Measurement system analysis of viscometers used for drilling mud characterization

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Abstract. Viscometers in the Faculty of Chemical Engineering, University Teknologi MARA, are subject to heavy utilization from the members of the faculty. Due to doubts surrounding their result integrity and maintenance management, Measurement System Analysis was executed. 5 samples of drilling muds with varied barite content from 5 – 25 weight% were prepared and their rheological properties determined in 3 trials by 3 operators using the viscometers. Gage Linearity and Bias Study were performed using Minitab software and the result shows high biases in the range of 19.2% to 38.7%, with non-linear trend along the span of measurements. Gage Repeatability & Reproducibility (Nested) analysis later produces Percent Repeatability & Reproducibility more than 7.7% and Percent Tolerance above 30%. Lastly, good and marginal Distinct Categories output are seen among the results. Despite acceptable performance of the measurement system in Distinct Categories, the poor results in accuracy, linearity, and Percent Repeatability & Reproducibility render the gage generally not capable. Improvement to the measurement system is imminent.

1. Introduction

A bad gage will lead to wrong and perhaps costly decision [1]. Measurement system always increases the total observed variability of the parts measured. Total variability is equal to process variability plus measurement variability. While process variability only relates to variation caused by production process, raw material, equipment condition and environment, measurement variation on the other hand is a variation due to gage. Variation due to gage consists of four components which are accuracy, linearity, stability and precision.

MSA is a statistical tool specifically designed to determine the amount of variation contributed by measurement system [2]. It examines the collection of measurement tool, procedures, operations, software and operators that influence a measurement characteristic. MSA is capable of measuring gage characteristics such as accuracy, bias, and precision [3]. The importance of MSA in manufacturing industry is reiterated by many researchers [4-6]. Industry must use valid measurement data to ensure quality measurement results. As with the case of any measurement system, proper data collection and capability evaluation are needed to meet the measurement requirements in production and to improve quality control. MSA is currently practiced by many giants in manufacturing industry such as General Motor Corporations, Ford Motor Company, and Chrysler Group LLC to achieve required reliability of the production measurement [7].

Reports in MSA application and measurement system improvement are abundance. In 2010, Wu, Wei, and Li [8] evaluated the application of MSA in quality control process. The study laid down the findings of bias, linearity, stability, and precision in the experimental platform of large electronic

current in manufacturing environment. In another research, Huang and Wang [9] studied the factors of measurement deviations across different operators. Operators were observed and recorded during the gage reading with causes affecting the judgment were examined. The causes then were mitigated with standardized operating procedures and the variation later was reduced, proving the effectiveness of MSA. Then there was a proposal made by Hajipoura et al. [10] to analyze measurement systems under fuzziness of indices in order to make the environment more realistic. Fuzzy measurement system analysis with gage repeatability and reproducibility (GR&R) index as a triangular fuzzy number was suggested. The proposed method was validated in a case study in automotive parts industry to display the impact of the innovation.

Apart from industrial applications, analysis of experimental equipment in learning institution is not uncommon as "the quality level of experimental devices impacts experimental teaching in colleges and universities directly" [11]. Therefore, this project was conducted to investigate the accuracy and precision of the viscometers in the Drilling and Geology Laboratory, Faculty of Chemical Engineering, Universiti Teknologi Mara (UiTM). The viscometers in focus are greatly utilized for drilling mud characterization by students and researchers. In drilling mud formulation, decision on process change depends a lot on measurement. From the interview with lab technician [12], the viscometers undergo scheduled maintenance once in three months. On top of that, he claimed records of usage, calibration, maintenance and any relevant certificates are all in place. However, this is highly doubted since there are no logbooks near the equipment to support that claim, thus, led to this investigation. Furthermore, lots of academic data have been coming out from the viscometers and published in scientific reports, making it even more vital to ensure that the equipment produce valid data. In this research, MSA methodology and analysis was accessed and generated from statistical software Minitab. Minitab was chosen as it finds wide applications in manufacturing industry as well as in education and research [13-14].

2. Methodology

2.1. Materials
The drilling fluid used was water-based mud with barite and bentonite as additives. Two units of viscometers under investigation were Grace Instrument viscometer model M3600 and Fann viscometer model 35SA 6-Speed. Fann viscometer was set at standard rotor R1, bob B1, and torsion spring F1 operating at 300 RPM.

2.2. Mud preparation
5 samples were prepared to cover the normal range of drilling mud, each with different percentage of barite. Barite was used as a weighting agent to increase the mud density [15]. Table 1 shows the composition for each sample. After mixing process, the muds then were characterized by the measurement system in place.

Table 1. Composition of drilling mud samples.

Mud samples	Percentage of barite (weight %)	Volume of water (mL)	Mass of bentonite (g)	Mass of barite (g)
S1	5	400	32.00	22.74
S2	10	400	32.00	48.00
S3	15	400	32.00	76.24
S4	20	400	32.00	108.00
S5	25	400	32.00	144.00

The first rheological property, plastic viscosity (PV), is a flow resistance of a fluid caused by mechanical friction within the fluids itself with solid particles [15]. The equation is given as

$$PV = \theta_{600\,RPM} - \theta_{300\,RPM} \tag{1}$$

where θ_N is the viscometer dial reading at any rotational speed of N. The intersection between shear stress and shear rate is known as yield point (YP) and is given by

$$YP = \theta_{300\,RPM} - PV \tag{2}$$

The final mud property is 10 min-gel strength (GS). GS can be obtained by taking the reading of drilling fluid at 600 RPM and 3 RPM. The drilling fluid was stirred at 600 RPM for 30 seconds. Then, the drilling fluid was left to rest for 10 minutes, before stirred again at 3RPM, and the very first peak reading was the GS.

On the other hand, characterization of the standard samples was outsourced to SCOMI Group Bhd., an international drilling service company with qualified laboratory. The data for the standard drilling mud samples is tabulated in the table 2.

Table 2. Standard sample values

Sample	Percentage of barite (wt%)	Plastic Viscosity, PV (cP)	Yield Point, YP(cP)	10 mins- Gel Strength, GS (lb/100ft^2)
S1	5	7	52	50
S2	10	9	54	61
S3	15	10	42	65
S4	20	11	56	73
S5	25	13	56	86

3. Measurement System Analysis (MSA)

3.1. Accuracy and linearity study
Gage Linearity and Bias Study analysis in Minitab was run using the collected data. Bias is a measure of accuracy of a set of measured values against the standard values of the characteristic being measured. To calculate bias

$$Bias = X - \mu \tag{3}$$

where X refers to the mean of the experimental data while μ is mean of the standard sample. After that, linearity was computed through the slope of mean error versus true value plot. Linearity is the difference in bias throughout the expected range of measurements, and is given by

$$Linearity = Slope \times Process\ Variation \tag{4}$$

However, since Process Variation can only be obtained from historical data, Study Variation (or standard deviation multiplied by six) from the GR&R analysis was used.

3.2. Precision study
Gage Repeatability & Reproducibility (Nested) analysis in Minitab was chosen since the experiment was a destructive test in nature. The study was initiated by calculating MSA matrix to decide on the number of samples, trials and operators. The equation of MSA matrix is

$$(\#samples) \times (\#operators) \times (\#trials\ \text{-}1) \geq 30\ (minimum) \tag{5}$$

30 is the minimum number of required MSA matrix that is widely applied in the manufacturing industry [16]. To meet this requirement, 5 samples, 3 operators, and 3 numbers of trials were decided.

Operators were randomly selected among Oil and Gas Engineering students. No specific training was conducted and they were asked to complete the task by using their existing knowledge and experience. The experiment then took place according to the order generated by Minitab.

Precision study can be broken down into two parts, repeatability and reproducibility. From this study, Percent Repeatability and Reproducibility (%R&R), Percent Tolerance (%Tolerance) and Distinct Categories (DC) were determined. %R&R is given by %Tolerance was calculated by dividing the Study Variation for each component with process tolerance.

$$\%R\&R = \frac{\sigma^2}{\sigma^2} \; or \; \frac{\sigma^2_{Gage}}{\sigma^2_{Parts}} \tag{6}$$

The tolerance range for PV, YP, and GS were 5-15 cP, 39 – 61 cP, and 48 – 88lb/100ft^2, respectively. These ranges were the assumption of lower and upper tolerance for each drilling mud property, made from the normal operating range of the measurement system. Therefore

$$\%Tolerance = \frac{5.15 \, \sigma_{Measurement}}{Tolerance} \; or \; \frac{5.15 \, \sigma_{Gage}}{Tolerance} \tag{7}$$

where 5.15 is the standard deviations that accounts for 99% of measurement system variation and it is used as an industry standard [16].

Lastly, DC is a smallest detectable increment between the two measured values. It is given as

$$DC = \frac{\sigma^2_{Parts}*1.41}{\sigma^2_{Gage}} \tag{8}$$

4. Result and Discussion

4.1. Gage linearity and bias study

Among the drilling mud properties, the lowest bias is shown in PV analysis with average bias percentage of 19.2%. GS follows closely at 24.7% and finally YP gives 38.7%. These data indicate incapable measurement system. In terms of linearity, the gage is poor as the highest linearity shown is only 54.2% for PV and thelowest is 8.3%. This suggests that the accuracy of the measurement system is not linear throughout the range of measurements, as some locations show better accuracies than others. The example of plot for Gage Linearity & Bias Study from Minitab is shown in figure 1.
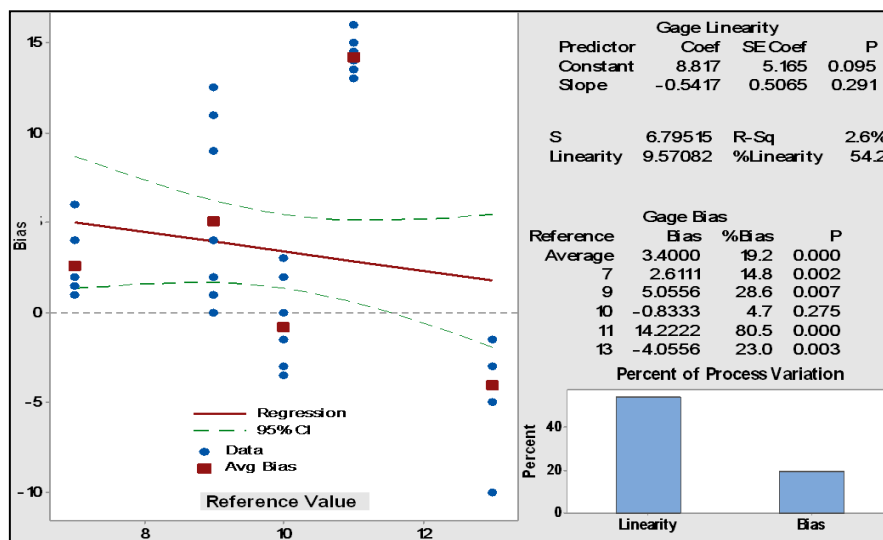

Figure 1. Gage Linearity and Bias for PV.

4.2. Gage repeatability & reproducibility (nested) analysis
From figure 2, in terms of total %R&R, YP portrays marginal performance at 5.11%. This is followed by poor indicator of GS with 8.05% and PV with 15.85%. All the %R&R contributions come from repeatability alone. The reproducibility contribution shows 0% contribution, indicating that operators' influence in gage variation is very small or none. This is similar to a finding by Špeťuch et al. [17] who studied the MSA of viscometers for vegetable and mineral oils. They found that the operators did not account for statistically significant outcome on the measured viscosity. Repeatability is the ability of a gage to repeat a measurement on the same sample under the same operating conditions while reproducibility is the ability to reproduce a measurement on the same unit under different operators. The standard range for good %R&R is from 0-2%, and over 7.7% is considered a bad range [16].

For %Tolerance, the lowest is displayed for GS at 54.82%, YP at 70.78%, and finally PV at 176.69%. %Tolerance is the ratio of precision to tolerance, with lower value is preferred as it suggests that the impact of variation due to gage precision is low with the given tolerance range. Since GS has the highest tolerance it is the likeliest to have lowest %Tolerance and vice versa. The industry-recommended value for &Tolerance is below 10% [16] and thus gage is deemed incapable for PV, YP and GS.

Finally, DC for PV, YP, and GS are 3, 6, and 4, respectively. This suggests that the gage is most favourable to YP, GS, and PV, in this order. It is good for YP, and marginal for GS and PV. Below DC of 3, the gage would be regarded as poor. DC means the number of groups within process data that measurement system can discern.

Generally, through %R&R and %Tolerance, it can be deduced that the measurement system in focus is not capable for drilling mud characterization. Improvement towards the gage needs to be carried out. The example of graphical representation of Gage Repeatability & Reproducibility (Nested) analysis in Minitab for PV is as shown in figure 3.

Gage R&R (Nested)	Plastic Viscosity					Yield Point					Gel Strength				
Source	DF	SS	MS	F	P	DF	SS	MS	F	P	DF	SS	MS	F	P
Operators	2	1.30	0.650	0.0044	0.996	2	22.40	11.217	0.0139	0.986	2	3.74	1.872	0.0040	0.996
Parts (Operators)	12	1761.83	146.819	16.9299	0.000	12	9690.30	807.52	56.6682	0.000	12	5651.07	470.922	35.2604	0.000
Repeatability	30	260.17	8.672			30	427.50	14.25			30	400.67	13.356		
Total	44	2023.30				44	10140.20				44	6055.48			

Gage R&R												
Source	VarComp	%Contribution (of VarComp)		VarComp	%Contribution (of VarComp)		VarComp	%Contribution (of VarComp)				
Total Gage R&R	8.6722	15.85		14.2500	5.11		13.3560	8.05				
Repeatability	8.6722	15.85		14.2500	5.11		13.3560	8.05				
Reproducibility	0.0000	0.00		0.0000	0.00		0.0000	0.00				
Part-To-Part	46.0491	84.15		264.4240	94.89		152.5220	91.95				
Total Variation	54.7213	100.00		278.6740	100.00		165.8780	100.00				

Process Tolerance   10   32   40

Souce	StdDev (SD)	Study Var (6*SD)	%Study Var (%SV)	%Tolerance (SV/Toler)	StdDev (SD)	Study Var (6*SD)	%Study Var (%SV)	%Tolerance (SV/Toler)	StdDev (SD)	Study Var (6*SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	2.94486	17.6692	39.81	176.69	3.77490	22.6500	22.61	70.78	3.65450	21.9272	28.38	54.82
Repeatability	2.94486	17.6692	39.81	176.69	3.77490	22.6500	22.61	70.78	3.65450	21.9272	28.38	54.82
Reproducibility	0.00000	0.0000	0.00	0.00	0.00000	0.0000	0.00	0.00	0.00000	0.0000	0.00	0.00
Part-To-Part	6.78595	40.7157	91.73	407.16	16.26110	97.5670	97.41	304.90	12.35000	74.0999	95.89	185.25
Total Variation	7.39738	44.3843	100.00	443.84	16.69350	100.0000	100.00	313.00	12.87940	77.2761	100.00	193.19

Distinct Categories =   3   6   4

Figure 2. Gage R&R (Nested) report for PV, YP, and GS.

4.3. Cause analysis for measurement system variation
There are a few possible factors contributing to this overall poor measurement system capability. Firstly, the maintenance program for the viscometers is suspicious. There is no strong proof of maintenance plan and execution in place. Without it, wear and tear, calibration, and even safety of the gage are questionable.

Secondly, there is no standard operating procedure (SOP) established for the viscometers. It is important to ensure proper handling when dealing with viscometers' speed setting and choosing the

right rotor. SOP also helps in judgement when reading analog display, recognizing peak in dial reading, and providing correct formulas for PV, YP, and GS calculations.
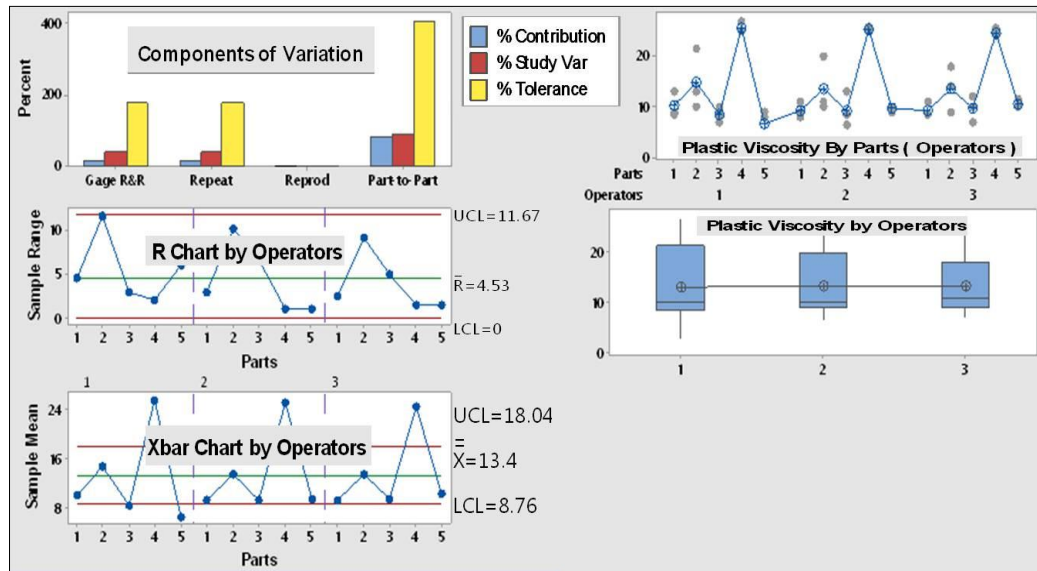

Figure 3. Gage R&R (Nested) plot for PV.

5. Conclusion

This work is about MSA for drilling mud characterization in the Faculty of Chemical Engineering, UiTM. This measurement system mainly involves the viscometers and operators within a setting of the Drilling & Geology Laboratory. Through the Gage Linearity & Bias study, biases values range from 24.7% to 38.7%. The bias also portrays non-linear trends throughout the range of measurements. From the Gage Repeatability & Reproducibility (Nested) study, %R&R is marginal for YP but poor for GS and PV. The gage is then estimated to be incompetent for all mud properties as they exhibit more than 30% in %Tolerance. Lastly, DC is good for YP but marginal for GS and PV determination. Overall, the findings definitely call for the measurement system to be improved.

6. Recommendation

It is a good practice to start logging measurement data in order to measure gage stability through control chart. From it, causative factors for variability may be discovered and the frequency of calibration can be planned accordingly to minimize error due to instability. Besides, MSA will become more accurate with historical Process Variation available. Furthermore, it is suggested that blind or random sampling is applied to eliminate noise in analysis

Improvement to the measurement systems is definitely required until accuracy, %R&R, %Tolerance, and DC fall within good ranges. Apart from keeping a logbook and sound maintenance/calibration plan, SOP for the viscometers will be helpful to reduce error due to measurement system.

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