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Material Transition Detection in Drilling Using Data Analytics

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ABSTRACT: To better detect Wellbore defects it may be desirable to probe or place sensors in a material transition area without breaking all the way through a given material**.** This paper presents the work that has been completed towards the development of an autonomous, small-diameter, precise drilling real-time diagnostic tool to enable sensor emplacement for wellbore integrity monitoring. Test samples composed of Mancos shale, cement, and steel were constructed. Using these test samples drilling force data was collected and analyzed to help aid the automation and understanding of the interactions between the drill and wellbore materials. The data collected demonstrates there is a unique force signature for each given material. Steel, cement, and shale only drilling was performed to better understand the force characteristics of each material and the variability in force between the materials. However, the force data collected while drilling into the shale only material samples yielded inconsistent force data. This data shows that the shale material is highly inhomogeneous, even within a single test sample. Using this data, we used temporal kurtosis and analysis of variance in force data to identify any rapid change in the force data which we hypothesize to be related to the drill transition between materials in real time. The greatest similarity in force between materials has been observed between the shale and the cement. This may make them more difficult to distinguish between. However, there appears to be a noticeable difference between the variance observed in the cement material and the variance observed in the shale material. Analysis of these differences may allow us to better distinguish between cement and shale where temporal kurtosis alone could not.

1. BACKGROUND/INTRODUCTION

Wellbore Integrity is a significant environmental and energy security problem for our nation. An estimated 30% of the 4 Million wells worldwide show signs of integrity failure (Davies et al., 2014). Current industry paradigms for well design include using cement as a barrier with envisioned lifetimes of ~50 years; however, the number of cementing problems which can go undetected can be staggering (Yakimov, 2012) As a result, evaluation, characterization and remediation of wells has become a priority for industry, regulators and the public. A primary challenge of wellbore integrity assessment is that operators rely on a combination of indirect measurements (through casing) and models to assess these very complex systems (wellbore and flaws, see Figure 1). Results are often subjective with large uncertainties.

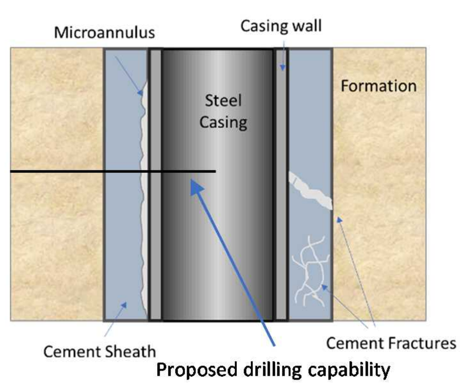

Fig. 1. Schematic of wellbore casing and cement sheath. Common flaws as cement fractures and microannulus are shown.

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We are developing a new capability, deployable through wireline, to drill at depth very small diameter holes through the sidewall of the casing as also shown in Figure 1. These small diameter holes would be drilled into the cement sheath and would enable direct, precise measurements of signatures (pressure, temperature, pH, chemical, void detection) in the cement that indicate potential failures. The drilled hole may subsequently be plugged with a sensor for future monitoring or inert plug that restores the casing's integrity and remains in place for the life of the well. Ongoing work addresses several key challenges to this vision including: the precision drilling of very small deep holes (aspect ratios exceeding 20:1; diameters from ~0.010-0.250in), in remote, confined environments, the characterization of wellbore integrity from novel measurements enabled by these holes, and the permanent emplacement of sensors for long-term monitoring. A significant development to support precise microdrilling is the ability to predict properties and transitions ahead of the drilling. This ability enables optimizing drilling conditions to suit the formation as well as precise placement of the sensor package in a multi-layered medium. Specifically, certain sensing applications may require probing or sensing in the transition region between materials (e.g. between casing and cement or cement and formation), or even to avoid breaking through from one material to the next. Current work is directed toward lab-scale experimentation to gather the force signals from drilling micro-holes and analyze them to determine their usefulness in providing 'look-ahead' capabilities for forecasting material transitions as well as natural and man-made drilling hazards.

Beyond the microdrilling application, the capability to 'look-ahead' while drilling would be useful at other scales. For instance, this would be a foundational step towards the development of fully autonomous well drilling that would be smart enough to automatically adjust drilling parameters accordingly to minimize or avoid problems.

This approach has many advantages over existing methodologies. Methods for direct behind-casing measurement are currently limited to installing fiber optic or electronic sensors during well completion. This is expensive, technically challenging, and risks introducing pathways for fluid to leak along the fiber /cable. Furthermore, this approach applies only to new wellbore installation and does not address the numerous, vulnerable, aging wells built under more lax regulations. The proposed approach runs counter to existing technology by intentionally breaching the casing in a controlled manner to enable precise assessment. While this may appear counter-intuitive and high-risk, if successful it will enable the future development of smarter, effective, remediation techniques/materials that are tailored to the wellbore flaw, reducing risk to the entire well.

Towards this goal, this paper focuses on the data analysis component of the materials that generally compose a wellbore— Mancos shale, cement, and steel. Using a bench top testing set-up to simulate drilling into a wellbore we collect a variety of force drilling data. In our data analysis we perform a novel temporal kurtosis analysis to study the correlation between material transitions in our wellbore and rapid changes in our temporal kurtosis analysis. We also present data analysis examining the differences force drilling data and force drilling data variances in wellbore material compositions and their interactions with drilling. Through the combination of this data analysis we seek to enable a better understanding of the interactions between the drill and these materials to aid the development of an autonomous, small-diameter, precise drilling real-time diagnostic tool, with the hope that this tool can then be used to enable sensor emplacement for long term wellbore integrity monitoring

2. BENCH TOP TESTING SET-UP

To simulate microdrilling into a wellbore casing, a single axis, ball-screw driven drilling tool was designed as a bench top testing system. This system is guided by Hi-Win linear rail guides. It is equipped with a plastic shield for protection while the drill bit is active and an emergency machine off (EMO) switch.

The bench top set-up consists of a Teknic Inc. ClearPath servo motor that acts as a pulse generator and controls the step size and direction of the drill. The ClearPath servo has built in software that then backdoors into a Mach3 CNC machine controller software that acts as the primary software control mechanism for our system. In addition, an Automation Technology NEMA23 stepper motor is used to drive the ball screw, providing linear feed. A Sherline Products lathe head with multi-axis bearings is used as the spindle body for the drill. A Futek bi-axial load cell is mounted to the sample to measure force and torque. The Futek sensor is held by a conventional vertical/horizontal collet index (spindex) tool. The force and torque are extracted from this sensor in combination with the feed rate supplied by the Mach3 software as well as an external LabView application. Data is acquired in real-time via this LabView application and then written to a .tdms file that is later used for data analysis. This set-up is shown in Figure 2.

Fig. 2. Benchtop set-up designed to simulate microdrilling into wellbore casing.

Test samples were constructed to simulate the materials in a wellbore—Mancos shale, cement, and steel. These materials were glued together with epoxy glue. Several test samples were made with the materials listed above in a different order. This was done to better understand the force interaction between the drill and the individual material. An example of a test sample is shown in Figure 3.

Fig. 3. Test sample material "sandwich" used for microdrilling with material in order of steel, cement, shale.

Additional samples were also made of each material separately so that drilling force data could be collected for each individual material.

3. DRILLING DATA ANALYSIS

A variety of different drilling data was collected analyzed using a 1/8-inch drill bit, 1800 RPM, and a 4.5 in/min feed rate. The first set of data consisted of drilling through all three wellbore materials in succession, but in a different order for each test sample. This data shows that there is a unique force signature for each given material (steel, cement, shale) that is independent of the order in which the material is drilled through as shown in Figure 5.

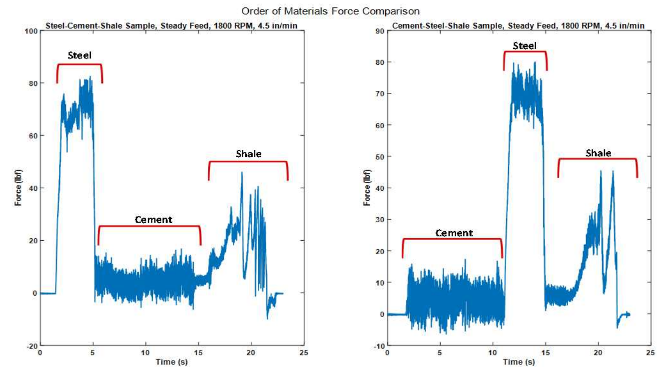

Fig. 5. Unique force signature observed for each material independent of order in which they were drilled.

To further understand the unique force signatures observed in each material, drilling force data was then collected for each of the individual material test samples. This data shown in Figure 6 also supports that each material has a unique force signature. In this figure each subplot is on a different axis to better view the characteristics of the force data.

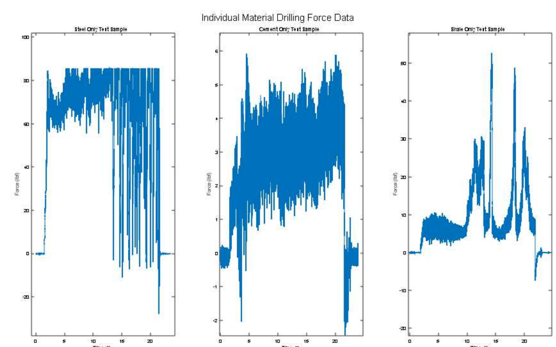

Fig. 6. Individual material drilling force data again showing a unique force signature for each material. Note the scale is different for each subplot.

Throughout data collection both from the multiple material test samples and the individual test samples it was observed that the Mancos shale material has a nonhomogeneous composition that could cause unexpected force variability from sample to sample as shown in Figure 7.

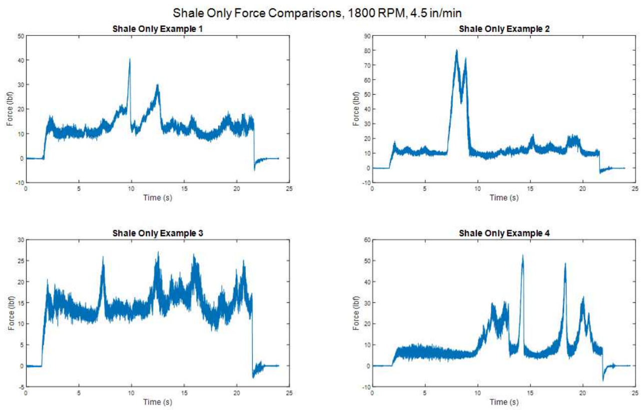

Fig. 7. Nonhomogeneous composition in Mancos shale sample causing unexpected force variability from sample to sample.

Using the data collected on the multiple material test samples we then performed temporal kurtosis analysis. Kurtosis, which is the ratio of the fourth moment to the squared second moment of a given continuous signal (Decarlo, 1997), shows the extreme values of either tail of a distribution and represents the "tailedness" of the distribution (Song and Cha, 2016). Using Temporal Kurtosis, we seek to identify any rapid change in the force data which we hypothesize to be related to the drill transition between materials in real time. To apply Temporal Kurtosis analysis to our data we utilized the equation shown in Eq. 1 below with a finite moving window size of 128. This window size of 128 was determined through an iterative trial and error data analysis process based on what yielded the best visual graphical results.

$$TK = \frac{\frac{1}{N}\ \sum_{i=1}^{N}(\mu_i\ -\ \mu)^4}{(\frac{1}{N}\ \sum_{i=1}^{N}(\mu_i\ -\ \mu)^2)^2} \qquad (1)$$

An example of this Temporal Kurtosis analysis performed on a material "sandwich" is shown in figure 8. It shows there are rapid changes that may be detectable in real time and may help provide a 'look-ahead' ability to identify material transitions prior to or very quickly after drilling has begun.

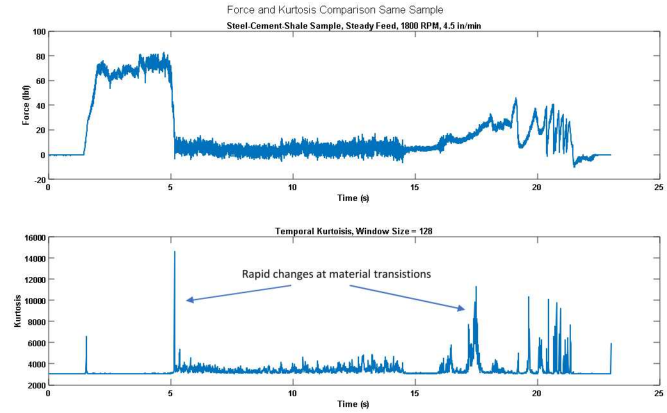

Fig. 8. Temporal kurtosis showing rapid changes in force data which his hypothesized to correspond to the drill transition between material in real time.

An interesting phenomenon observed in Figure 8 is the low level of kurtosis observed around 15 seconds at the transition from cement to shale. One hypothesis for this could be the small amounts of epoxy that were used to glue the different material types together in the bench top drilling simulation set-up. This is a variable introduced in our experiment and would not be observed in a real-world wellbore drilling application. In an effort to better understand this phenomenon, epoxy only test samples were made, and force drilling data was collected. This data collection showed that it is possible that the material interfaces in the material "sandwich" test samples may be affected by the epoxy as shown in Figure 9.

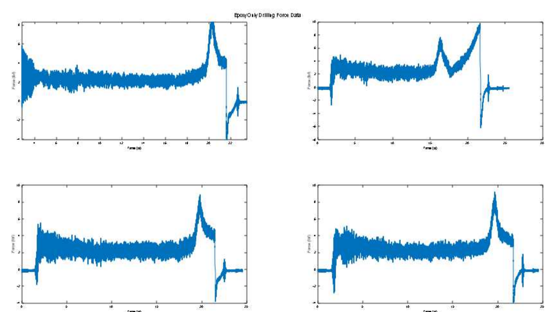

Fig. 9. Epoxy only force drilling data showing a similar force characteristic to that seen in Figure 8 at the interface between the cement and shale materials at around 15 seconds in time.

The greatest similarity in force between materials has been observed in the shale and the cement which may make it more difficult to differentiate between in real time than between that of steel and cement and that of steel and shale. However, there appears to be a noticeable difference between the variance observed in shale force drilling data and the variance observed in the cement force drilling data. To quantify this, temporal variance with a finite moving window size of 512 was performed on 9 shale drilling tests and 9 cement drilling tests and the mean temporal variances for these tests were compared. As with the temporal kurtosis analysis, this window size was determined through an iterative trial and error data analysis process based on what yielded the best overall visual graphical results. These variances are shown in Table 1. These temporal mean variances are consistent with properties previously observed for the given materials.

Table 1. Temporal variance comparisons between individual shale drilling tests and individual cement drilling tests. The maximum and minimum values are highlighted in yellow.

Shale Test #	Temporal Variance	Cement Test #	Temporal Variance
Shale 1	0.5773	Cement 1	0.2278
Shale 2	1.2759	Cement 2	0.2117
Shale 3	1.6078	Cement 3	0.2199
Shale 4	0.9323	Cement 4	0.2326
Shale 5	1.3284	Cement 5	0.2114
Shale 6	1.2656	Cement 6	0.2316
Shale 7	3.6535	Cement 7	0.2186
Shale 8	4.0809	Cement 8	0.2232
Shale 9	0.8130	Cement 9	0.2694

The shale mean temporal variances are much less consistent with a minimum of 0.5773 and a maximum of 4.0809 resulting in a range of 3.5036. In contrast the cement mean temporal variances are nearly constant with a maximum of 0.2694 and a minimum of 0.2114 resulting in a range of 0.0058. This stark contrast between the material's temporal variances again shows the inhomogeneous nature of the shale material versus that of the cement material. Knowledge of this inherent difference in material property between the shale and cement material can be leveraged in future work towards the development of an autonomous, small-diameter, precise drilling real-time diagnostic tool to enable sensor emplacement for wellbore integrity monitoring

4. FUTURE WORK

The work presented in this paper is preliminary work and research towards the realization of an autonomous, small-diameter, precise drilling real-time diagnostic tool. Several necessary next steps towards this goal have already been identified and started.

One of the next steps of interest is to experiment drilling at different rotational speeds, different feed rates, and/or with different drill bit sizes. Some of this data acquisition has already been initiated by using a larger drill size of 3/16 inches. Force drilling data was collected using this larger drill bit on individual shale test samples. The rotational speed of the drill was decreased to 1200 RPM to maintain a feed rate of 4.5 in/min. This drilling data again shows inhomogeneity in the shale material that appears to also be independent of drill bit size. However, further data still needs to be collected to fully verify this phenomenon. This data is shown in Figure 10.

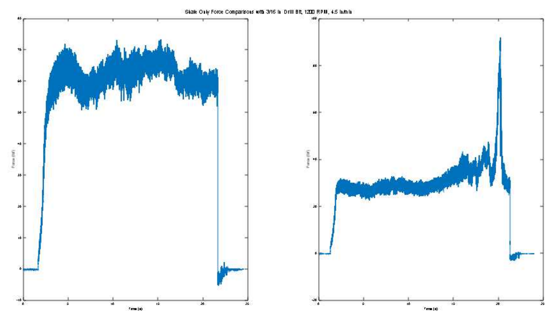

Fig. 10. Individual shale force drilling data collected with larger drill bit of 3/16 inches showing that shale material is still inhomogeneous.

Another avenue of future work that will need to be explored is the addition of depth measuring instrumentation to the current benchtop setup. Currently, our data leads us to believe that there is a correlation between the Temporal Kurtosis and the material transition in a drilling test sample. However, with the addition of a depth sensor we will more precisely and accurately be able to define the exact moment of material transition with relation to depth placement and thus better correlate our Temporal Kurtosis analysis as the drill transitions between materials. Depth of cut is a key parameter in drilling models (Detournay and Defourny, 1992), and may be estimated from instantaneous drill bit depth measurements.

Once we have more precisely correlated our Temporal Kurtosis to our material transitions with relation to depth placement we can utilize the knowledge gained of the material differences between shale and cement to develop an algorithm based around the difference in variance. One potential avenue would be to use a chi-square test or similar statistical test to determine whether we are in shale or cement based on whether a large change or swing in variance is observed. As supported by the data in table 1, this would indicate that a large variance change would indicate the drill was in shale and not cement. It is possible that this can also be explored or implemented through machine learning applications and methods.

Lastly, because of the contrast in variance observed between the shale and cement materials, some exploration into whether there is frequency dependence with variance will be explored.

5. CONCLUSION

The development of an autonomous, small-diameter, precise drilling real time diagnostic tool to enable sensor emplacement for wellbore integrity monitoring will be a significant contribution to ensuring wellbore integrity. This paper seeks to act as a stepping stone towards this goal presenting a variety of newly gained knowledge regarding the interaction between small drilling and wellbore materials. Force drilling data was collected showing there is a distinct force characteristic for a given individual material. When analyzing these unique force characteristics, it was shown that the greatest commonality was observed between cement and shale. Because of this, these two materials will be more difficult to differentiate between when utilizing the autonomous, small-diameter, precise drilling real time diagnostic tool. Uniquely from cement it was also observed that the shale material is very inhomogeneous in nature. This was more specifically observed when force drilling data was collected and compared for each individual material type.

We anticipate that this unique force characteristic can be used to identify material transition between the wellbore materials of steel, cement, and shale. Towards this end, a novel temporal kurtosis analysis on force drilling data was performed on the force drilling data showing a correlation between the kurtosis analysis and the drilling data. The fact that these rapid changes are observable in the kurtosis analysis suggest that they may be detectable in real time and may help provide a 'look-ahead' ability to identify material transitions. To better utilize the temporal kurtosis analysis, it is planned to add a depth sensor to the bench top testing set-up. The addition of a depth sensor will allow us to more precisely correlate the exact depth of the drill bit with the rapid changes observed in the kurtosis analysis and thus the material transitions in the wellbore. Temporal variance analysis between the individual cement test samples and the individual shale test samples was also performed. This data further showed the inhomogeneous nature of the shale material. Due to the differences in temporal variance observed between the cement and shale it is likely an algorithm can be developed based on this to help differentiate the two materials in real time. This difference in temporal variance between cement and shale will also be further explored to determine if there is any dependence of frequency on variance.

A variety of future work has either already begun for this project or has already been planned. Some future work includes experimenting with different variables in the bench top testing set-up such as rotational speed, bit size, bit length, feed rate, and the addition of a depth sensor. Another avenue of future work that will be explored is whether machine learning applications and methods can be utilized with our data.

REFERENCES

1. Davies, R.J., S. Almond,, R.S Ward, R.B. Jackson, C. Adams, F. Worall. L.G. Herringshaw, J.G. Gluyas, and M.A. Whitehead. 2014. Oil and gas wells and their integrity: implications for shale and unconventional resource exploration. *Marine and Petroleum Geology,* 56: 239-254.

2. DeCarlo, L. T., 1997, On the Meaning and use of kurtosis. *Psychol. Methods*, 2:292-307

3. Detournay, E., and Defourny, P., 1992, A phenomenological model for the drilling action of drag bits, *International journal of rock mechanics and mining sciences & geomechanics abstracts*, 29:13-23.

4. Song, W.J., and D. Cha. 2016. Temporal kurtosis of dynamic pressure signal as a quantitative measure of combustion instability. *Applied Thermal Engineering,.* 104: 577-586

5. Yakimov, M., 2012, The Dark Art of Cement Bond Log, SPE Presentation, Queensland Section (Available online at http://docplayer.net/42277043-The-dark-art-of-cement-bond-log-28-sep-2012-mikhail-yakimov-seic-tdd.html)