dispersion analysis is introduced to quantitatively analyze not only the contribution of individual variables but also the interactions among different variables. Using the explicit Green function of Eq. 2, the vector auto-covariance matrix γ_o can be determined as follows :

$$\gamma_o = E\{X_t . X_t^T\} = \sum_{k=0}^{\infty} G_k . \sigma_a^2 . \overline{G}_k^T \tag{4}$$

where σ_a^2 is the residual matrix. It has been shown that the explicit Green function can be obtained from the established ARV(n) model under the assumption of distinct eigenvalues [22].

$$G_k = \sum_{i=1}^{n} T_i \lambda_i^{k+n-1} U^{-1} U_i T_i^{-1} \tag{5}$$

and

$$U = \prod_{i,j=1 \,\&\, i>j}^{n} (\lambda_i - \lambda_j) \tag{6}$$

$$U_i = (-1)^i \prod_{i,j=1 \,\&\, i>j \,\&\, i,j\neq k}^{n} (\lambda_i - \lambda_j) \tag{7}$$

The eigenvalue matrices $\lambda_i = \text{diag}[\lambda_{xi}, \lambda_{yi}, \lambda_{zi}]$ and eigenvector matrix T_i , i=1, ..., n, are found by adjoining the parameter matrices Φ_k's of the ARV(n) model, and we finally derive the following form of the equation for a symmetric vector auto-covariance matrix γ_o.

$$\gamma_o = \begin{bmatrix} \gamma_{oxx} & \gamma_{oxy} & \gamma_{oxz} \\ & \gamma_{oyy} & \gamma_{oyz} \\ & & \gamma_{ozz} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n}\sum_{j=i}^{n} D_{ixxj} & \sum_{i=1}^{n}\sum_{j=1}^{n} D_{ixyj} & \sum_{i=1}^{n}\sum_{j=1}^{n} D_{ixzj} \\ & \sum_{i=1}^{n}\sum_{j=i}^{n} D_{iyyj} & \sum_{i=1}^{n}\sum_{j=1}^{n} D_{iyzj} \\ & & \sum_{i=1}^{n}\sum_{j=i}^{n} D_{izzj} \end{bmatrix} \tag{8}$$

In this way, the vector auto-covariance of the whole process is decomposed into the contributions of process eigenvalues as well as the complex interactions among various eigenvalues in terms of multiple dispersion D_{ixxj}, D_{ixyj}, etc.

Of specific interest are the multiple dispersions corresponding to the complex eigenvalues which reflect the oscillating characteristics of the machining process. The characteristic frequency (f_n) as well as the damping ratio (ζ) corresponding to a pair of underdamped complex conjugate roots (λ_1 and λ_2) can be determined by the following equations [21] :

$$f_n \text{ (Hz)} = \frac{1}{2\pi\Delta} \sqrt{\frac{\left[\ln(\lambda_1 \lambda_2)\right]^2}{4} + \left[\cos^{-1}\left(\frac{\lambda_1 + \lambda_2}{2\sqrt{\lambda_1 \lambda_2}}\right)\right]^2} \tag{9}$$

$$\zeta = \sqrt{\frac{\left[\ln(\lambda_1 \lambda_2)\right]^2}{\left[\ln(\lambda_1 \lambda_2)\right]^2 + 4\left[\cos^{-1}\left(\frac{\lambda_1 + \lambda_2}{2\sqrt{\lambda_1 \lambda_2}}\right)\right]^2}} \tag{10}$$

4. A CRITERION FOR CRITICAL GROOVE WEAR DETECTION

Shown in Fig. 9 is a representative set of raw vibration signals at the three typical stages of tool wear, e.g., initial-steady-severe stage. The signals are normalized within the range of -1 to 1 for the purpose of comparison. The vibration at the initial stage is slightly higher than that at the steady stage due to the running-in period of a fresh tool. Although the signal at the severe stage has increased, more detailed analysis is required to understand the vibration and formulate a more realistic yet reliable criterion.

The vibration signal was modelled as a stochastic ARV(n) model using the procedure outlined in the last section and the results of dispersion analysis were plotted in Figs. 10-12.

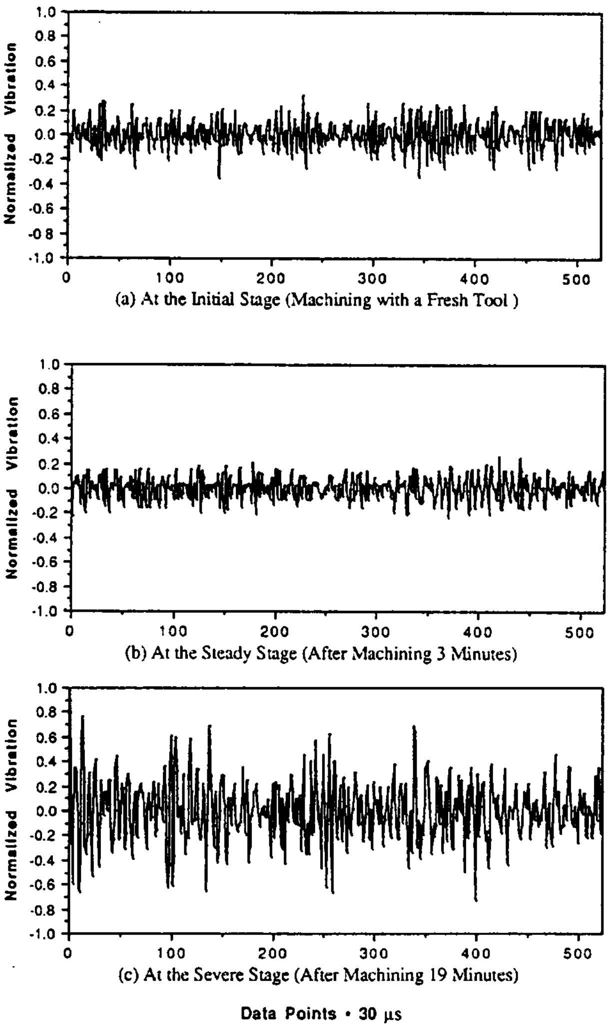


Fig. 9 Vibration (Thrust Direction) at the Different Stages of Groove Wear
Group B : V = 500 rpm, f = 0.04 mm/rev, d = 0.25 mm

In the high frequency range, two clear patterns of multiple dispersion related to the development of groove wear were found. One is the dispersion in the thrust direction (D_{yy}) at around 9.3 KHz and another is that in the main cutting direction (D_{zz}) at around 2.5 KHz. It was found that when the the number of grooves was decreasing from about 16 to 23 minutes (see Fig. 4), these dispersions (D_{yy} and D_{zz}) reached their maximum value, signifying the severe vibration happening under these frequencies. For the damping ratio, it can be seen that the lowest damping ratio is always associated with the highest dispersion, reflecting the severity of the vibration caused by the wipe-out of groove wear.

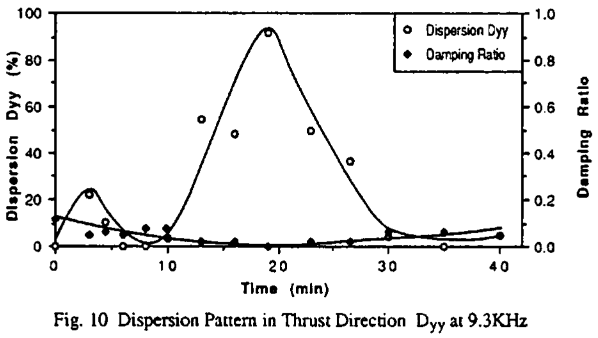


Fig. 10 Dispersion Pattern in Thrust Direction D_{yy} at 9.3KHz

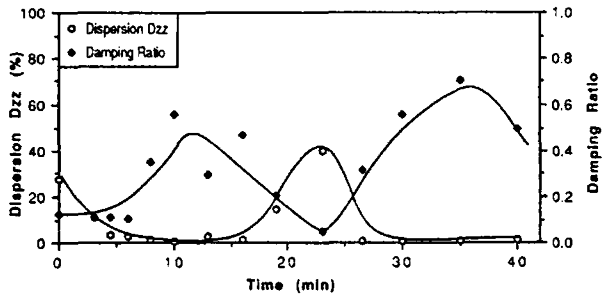


Fig. 11 Dispersion Pattern in Main Cutting Direction D_{zz} at 2.5KHz

In the low frequency range, there exists a particular pattern of cross-dispersion between the vibrations in the thrust direction at 150Hz and the main cutting direction at 145Hz (D_{yz}), as shown in Fig. 12. The moment at which D_{yz} reaches its top value, also coincides with that when the number of grooves decreases and the roughness deteriorates rapidly. If one compares the times of peek dispersions (Figs. 10-12), it is seen that D_{yy} occurred at about 19 minutes and D_{zz} and D_{yz} at about 22 minutes. This may indicate that vibration is first induced in the thrust direction which disturbs the regular grooves formed. The disturbed minor cutting edge in turn excites vibration in the main cutting direction. Therefore, the following criterion can be established: the peak value of D_{yy} indicates the starting of groove wipe-out, while that of D_{zz} and D_{yz} the ending of groove wipe-out. This criterion can be used in finish-machining to determine the necessity of tool replacement. The physical intepretation of the criterion is given in the next section.

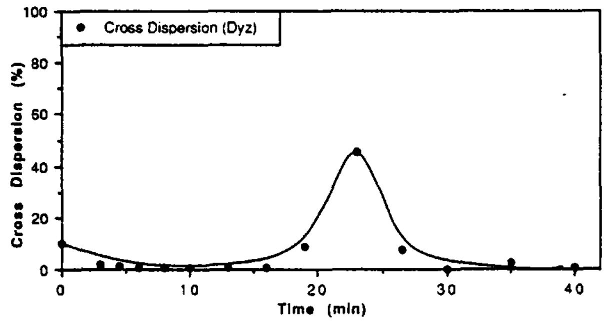


Fig. 12 Cross Dispersion Pattern (D_{yz}) at Fy=150Hz and Fz=145Hz

5 PHYSICAL INTERPRETATION AND DISCUSSION

As observed in the experiments as well as revealed in the analysis above, the vibration resulting in the "wipe-out" of grooves is extremely complicated in terms of both direction and frequency. It is this complication that causes the discrepancy between theory and practice, that is, the minor cutting edge with grooves being wiped out should theoretically give a better surface, while in practice the surface is so badly disturbed by vibration marks that the tool must be replaced. It was conjectured before the experiments that the vibration occurs primarily in the thrust direction for the following two reasons: 1) the surface is badly disturbed by vibration marks, and 2) vibration in the feed direction improves surface quality instead of worsening it [13,16]. The conjecture was fully confirmed in the experiments. No significant changes were observed for vibration in the feed direction, while the vibration characteristics in the thrust direction changed significantly at the critical point. Noticeable changes were also observed in the main cutting direction. Therefore, it seems more appropriate to say that the grooves are "chiseled out" primarily by the vibration in the thrust direction instead of being "wiped out" by that in the feed direction.

Attention has been concentrated on the vibration changes in the thrust direction. It was conjectured before the experiments that this vibration, the relative displacement between the workpiece and the tool tip in the radial direction, is a compound effect of the workpiece lateral dynamics and the tool/tool holder dynamics. This conjecture was again fully confirmed by the dispersion analysis results based on the stochastic model developed from the experimental data directly. It was shown in the last section that the dispersions of the thrust vibration at about 150 Hz and 9,300 Hz reached their peaks, respectively, with the higher one dominant, when the number of grooves began to decrease, that is, the surface roughness began to deteriorate rapidly. These frequencies, as expected, correspond to the natural frequencies of the workpiece and tool/holder assembly, which were determined to be around 155 Hz and 9,340 Hz, respectively, by using conventional excitation tests (Table 2). These close agreements may indicate that, when a sufficient number of grooves have been formed, the dynamics of the cutting process is excited, so that more severe vibration with the characteristic frequencies is induced. Similar results were obtained in the dispersion analysis of vibration in the main cutting direction (Table 2).

Table 2 Comparison between Dispersion Analysis Results and Physical Quantities

	Peak Frequencies detected by using the Dispersion Analysis when the number of grooves began to decrease		Natural Frequencies of Mode 1 (determined by using conventional excitation tests)	
			Workpiece	Tool/ Holder Assembly
Thrust Direction	150 Hz	9,300 Hz	155 Hz	9,340 Hz
Main Cutting Direction	145 Hz	2,500 Hz	155 Hz	2,610 Hz

Comparing the groove wear development patterns between the lower feed groups and higher feed groups, it is noticed that, in the case where grooves are formed, the lower feed condition did not produce better surface finish, while giving rise to earlier vibration than the higher feed condition.

6 CONCLUDING REMARKS

1. The purpose of this work is to investigate the relationships between off-line measurements of groove wear and multiple dispersion analysis based on the 3-D vibration signal in finish-machining, such that the latter alone will be capable of predicting groove wear on-line.

2. Dispersion analysis of the vibration in the thrust direction, complemented by that in the main cutting direction, is proven to be effective in detecting the critical point at which the grooves are being chiseled, surface roughness is deteriorating rapidly, and the finishing tool is to be replaced. The criterion derived from the dispersion analysis is based on the frequencies which can be physically interpreted. Although these frequencies may vary for different workpiece geometry, and tool/tool holder assembly, they are not difficult to determine.

3. There were no characteristic changes observed from vibration in the feed direction. This agrees with the results reported elsewhere that an added vibration in the feed direction will improve the surface finish. This also indicates that the grooves are more "chiseled out" than "wiped out".

4. The groove wear in the minor cutting edge may occur during finish-machining under a fairly wide range of cutting conditions for the commonly-used cutting tool and work materials. Should grooves be formed, vibration occurring sooner or later may significantly shorten the finishing-tool life. Therefore, the detecting method presented in this paper may in future prove to be essential for quality assurance in automated finish-machining.

ACKNOWLEDGEMENT

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REFERENCES

1. Tlusty, J., "A Critical Review of Sensors for Unmanned Machining", Annals of the CIRP, Vol. 32/2, 1983, pp 563-572.
2. Toenshoff, H.K., et. al., "Developments and Trends in Monitoring and Control of Machining Processes", Annals of the CIRP, Vol. 37/2, 1988, pp 611-622.
3. Lister, P.M. and Barror, G., "Tool Condition Monitoring Systems", Proc. of 26th Int. MTDR Conf., 1986, pp 271-288.
4. Monostori, L., "Signal Processing and Decision Making in Machine Tool Monitoring Systems", Proc. of 16th NAMRC, 1988, pp 277-284.
5. Shiraishi, M., "Scope of In-process Measurement, Monitoring and Control Techniques in Machining Processes--Part 1 : In-process Techniques for Tools", Precision Engineering, Vol. 10/4, 1988, pp 179-189.
6. Yao, Y., Fang, X.D., and Arndt, G., "Comprehensive Tool Wear Estimation in Finish-Machining via Multivariate Time-Series Analysis of 3-D Cutting Forces", Annals of the CIRP, Vol.39/1, 1990, pp 57-60.
7. Pekelharing, A.J. and Schuermann, R.A., "Wear of Carbide Tools - its effect of surface finish and dimensional accuracy", The Tool Engineer, October, 1953, pp. 51-57.
8. Hovenkamp, L.H. and Van Emden, E. "Some Remarks Regrading the Wear on the flank of Carbide Cutting Tools", Microtecnic, Vol. 7, No. 3, 1953, p117.
9. Albrecht, P., "An Explanation of the Formation of Groove Wear on Cutting Tools", Microtecnic, Vol. 10, No. 3, 1953, pp. 145-148.
10. Shaw, M.C. and Dirke, O., "On the Wear of Cutting Tools", Microtecnic, Vol. 10, 1956, p187.
11. Solaja, V., "Wear of Carbide Tools and Surface Finish Generated in Finish Turning of Steel", Wear, Vol. 2, 1958/1959, pp. 40-58.
12. Pekelharing, A.J., "Finish Turning", Annals of the CIRP, Vol. 8, 1959, pp. 112-120.
13. Lambert, B.H., "Two Years of Finish-Turning Research at the Technological University, Delft", Annals of the CIRP, Vol. 10, 1961-1962, pp. 246-255.
14. Pekelharing, A.J., "Some Special Aspects of Carbide Tool Wear", International Production Engineering Research Conference, (Pittsburgh, 1963) New York, ASME, 1963.
15. Shaw, M.C. and Crowell, J.A., "Finish Machining", Annals of the CIRP, Vol. 13, 1965, pp. 5-22.
16. Pekelharing, A.J. and Hovinga, H.J., "Wear at the End Cutting Edge of Carbide Tools in Finish and Rough Turning", Proc. of 8th Int. MTDR Conf., 1967, pp. 643-651.
17. Tuininga, E.J., "Wear and Oxidation Phenomena on the End Cutting Edge of Carbide Turning Tools", Annals of the CIRP, Vol. 14, 1967, pp. 449-463.
18. Pekelharing, A.J. and Gieszen, C.A., "Material Side Flow in Finish Turning", Annals of the CIRP, Vol. 20/1, 1971, pp. 21-22.
19. Hoglund, U. "Cutting Edge Wear in Microscale Physical Conditions - Wear Processes", Annals of the CIRP, Vol. 25, 1976, pp. 99-103.
20. Pekeharing, A.J., and Van Luttervelt, C.A., CIRP Terminology and Procedures for Turning Research.
21. Pandit, S.M. and Wu, S.M., Time Series and System Analysis with Applications, John Wiley, 1983.
22. Pandit, S.M., "Data Dependent Systems : Modeling Analysis and Optimal Control via Time Series", PhD Thesis, University of Wisconsin, Madison, WI, U.S.A., 1973.
23. Eman, K. and Wu, S.M., "A Feasibility Study of On-Line Identification of Chatter in Turning Operations", J. of Eng. for Ind., Trans. of the ASME, Vol. 102, Nov., 1980, pp. 315-321.
24. Yao, Y., Fang, X.D. and Rudziejewski, R., "Analysis of Dynamic Components of 3-D Cutting Forces in Oblique Machining", Proc. of 5th Int. Conf. on Manuf. Eng., Wollongong, Australia, July 1990, pp 349-353.