MEASUREMENT AND ANALYSIS OF CHATTER IN A COMPLIANT MODEL OF A DRILLSTRING EQUIPPED WITH A PDC BIT

M. A. Elsayed
Mechanical Engineering Dept.
University of Southwestern Louisiana, Lafayette, LA
David W. Raymond
Sandia National Laboratories, Albuquerque, NM

ABSTRACT

Typical Laboratory testing of Polychrystalline Diamond Compact (PDC) bits is performed on relatively rigid setups. Even in hard rock, PDC bits exhibit reasonable life using such testing schemes. Unfortunately, field experience indicates otherwise. In this paper, we show that introducing compliance in testing setups, provides better simulation of actual field conditions. Using such a scheme, we show that chatter can be severe even in softer rock, such as sandstone, and very destructive to the cutters in hard rock, such as sierra white granite.

INTRODUCTION

Chatter in PDC bits has gained a great deal of attention recently. This is caused by the recognition that the primary mode of failure of PDC cutters in hard rock is that of catastrophic failure caused by impact loading. Typically this mode of failure takes place in advance of any appreciable wear that may dictate cutter replacement. Since chatter is a phenomenon in which the drillstring becomes unstable and excessive sustained vibrations ensue, it is considered one of the primary suspects in this mode of failure. A great deal of theoretical work has been performed in an effort to understand this phenomenon as it applies to PDC bits [see for example Elsayed et al., 1997] . Many of the concepts were borrowed from the metal cutting industry, where chatter has been recognized and studied for decades. The problem as it applies to PDC bits drilling in rock is more difficult to analyze. For a theory to be tested on a machine tool, one goes to the laboratory and uses a similar machine for that purpose. Should the test require changes, it is a simple matter to do so. The basic dynamics of the machine is the same, and any changes can be made relatively quickly. On the other hand, a drillstring changes its dynamic characteristics as drilling gets deeper. Should a change in bit or in drillstring configuration is required, the whole length must be extracted before any changes can be made. Moreover, rock properties are different than those of metal. One of the complicating factors is that rock is less homogeneous than metal.

Due to the difficulties expressed above, laboratory testing must be configured in such a way as to approximate field drilling conditions as much as possible. One major area is the compliance of the drilling setup. Typically laboratory rigs are stiff. Tests to evaluate cutter wear and bit performance are generally performed with limited chatter. This chatter takes place at higher frequencies than those experienced in the field [Elsayed, 1999]. In this work, this situation was addressed by adding compliance to the drilling apparatus as discussed below. Drilling tests were performed where the weight-on-bit (WOB), rate of penetration (ROP), rotational speed, and vibration characteristics are measured. The testing procedure and analysis of the results are presented in the following sections.

DISCLAIMER

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EXPERIMENTAL SETUP

To be representative of field-drilling conditions, the range of parameters used in the experimental setup must reflect conditions which a PDC bit might typically experience. Weight-on-bit, rotary speed, and the fundamental frequencies of the drillstring are important parameters in the experimental design. The WOB applied to the test fixture should result in individual cutter penetrating forces characteristic of what PDC cutters are subjected to in the field. In a drillstring, the WOB is less than the static weight of the drillstring. For this reason, the maximum WOB applied in our tests has an upper bound corresponding to the effective mass of the test fixture's drillstring. The rotary speed should range from low-end values where stick-slip occurs to maximum values which produce tangential speeds on the test bit comparable to those experienced by gage cutters on full-scale bits. The rotary speed range should traverse the fundamental frequencies of the drillstring to allow investigation of chatter effects at these transition speeds. The frequency of longitudinal vibration of the experimental setup should be as low as possible since in deep drilling natural frequencies of a drillstring can be very low (say 0.3 Hz) [Elsayed, 1996]. However, since it is important to analyze chatter behavior close to the natural frequencies of the system, the experimental setup is designed to make the fundamental frequencies of the test fixture as low as possible. Using this approach, chatter effects observed at this frequency are representative of the system characteristics at frequencies which may be encontered in the field.

Drilling tests were conducted in a laboratory-based drill rig at Sandia National Laboratories shown in figure (1). The setup consists of a drillstring supported by a stiffened beam within a structural steel frame. The drillstring is restricted to vertical movement by guide shafts. A fixed-displacement hydraulic motor rotates the drillstring and hydraulic cylinders allow application of axial load to the drillstring. Proportional valves control the motion of the hydraulic cylinders. A thrust bearing housing supporting the drillstring is pin-connected to the stiffened beam to de-couple bending moments and only transmits thrust to the drillstring. A rock cube (3x3x3 ft) is positioned on the base plate of the frame and can be indexed with respect to the bit by an internal air caster allowing multiple holes to be drilled in a single rock sample. A 3.25-inch PDC bit was used as shown in Fig. (2). It incorporates three, half-inch diameter PDC cutters in a coring configuration. The bit was designed using the computer code PDCWEAR [Glowka, 1989] with the cutters geometrically distributed to balance the static rock cutting forces. Water is used as a drilling fluid and is circulated through the bit.

The setup is typically used for PDC bit wear investigations, and hence referred to as the Cutter Wear Testing facility (CWTF), was modified for the present work. A set of springs was added to the CWTF between the hydraulic cylinders and the stiffened beam to introduce compliance in the axial direction as shown in Fig. (3). This configuration produces a spring-mass system simulating field conditions of a drillstring. The fixture allows a variety of spring combinations to be used resulting in translational frequencies in the 1-6 Hz range.

The CWTF is controlled through a central computer, which also records pertinent data. Recorded data include WOB, torque, RPM, drillstring position and acceleration, left and right cylinder positions, and left and right spring-suite compression. Weight-on-bit is measured using the differential pressure across the hydraulic cylinders. A centrally positioned displacement transducer (CPDT) is used to monitor the drillstring's position with respect to the frame. An accelerometer is mounted at the centerline on the drillstring support fixture. Additional accelerometers were used on the spring support beams of the compliance fixture to characterize its modal response.

EXPERIMENTAL APPROACH

Using a roving accelerometer and an impact hammer, modal testing was conducted to characterize the frequency response of the drillstring and its compliant support. As planned in our experimental design, the fundamental mode corresponds to axial translation of the drillstring at approximately 6 Hz. However, subsequent modes at higher frequencies at approximately 10, 12 and 16 Hz are associated with several "rocking" modes in the stiffened beam supporting the drillstring. These rocking modes can also result in axial translation of the drillstring as the center of rotation often occurs at either end of the stiffened beam. This multi-mode system allowed us to observe some effects of similar modal frequencies that are also characteristic of field drillstrings. The displacement transducer on the drillstring centerline (CPDT) provides a response, which is a direct measure of vibration amplitude at the centerline. This was used in our analysis of chatter and to discern the position of the cutters in relationship to the rock.

Drilling tests were conducted in two rock types. Berea Sandstone, a soft formation typically encountered in oil and gas formations, was used first to allow the modifications of the rig to be evaluated under moderate operating conditions. Subsequent testing was conducted in Sierra White Granite, a hard, abrasive rock typical of geothermal reservoirs. Tests consisted of drilling a series of holes at constant weight-on-bit and constant rotary speed and recording drilling parameters for post-test analysis. However, vibration caused a great deal of fluctuations in the WOB, and hence the WOB values reported are time averages recorded once the "average" WOB was relatively stable. The rate of penetration of the drillstring, and hence WOB, is controlled by the position of a spool within the proportional valves which control the motion of the hydraulic cylinders. A control voltage sent to the proportional valves determines the location of the spool and hence the operating characteristics of the hydraulic cylinders. Accordingly, we developed calibration charts for the WOB as a function of proportional valve control voltage for drilling in the two rock types. With this calibration, we operated the proportional valves at a constant voltage corresponding to the target WOB. This allowed us to conduct our testing at an average value of the target WOB without regard to its fluctuations. Generally, the drilling procedure consisted of rotating the drillstring at the desired RPM, stabilizing the PDC bit within the rock and increasing the WOB to the target value based upon the voltage calibration. A five-second data interval was captured at a sampling frequency of 500 Hz at each operating condition. In sandstone, data was collected at target weight-on-bit values of 500, 1000, and 1500 Lb. at rotary speeds of 60, 100, 140, 180, 200, 220, 240, and 260 RPM. WOB values greater than 1500 Lb. were not tested in sandstone as these resulted in penetration rates that were too large for the available rig stroke and data recording time.

The former approach to stabilize the bit was inappropriate in Sierra White Granite due to PDC bulk cutter failure resulting from impact loading at high RPM. Hence, a modified procedure was adopted consisting of stabilizing the bit in the rock at low RPM, increasing the voltage to that corresponding to the target WOB, and then increasing the rotary speed to the desired level. In Sierra White Granite, data was collected at WOB of 750, 1500, and 2500 Lb. and at rotary speeds of 60, 100, 140, 180, 200, 220, 240, and 260 RPM. Weight-on-bit values above 2500 Lb. were not addressed as this corresponds to the weight of our drillstring fixture. In both rock types, the PDC cutters were inspected after each hole to ensure they remained in a sharp, unworn condition. (Future investigations will include the influence of PDC cutter wear on chatter.) The drillstring was also inspected before each subsequent hole to ensure that rock core was extracted.

ANALYSIS OF RESULTS

A- Sandstone

A typical plot of the displacement at the drillstring's axis as measured by the Center Position Displacement Transducer (CPDT) for a low WOB (500 Lb.) is given in Fig. (4) and for a high WOB (1000 Lb.) is in Fig. (5). The slope of the trend line of these plots is used to calculate the ROP. The ROP is plotted against speed for different values of WOB is given in Fig. (6). The lowest speed used for each WOB was limited by the "stick-slip" behavior of the system caused primarily by excessive process damping [Elsayed et al., 1994, Tlusty, 1978]. The ROP was in turn used to calculate the cutter feed (in/rev), sometimes referred to as the depth-of-cut (DOC). In order to obtain a measure of vibration amplitude at the drillstring's centerline, FFT analysis is performed on the CPDT time data. Typical results are shown in Figs. (7) and (8). These plots correspond to the time data in Figs. (M4) and (M5) for 500 and 1000 Lb. WOB respectively. The average power spectral density (PSD) in the 1 to 20 Hz range is plotted in Fig. (9). Doubling the amplitude at the dominant frequency gives a measure of the peak-to-peak value of longitudinal vibration in the drillstring. A comparison of the peak-to-peak value with the DOC reveals the position of the cutter at peak motion in relationship to the rock surface. This was used to determine whether the cutter moved out of the cut or remained below the rock surface during each test. This data was used to plot Fig. (10). In this figure, we see that certain combinations of speed and WOB produce high enough chatter amplitudes for the cutters to move above the rock surface. In these tests, this was more likely to occur at low WOB. At high WOB, higher out-of-cut values generally took place at higher speed. The crossover speed, beyond which the cutter moves above the rock surface at peak oscillation, for a 1000 Lb. WOB is about 160 RPM, and for 1500 Lb. WOB is approximately 250 RPM. This figure shows severe chatter condition (over o.2 in. cutter movement above the rock surface at the highest point in Fig. (10), even in a soft rock commonly encountered in oil and gas drilling such as sandstone. Since sandstone is a soft rock, cutters escaped damage. However, these vibrations are typically transmitted to the drillstring's bottom hole assembly, with subsequent reduction in its survival rate.

An examination of Fig. (9) of the PSD reveals that the energy channeled into longitudinal vibrations is highly dependent on speed and WOB. For a WOB of 500 Lb., the 200 RPM rotational speed represents the most unstable condition in our speed range. On the other hand, at 1000 Lb. WOB the PSD decreases beyond 200 RPM only to increase again at 220 RPM. Similar zigzag behavior is exhibited at the 1500 Lb. This can be explained by examining Figs. (7) and (8). As mentioned above these figures represent the FFT of the CPDT time data at 500 and 1000 Lb. WOB at 200 and 220 RPM respectively. Examination of Fig. (7) for the 500 Lb. WOB reveals a single dominant mode at 6.35 Hz, while Fig. (8) corresponding to 1000 Lb. WOB shows two modes at 7.32 and 10.25 Hz. The 7.32 Hz mode at 1000 Lb. is a longitudinal mode corresponding to the 6.35 Hz mode at 500 Lb. WOB. The 10.25 Hz component appears in the longitudinal direction as a result of an asymmetric rocking mode of the support beam. The stability diagram for a single mode is typically composed of a set of lobes corresponding to this mode. However, when two modes are active, two sets of lobes are superimposed on the top of each other. As the speed is increased for a given WOB, the corresponding stability diagram comes into play. When chatter takes place, the operating condition is above the stability limit. The closer the operating condition to the stability limit, the less the vibration amplitude, and vice-versa. This explains the trend of the PSD curve at 500 Lb. WOB in Fig. (9). The farthest point from the stability lobe is at 200 RPM. Similar approach can be used to explain the behavior of the PSD curve at 1000 Lb. WOB in Fig. (9). The superposition of the lobes corresponding to the two active modes causes the zigzag pattern shown the figure. Since the data showed that high WOB generally tends to excite multiple modes, this trend is also seen in Fig. (9) for the 1500 Lb. WOB, and is expected to continue at higher values of WOB.

In order to illustrate the above correlation between chatter level and degree of instability, a stability diagram for a simplified model of the drillstring and bit was developed. The following assumptions were made in establishing the stability diagram:

a- The stability diagram is based on the active modes at the current WOB and that the frequencies of those modes do not change substantially with speed.
b- Only the dominant modes are included in the stability diagram.
c- Modes are represented by the Real part of their Frequency Response Functions calculated to match the minimum value and frequency at each mode.
d- The bit has three "blades" rather than discrete cutters. The blades are radial and equally spaced.
e- The cutting stiffness of the rock is constant and independent of WOB or speed.
f- Process damping is neglected.

The stability lobes obtained in the 140-260 RPM speed range are represented as "relative instability" with arbitrary units, since the trend is what we are interested in at this time. A superposition of the relative instability lobes on the PSD plots is given in Figs. (11) and (12). Figure (11) represents the 500 Lb. WOB dominated by one mode and shown in Fig. (7). As we can see from Fig. (11), the general trend is for chatter to increase as instability increases. Similar plot is given in Fig. (12) for the 1000 Lb. WOB. Here we have two dominant modes as shown in Fig. (8). Both these two modes come into play. Again, the general trend is for chatter to correlate with instability in a zigzag pattern as shown. The PSD at 140 RPM in Fig. (12) is low due to the high value of process damping at low speeds and high WOB. Process damping was neglected in the stability analysis as indicated in the assumptions above. Attempt should not be made to match the chatter PSD and instability curve point-for-point. One must consider the assumptions listed above and rather look for the general trend between the PSD and instability curves, which is clearly shown in Figs. (11) and (12). Currently work is progressing towards refining our model for a better representation of the bit and drillstring.

A correlation can also be seen between the decrease in chatter amplitude and increase in the ROP by examining Figs. (9) and (6). As the chatter energy drops drastically at the 500 Lb. WOB and 200 RPM in Fig. (9), the ROP increases at a higher rate as seen in Fig. (6). This trend is not as dramatic at the higher values of WOB since chatter energy in those cases was small and its change with speed was not as drastic.

B- Sierra White Granite

Similar tests were conducted in SWG. Chatter was so severe and so destructive to cutters, that the outside cutter, which runs at the highest speed, broke frequently. The design of the bit was such that cutters lacked sufficient support, with the outside one least supported. This placed the cutters in shear, rather than in compression. In order to eliminate the lack of support as a factor in cutter failure, the design of the bit was modified to provide sufficient support for all cutters. Even with the new design, outside cutter failure often occurred. Failure also occurred in the middle cutter and in cutter support wedges. On more than one occasion, the screws holding the bit to the drillstring were sheared due to load fluctuations. A typical cutter failure is shown in Fig. (13). As we can see, failure is catastrophic and caused by the heavy impact encountered under chatter conditions. This bit – with the original design prior to improving cutter support - has performed well during extensive wear testing conducted on the same setup but without the added compliance along the drillstring's axis. The added flexibility however allowed for high chatter amplitudes and increasing impact loads which led to cutter failure. This condition is analogous to actual drilling in hard rock. Under field conditions, bit bounce at the hole bottom is severe, and yet is not easily detected at the surface. This has been proven theoretically using a simulation model of a typical drillstring undergoing instability associated with severe chatter [Elsayed, 1996]. The attenuation of vibration as it travels from the bit to the surface was shown to be substantial.

Figure (14) shows the average PSD in the 1-20 Hz range for Sierra White Granite. As we can see, the trend is similar to that of Sandstone in Fig. (9). This is expected, since this behavior is primarily a function of the system dynamics as explained above. At low WOB=700 Lb., one mode dominates, while at higher WOB values two modes generally play a role. A plot of out-of-cut distance is shown in Fig. (15). Here we observe that at 1500 Lb. WOB, the cutters were out of the cut in all tests. A comparison with Fig. (10) for sandstone shows that at 1500 Lb. WOB, the cutters were within the cut except at the high speed of 260 RPM. The primary reason is that for the same WOB and speed, the DOC is smaller in SWG than in sandstone due to its high cutting stiffness.

CONCLUSIONS

From the above data we see that chatter analysis is best performed on a system whose compliance approximates that of a drillstring. Chatter takes place when using PDC bits even in soft rock such as Sandstone. In hard rock, such as Sierra White Granite, the effect of chatter is so severe that it causes frequent catastrophic failure of the cutters. It was also found that chatter severity correlates to the lack of stability in the system. Chatter causes a deleterious effect to the ROP. Future efforts to control chatter in PDC bits will be of great benefit to not only geothermal, but also oil and gas operations.

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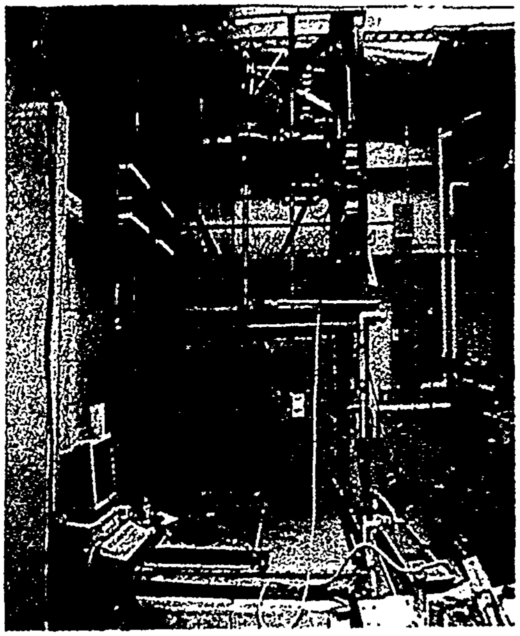

Fig. (1): Cutter Wear Testing Facility (CWTF) As Modified for Chatter Testing

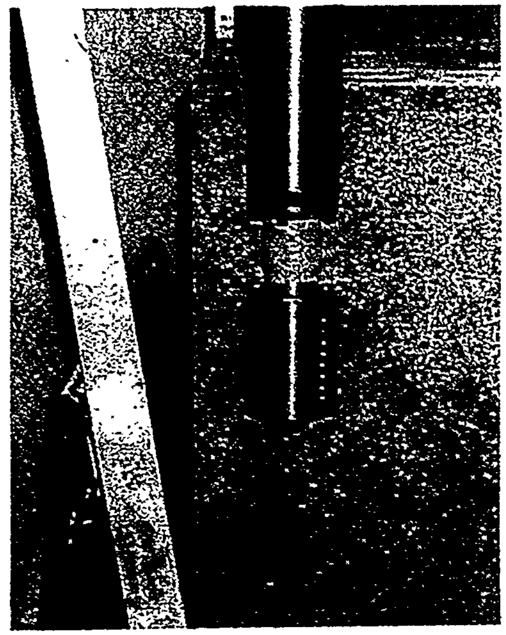

Fig. (2): Three-Cutter PDC Bit

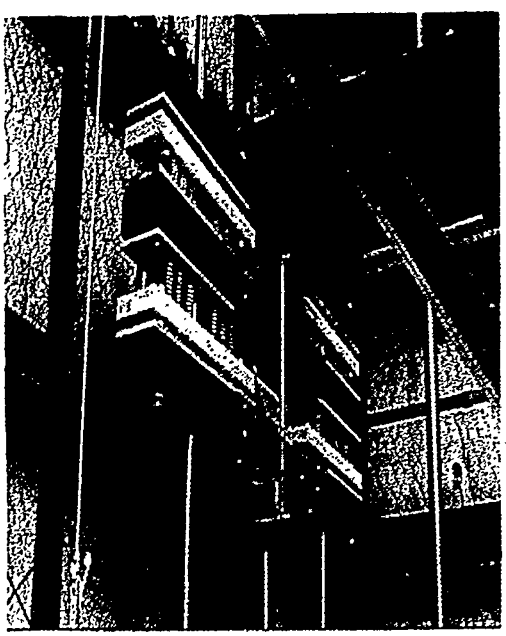

Fig. (3): Compliance Fixture

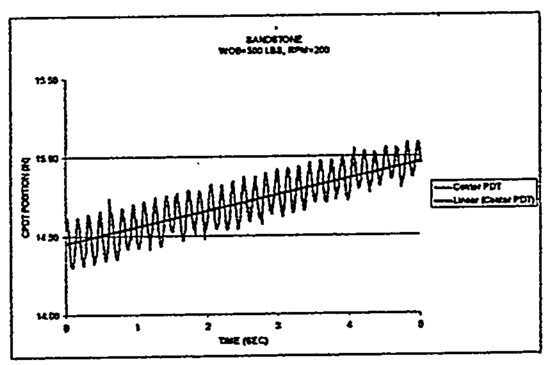

Fig. (4): CPDT Response, Sandstone, WOB=500 Lb., RPM=200

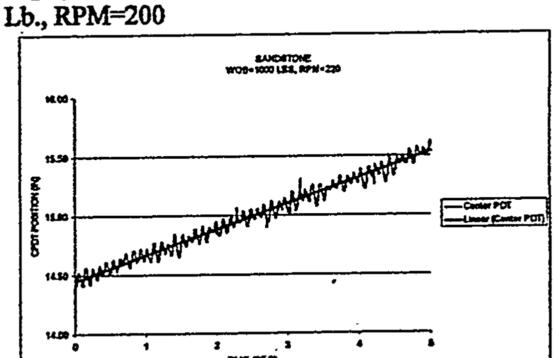

Fig. (5): CPDT Response, Sandstone, WOB=1000 Lb. RPM=220

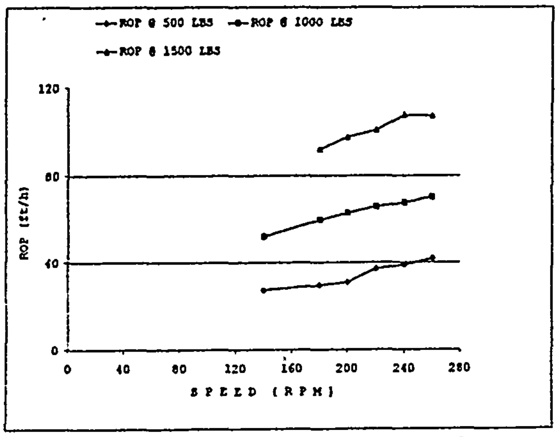

Fig. (6): Variation of ROP with Speed, Sandstone WOB =500 – 1500 Lb.

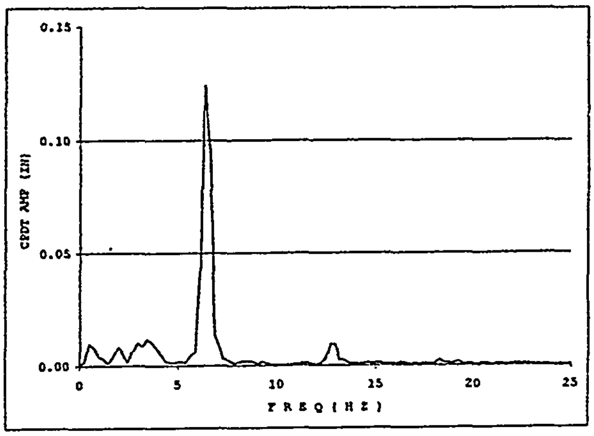

Fig. (7): FFT of the CPDT Response, Sandstone, WOB =500–1500 Lb., RPM=200

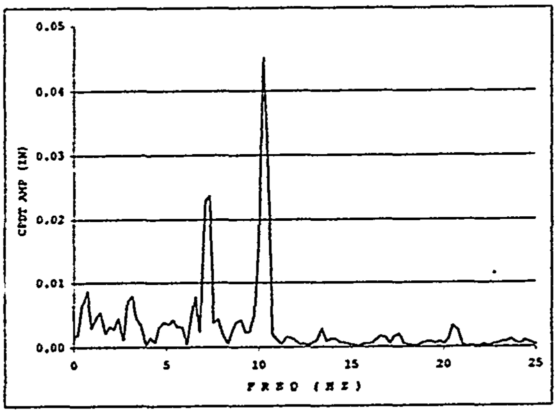

Fig. (8): FFT of the CPDT Response, Sandstone, WOB= 1000 Lb., RPM= 220

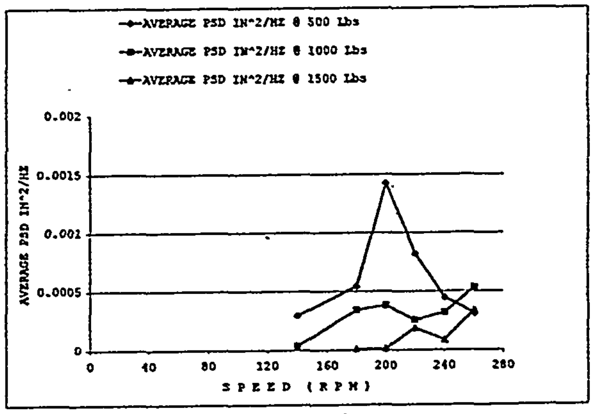

Fig. (9): Average PSD (1-20 Hz), Sandstone, WOB= 500 – 1500 Lb.

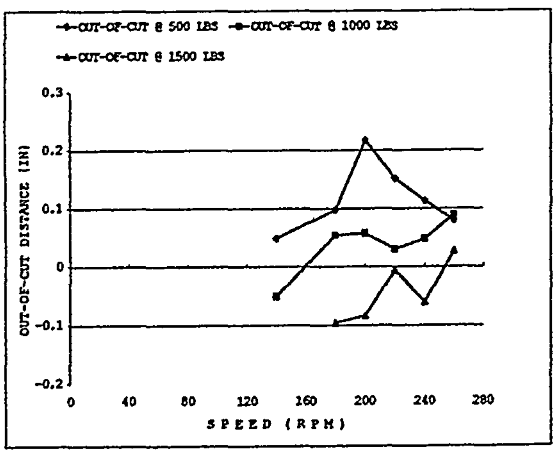

Fig. (10): Out-of-Cut Distance, Sandstone, WOB= 500 – 1500 Lb.

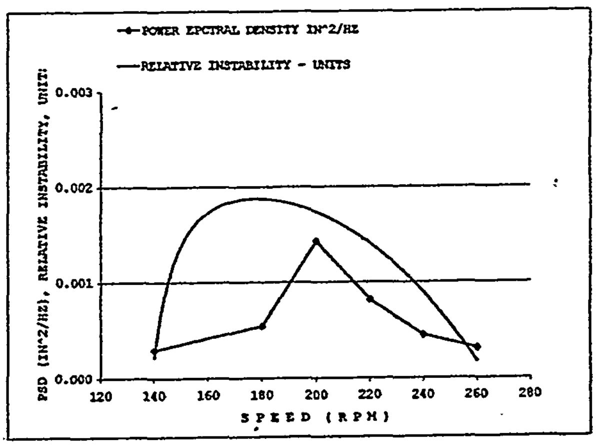

Fig. (11): Correlation Between Severity of Chatter and System Instability, Sandstone, WOB= 500 Lb.

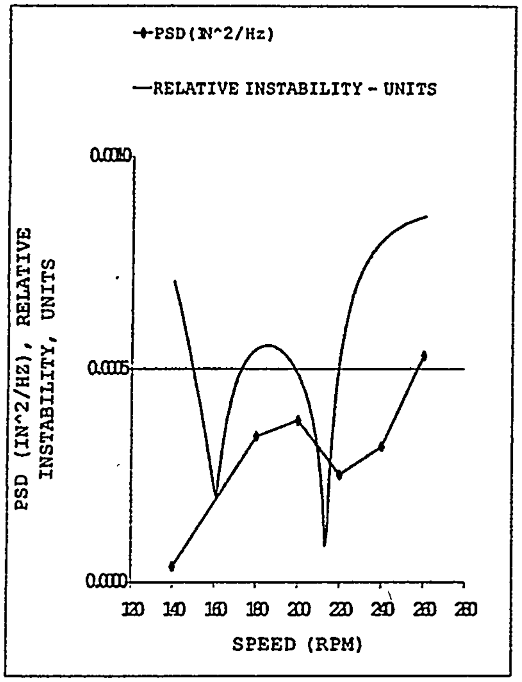

Fig. (12): Correlation Between Severity of Chatter and System Instability, Sandstone, WOB= 1000 Lb.

Fig. (13): Typical Failure of Outside Cutter

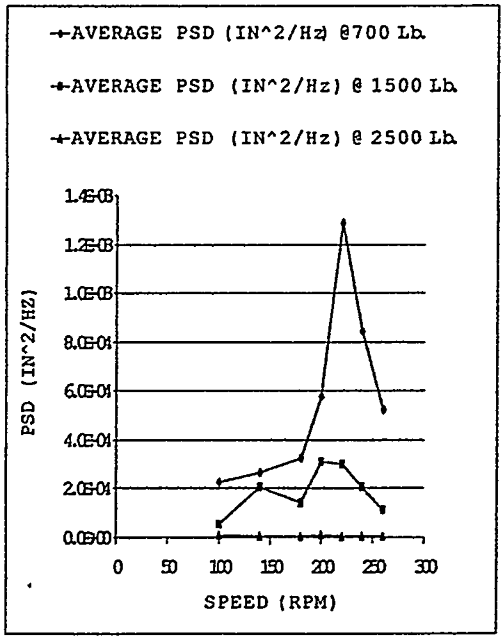

Fig. (14): Average PSD (1-20 Hz), SWG, WOB= 700 – 2500 Lb.

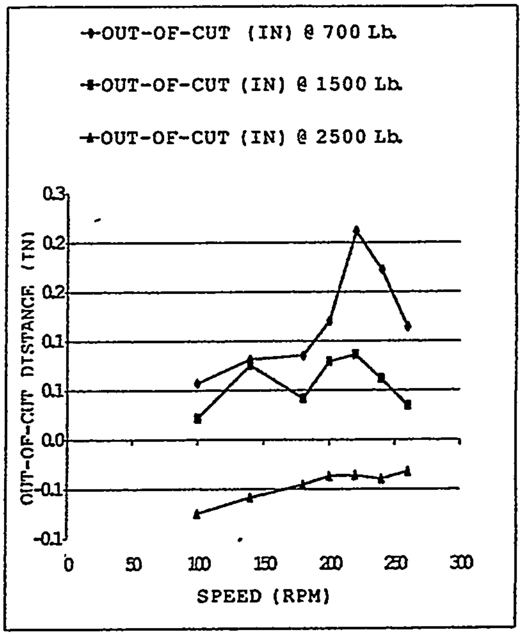

Fig. (15): Out-of-Cut Distance, SWG, WOB= 700 – 2500 Lb.