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Dynamic effects influencing drill wear monitoring

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DYNAMIC EFFECTS INFLUENCING DRILL WEAR MONITORING

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Abstract: Tool wear monitoring is economically very important but technically a rather demanding task. In this paper an attempt is made to get further understanding of the dynamics that influence the drilling process and especially what happens when a drill is worn. A very simplified approach is tested in the development of the cutting forces and modeling the influence of wear in these forces. The developed horizontal forces are used for excitation of a simplified one degree of freedom model of the drill. The dynamic model is used for producing vibration velocity signal as a function of drill wear. Using this signal the most typical and widely used signal analysis techniques are tested. The signal analysis data produced with the developed simplified model shows similar trends as data measured in laboratory tests and can be considered useful in the development of an automatic diagnosis program for drill wear monitoring.

Key Words: Tool wear; Drilling; Monitoring methods; Signal analysis; Dynamic model; Cutting force

Introduction: Tool wear monitoring is important due to a number of reasons such us: Unmanned production is only possible when machine tools are equipped with a reliable tool wear monitoring system. Tool wear influences the quality of surface finish of the products produced and thus, if unnoticed, can cause high costs. The economical tool life can not be benefited from without tool wear monitoring. Unfortunately tool wear monitoring is a very difficult task. There are methods available that monitor the tool directly i.e. measure the tool wear but these methods are not practical enough to be used outside laboratories. Indirect monitoring methods such as measurement of cutting forces or vibration are technically demanding to be used. Reference [1] gives a summary of the indirect monitoring methods that have been used for drill wear monitoring. Feed force and torque measurements have been widely used in laboratory tests but it could be claimed that they are not methods practical enough for everyday use, especially if they are measured between the tool and the spindle. If measured from the table the measuring points are located further away from the point where the forces are initiated, and consequently these measuring points do not give as reliable results. Vibration monitoring is one of the most widely used methods which according to the literature survey [1] and reported tests [2] has proved to work well in practice. In this paper a simplified simulation model is developed in order to gain further understanding how horizontal forces and vibration could be used for drill wear monitoring. It is also hoped that the simplified model could serve as a testing and training tool when automated diagnostic tools such as fuzzy logic, neural networks or rule based expert systems are developed.

Cutting force model: In theory drilling does not induce horizontal forces i.e. forces that are perpendicular to the drill axis, if the drill has two cutting lips because these two lips cancel the influence of each other. In practice horizontal forces exist and they can be measured, and also due to these forces horizontal vibration occurs. There are a number of reasons for these forces: The drill geometry is not perfect i.e. the cutting lips do not have exactly similar geometry and consequently forces are induced, the work piece material is never exactly homogeneous causing some horizontal force components, the drilling process does not take place exactly perpendicular to the surface of the work piece. When the drill is worn the two cutting lips do not wear exactly to the same extent causing some unbalance of forces which can vary from side to side depending on which cutting lip has worn more [3]. When the drill starts to vibrate because of the reasons described above, and also due to forces that are induced to the drill from the spindle, the vibration causes horizontal movement resulting in unbalance in the horizontal forces and further vibration. The proposed model tries to take into account all the above named factors. However, the model does not try to predict the exact drill forces nor the unbalance in horizontal direction, but instead it merely tries to show the influence of various factors so that the force predicted and the vibration velocity calculated with the model would have the characteristics of those forces and vibrations measured in laboratory tests.

The first component in the drilling force model is a factor that takes into account the discontinuous nature of the drilling process i.e. always when a new hole is drilled the forces start from zero see e.g. reference [4]. This process can be described mathematically in a simplified form with the following feed force function:

$$F_{dh}(t) = (t - i \cdot t_d)/(t_d/b_l) \qquad \text{if} \qquad i \cdot t_d \leq t < i \cdot t_d + t_d/b_l \tag{1}$$

$$F_{dh}(t) = 1 \qquad \text{if} \qquad i \cdot t_d + t_d/b_l \leq t \leq i \cdot t_d + t_d \tag{2}$$

Where t is time, i is a counter for the hole number, t_d is the time it takes to drill one hole and b_l is a coefficient which defines the relation of the increasing part and the stable part of the thrust force. Figure 1 shows the simulated feed force when t_d is 4 seconds and altogether 15 holes are drilled. It should be noted that all the forces i.e. torque and horizontal forces can be expected to perform similarly.

The second step in the development of a simulation model is to introduce the actual drilling force models. Based on a series of drilling tests the following relations in drilling cast iron have been observed [5]:

$$\text{torque } (M) = a_1 \cdot H_B \cdot d^2 \cdot f + a_2 \cdot H_B \cdot d^2 \cdot r + a_3 \cdot H_B \cdot d^2 \cdot w \tag{3}$$

$$\text{thrust } (T) = a_4 \cdot H_B \cdot d \cdot f + a_5 \cdot H_B \cdot d \cdot w + a_6 \cdot H_B \cdot d \cdot r + a_7 \cdot H_B \cdot d^2 \tag{4}$$

where H_B is Brinell hardness of work material, d is diameter of the drill, f is feed per revolution, w is average flank wear, r is radius at the cutting edge and a_1 ... a_7 are constants. The use of the above formulas enables the scaling of force defined in formulas 1 and 2. In the above relationships there is a strong dependency on work piece hardness which actually means that tool life varies remarkably as a function of this [5]. Consequently, cutting of a few random work pieces of high hardness may influence the drill life much more than a large number of work pieces of low hardness. Hence, in an industrial operation, drills may fail very early or after a long time, depending on the occurrence of these few work pieces of high hardness. This could explain the large variation in drill life observed in industrial conditions. Since the purpose in the development of a simulation model really is to be able to see the influence of wear in the measured signals, it can be concluded from the above formulas that it is logical to develop an approach where part of the forces is a function of wear, and part is not, and that both parts strongly depend on the drill diameter and hardness of the material. Another possible way to calculate the drilling forces would be the kind of approach developed by Chandrasekharan [4] and used by Yang et. al. [6] where drilling forces are calculated based on the geometry of the drill and results from turning tests which define the necessary parameters for the approach. In this kind of approach the cutting lips are divided into a number of sections where the forces are calculated and then integrated. However, since the purpose of this study is not to define the exact forces that could be measured, it is easier and much faster to use a statistical approach for scaling the forces so that the effect of work piece material and cutting conditions can be taken into account.

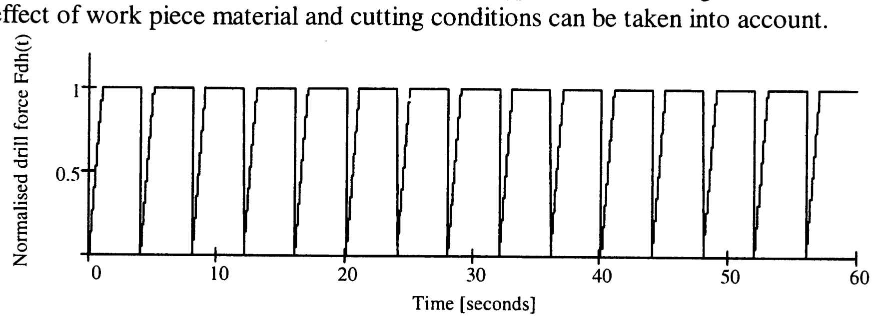

Figure 1. Simulated feed force in drilling.

In the developed approach it is assumed that there are a number of reasons for horizontal forces to appear in drilling. In theory these forces do not exist because typically there are two cutting lips in drills. However, according to the tests and various references [1] horizontal forces can rather well be used for drill wear monitoring. Possible reasons that can cause unbalance in these forces are e.g. geometrical differences between the two cutting lips and differences in the wear of the two cutting lips. In fact, it can be assumed that if there are differences in the beginning due to geometrical errors, there will be differences in wear of the two cutting lips since the forces, which are the cause of wear, are different. Following formulas have been developed in order to take into account the difference of the forces of the two cutting lips:

$$F_{rpm1}(t) := F_{dp}(t)\cdot\left(c_1 - c_2\cdot\ln\left(1-\frac{t}{t_c}\right)\right)\cdot\cos\left(2\cdot\pi\cdot\omega\cdot t + \phi_{ge} + \phi_{wd}\cdot\sin\left(\omega\cdot\frac{t}{c_3}\right)\right) \tag{5}$$

$$F_{rpm2}(t) := F_{dp}(t)\cdot\left(c_1 - c_2\cdot\ln\left(1-\frac{t}{t_c}\right)\right)\cdot\cos\left[2\cdot\pi\cdot\omega\cdot t + \pi\cdot\left(1 + \phi_{wd}\cdot\sin\left(\omega\cdot\frac{t}{c_4}\right)\right)\right] \tag{6}$$

where $c_1 \ldots c_4$ are constants, t_c is the total lifetime of the drill, ω is the angular speed of rotation, ϕ_{ge} is the angular geometrical error due to the tolerance in manufacturing the drills, ϕ_{wd} is the difference in wear of the two cutting lips of the drill and F_{dp} drilling process force that scales the size of the forces. The random variation of wear from one cutting lip to another is taken care of by varying the phase between the cutting forces i.e. the effect of the difference between the two constants c_3 and c_4. The use of a logarithmic wear function is based on the use of very simplified wear model which tries to describe progressive wear [7]. In this kind of case wear rate increases as the forces increase and since the forces are initiated by the wear this is an accelerating process. The drilling process force F_{dp} can e.g. be calculated based on equations 3 and 4 so that it would take into account the change of drilling parameters i.e. feed and also the hardness of the drilled material. Since the simulation model that is developed here is used for the purposes of development of tool wear monitoring and it is not supposed to predict the horizontal forces physically correctly, the effect of the tool diameter and radius at the cutting edge can be neglected as these are not variables for a specific drill that is monitored. Based on the above the following equation is used for drilling process force:

$$F_{dp} = c_5 \cdot H_B \cdot f \cdot F_{dh} \tag{7}$$

where c_5 is a constant, H_B is the Brinell hardness of the work piece material, f is feed per revolution and F_{dh} is calculated according to equations 1 and 2.

In the vibration velocity signal of most rotating machines, vibration amplitudes at the harmonics of rotating speed can be seen. There are a number of reasons for this i.e. if the vibration is distorted in the sense that it is not sinusoidal, Fast Fourier Transform (FFT) produces these harmonics and also there are quite a number of possible excitations at these frequencies such as bearing frequencies and those excited by the driving engine which most often is an electrical motor. In the developed approach a number of excitation forces at the harmonic frequencies of the rotating speed are assumed to exist. These are defined by the following summary function which defines harmonic components starting from the 3^{rd} and reaching to the 11^{th} harmonic force component:

$$F_{nrpm}(t) := \sum_{n=3}^{11} \left[F_{dp}(t) \cdot \left(\frac{c6}{n} - \frac{c7}{n} \cdot \ln\left(1 - \frac{t}{t_c}\right)\right) \cdot \cos(n \cdot 2 \cdot \pi \cdot \omega \cdot t) \right] \tag{8}$$

where c6 and c7 are constants, n defines the order of the harmonic component, $F_{dp}(t)$, ω and t_c as defined above.

Another typical factor that is always present in vibration measurements is the noise of the signal i.e. random fluctuation of the measured signal. Also in the case of noise there are a number of reasons for it, some of which originate from the measured machinery due to random excitation which could be caused by many sorts of reasons such as movement of the machinery or some other machine. In the cutting process the cutting fluid is one source, and also chip flow causes random vibration. The electrical measuring equipment is also a source of random fluctuation in the measured signal. In order to make the simulation model to provide more natural signals, a random component is also introduced to the calculation of the excitation force. The random force is defined by following formula:

$$F_{rnd}(t) = rnd(c_8) - c_8/2 \tag{9}$$

where c_8 is a constant and rnd denotes the MathCad program function [9] that produces an equally distributed random number between 0 and c_8.

When the drill starts to vibrate during the drilling process one consequence from this is that the cutting lips do not cut a round hole and as a result of that the horizontal forces are not in equilibrium [6]. Because the drill together with the tool holder basically vibrates like a beam that is only supported from one end it can be expected that vibration at the first natural frequency of that structure is rather pronounced. Following from this it is logical to introduce a horizontal force into the dynamic model that gives excitation to the model at the natural frequency:

$$F_o(t) := \cos(2\cdot\pi\cdot f_o\cdot t)\cdot F_{dp}(t)\cdot\left(c_9 - c_{10}\cdot\ln\left(1 - \frac{t}{t_c}\right)\right) \tag{10}$$

where c9 and c10 are constants, t_c total tool life time, drilling force F_{dp} as defined above and f_o is the first natural frequency of the drill and tool holder calculated with the following formula [8]:

$$f_o := \frac{1}{2\cdot\pi}\cdot\sqrt{\frac{k}{m}} \tag{11}$$

where m is the mass of the drill and tool holder, and k is the stiffness of the structure. It should be noted that although the above formula is very simple it is not easy to define the natural frequency exactly without measuring it. In the following analyses the mass m = 1.4 kg and the stiffness k = 395 N/mm have been chosen to be the same as used in reference [6] for a d = 15.9 mm drill.

It could also be assumed that due the inhomogeneous nature of the work piece horizontal forces would be seen. These are not modeled separately, instead it is assumed that a static force acting for some tenths of seconds into one direction would mainly induce vibration at the natural frequency of the drill and tool holder. This kind of source is taken care of by equation 10 and also partly by the random excitation defined by equation 9. In fact in reference [6] inhomogeneous work piece material is considered the main source of initial excitation and is induced to the model as a randomly acting force. The assumptions as described above apply also to the effect that is caused by the fact that drilling does not in practice start exactly perpendicular against the work piece surface i.e. it is assumed that equations 9 and 10 take care of this effect, too. Naturally it could be even argued that this geometrical error might in many cases be very small and consequently also the forces would be very small.

The final step in the development of the excitation force in the simulation model is to add together all the five components which have been introduced above. This can be done simply by calculating the sum of all the five components:

$$F_x(t) = F_{rpm1}(t) + F_{rpm2}(t) + F_{nrpm}(t) + F_{rnd}(t) + F_o(t) \tag{12}$$

Since the developed model is not physically exact i.e. it is assumed that the force components that have been presented above do exist in reality but it would be very difficult to calculate the exact size of each force, and instead of exact solution the model tries to bring out the features that can be seen in drill wear monitoring. Therefore the features of the calculated force sum function fully depend on the chosen parameters. It should be noted that in theory it would also be possible to try to approach the problem in a more precise way i.e. trying to look for the actual physical solution. In such a case one possible approach would be similar to the one that has been developed in reference [6]. The approach chosen by Yang et. al. follows the principles developed by Chandrasekharan [4]. In the approach the cutting lips of a drill have been studied in a number of sections, typically 50 sections and for each one of these the different force components have been calculated based on tests in oblique cutting. In principle it would be possible to introduce wear into such a model by looking at each individual section and by saving the history of the cutting process in each section so that when the forces get higher the probability of wear would get higher, and using a random function the material loss would be described. Naturally this kind of a solution would not really have an equivalent case in reality but statically this kind of a model could be adjusted to correspond to measured values in laboratory. The other force components that have been introduced above i.e. harmonic components and a random component could be with some accuracy defined based on laboratory tests. The influence of vibration could then be defined using a similar approach as has been used by Yang et. al. [6] where the actual cutting path influences the drilling forces. The approach suggested in reference [6] could be further developed if instead of two degrees of freedom a higher number would be used e.g. using finite element method (FEM). However, the purpose of this study is to show that even with a relatively simple approach with proper choice of parameters the typical features of vibration velocity signal can be seen. The sum force function calculated using equation 12 with the following values of constants $c1 = 20$, $c2 = 400$, $c3 = 2$, $c4 = 1.7$, $c6 = 0.04$, $c7 = 0.08$, $c8 = 0.5$, $c9 = 0.02$ and $c10 = 0.04$ and also assuming $F_{dp}= 0.102$ (equation 7) is shown in Figure 2 for the first hole and in Figure 3 for the last hole. In the example the total life time of the drill is defined to be 15 holes i.e. total tool life is 60 seconds when it takes 4 seconds to drill one hole. The signals shown in Figures 2 and 3 are supposed to show the development of the horizontal drilling forces in the sense that in the beginning the time signal of the force seems to be rather noisy and no one frequency component stands out of the others. Towards the end of the life of the drill the forces get bigger and the influence of the defined frequencies such as speed of rotation can be seen.

Dynamic model: The development of the dynamic model follows the principles used by Yang et al. in reference [6]. It is assumed that the drill and the tool holder can be modeled like a beam that is rigidly supported at one end and the excitation force influences at the other end. In the above mentioned reference [6] two degrees of freedom have been studied basically because of the development of a dynamic model for the drilling force based on the influence of vibration to the shape of the hole which becomes distorted if compared to the theoretically round shape. In this study only one degree of freedom is studied since the excitation force is supposed to take into account the above described phenomenon. The simplified dynamic model can then be described with the following differential equation [8]:

$$mx'' + cx' + kx = F_X(t) \tag{13}$$

where m is the mass of the vibrating tool and tool holder, c is damping, k the stiffness and Fx(t) the dynamic horizontal drilling force defined in the previous chapter. The forced vibration differential equation can be solved using Runge-Kutta method [8]. In the analysis MathCad program package has been used for calculation of the vibration response [9]. Figure 4 shows the excitation force and vibration displacement for the modeled tool life time of 60 seconds. In order to make Figure 4 clearer vibration displacement curve has been moved from above the force by adding five to the response and subtracting five from the force values so that the curves do not coincide each other.

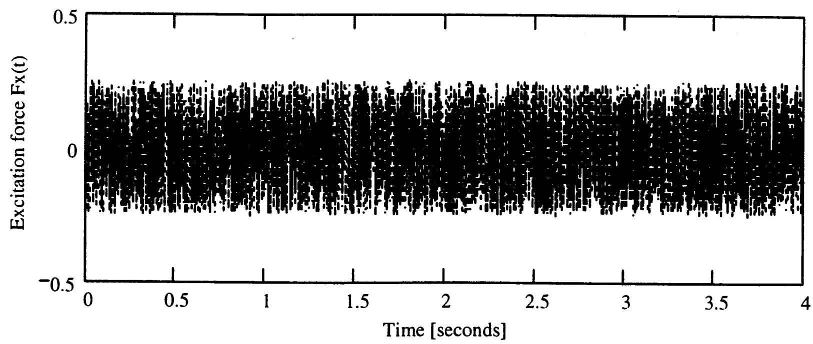

Figure 2. Excitation force in the beginning of the simulation.

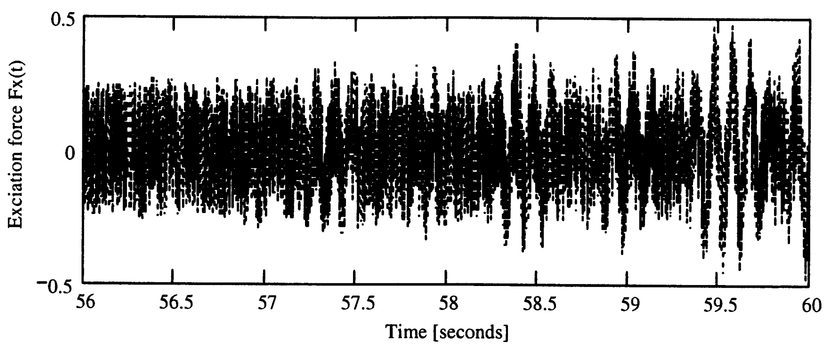

Figure 3. Excitation force in the end of the simulation.

Signal analysis: Reference [1] gives a summary of the signal analysis methods that have been used for drill wear monitoring. Most of the references that have been reviewed use statistical parameters such as root mean square (rms) value in analyzing the time domain signal. Figure 5 shows the development of such statistical parameters as rms and maximum value of simulated horizontal vibration velocity as a function of time for the total tool life time. (It should be noted that for this kind of a simulated signal, the rms value and the standard deviation value is actually the same.) The parameters have been calculated using a time constant of 0.05 seconds. The constants and parameters values have been the same as in the previous chapters for the development of the excitation force. In reference [2] it is reported that such statistical parameters as rms, mean deviation and maximum where the best statistical parameters in the analysis of the best measuring signal i.e. horizontal vibration. The reported findings correspond very well with the trends seen in Figure 5 with simulated data.

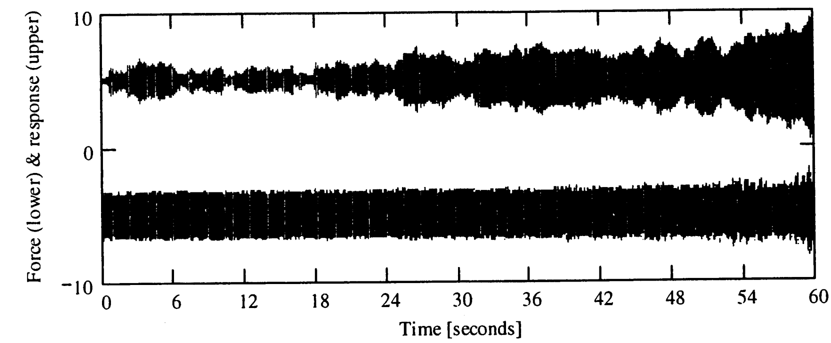

Figure 4. Excitation force from equation 12 (lower curve) and response (upper curve).

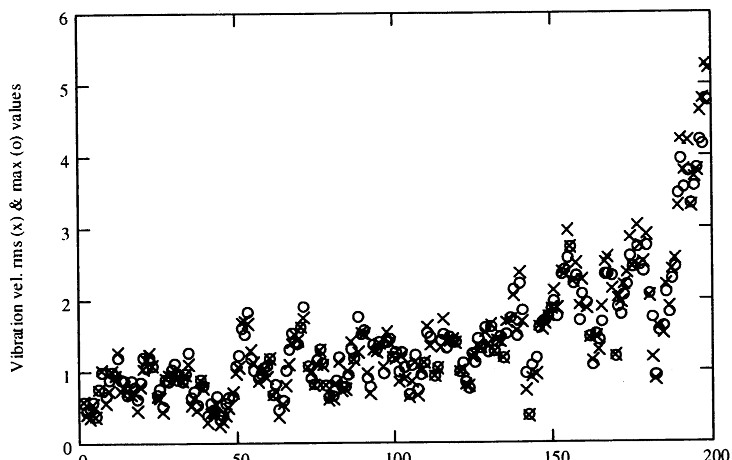

Figure 5. Simulated statistical vibration parameters as a function of drill wear (time).

Figure 6 shows the corresponding statistical parameters from laboratory tests reported in reference [2]. Although there are remarkable differences between laboratory tests and simulation the trend is very similar. The biggest difference is that in simulation there is not much difference whether normalized rms or maximum value is used but in laboratory tests there is more variation in the maximum value i.e. the process is not as stable as has been defined in simulation. However, it should be remembered that there is much more variation when the laboratory test results of individual drills are compared with each other. The life time of drills varies a lot and also the increase of the normalized statistical parameters during the lifetime of the tool varies remarkably. Based on the above it can be suggested that the simulation model can be used e.g. in the development and testing of expert systems for drill wear monitoring.

An other signal analysis method that has been widely used is the Fast Fourier Transform (FFT). Figure 7 shows the waterfall presentation of a simulated vibration velocity spectrum in the frequency range from 0 – 150 Hz. The FFT analysis has been done using the same constant and parameter values as in the case of statistical signal analysis. In spectrum analysis hanning window has been used and the number of points has been 2000 and in the analysis the shown logarithmic spectrums represent the average of three spectrums calculated with 50% overlap. In Figure 7 the drill wear can be seen rather clearly. This result again corresponds to the reported result in reference [2] i.e. more sophisticated analysis functions show the development of tool wear more clearly than just statistical parameters. However, it should be noted that with such analysis functions like FFT it is important to know at which frequencies the amplitudes should be followed.

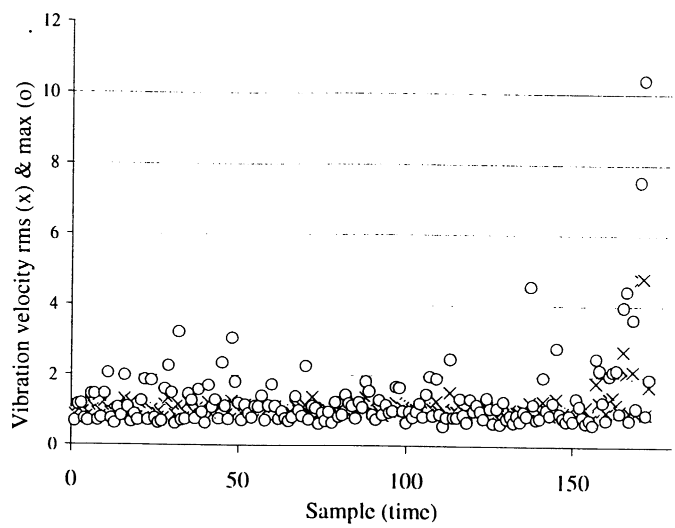

Figure 6. Statistical vibration parameters from laboratory tests.

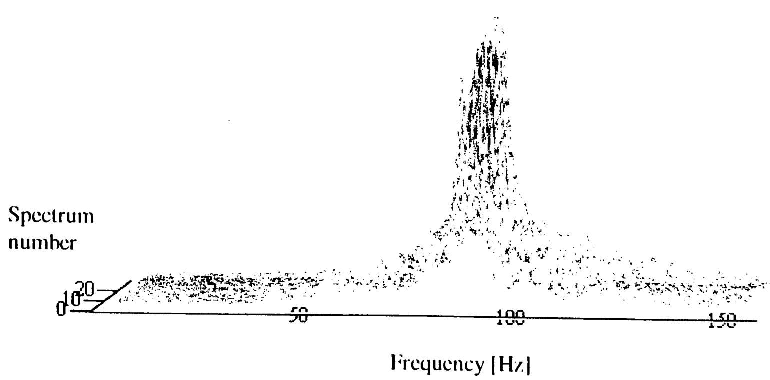

Figure 7. Waterfall presentation of frequency spectrum showing the influence of wear.

In this simulation the indication of drill wear can be seen at the excitation frequencies i.e. multiples of rotational speed and the first natural vibration of the drill and tool holder. In order for a tool wear monitoring system to work it should have the capability of calculating these frequencies and following the amplitude trend at these specific frequencies.

Conclusion: Tool wear monitoring is economically very important but technically a rather demanding task. In this paper an attempt has been made in order to reach further understanding of the dynamics that influence the drilling process and especially what happens when a drill is worn. A very simplified approach has been tested in the development of the cutting forces and modeling the influence of wear in these forces. Such factors as geometrical difference of the cutting lips, different kind of wear history of the lips, vibration at first natural frequency and excitation at harmonics of the speed of rotation have been taken into account in the development of the excitation force. The developed forces have been used for excitation of a simplified one degree of freedom model of the drill. The dynamic model has been used for producing vibration velocity signal as a function of drill wear and with this signal the most typical and widely used signal analysis techniques i.e. statistical time domain parameters and spectrum analysis have been tested. The signal analysis data produced with the developed simplified model shows similar trends as data measured in laboratory tests and can be considered useful in the development of an automatic diagnosis program for drill wear monitoring.

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