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Reliability analysis of a hydraulic shovel used in open pit coal mines

The paper basically deals on reliability of the hydraulic shovel machines used in coal mines. Reliability of machines defined as the probability of the machine that will carry out its specified function satisfactory for stated period of time and without undergoing failure when used under specified condition for the specified period of time. Reliability of machine depends on its failure, if the failure is frequent then we can say that machine is less reliable and vice-versa. Due to recent deployment of sophisticated and capital intensive mining machinery equipment in mining industry, interest in the field of maintenance and operational reliability has been created. Keeping this in view a reliability investigation is initiated for hydraulic shovel in a reputed mine. The goal is to estimate the operational reliability of these mining machines for coal production in order to enhance its profit. Failure data for period of 1.5 years are analyzed using various probability distribution methods. The importance of testing the reliability data for the presence of trends and serial correlation is also emphasized. The project aimed at analyzing the reliability of the two hydraulic shovel machine using suitable distribution methods and to study the IFR and DFR using TTT-plotting method.

Keywords: *Reliability; hydraulic shovel; time between failure (TBF); mean time to failure (MTTF); time to test (TTT); increasing failure rate (IFR); decreasing failure rate (DFR); parametric method.*

1. Introduction

Reliability of the machinery working in heavy industry is of utmost interest whether it is related to manufacturing industries or other industrial sector such as mining industry. When the machines of same capacity and of same manufacturer are compared on the basis of its reliability, differences can be seen relating to its performance. This paper involves the reliability of hydraulic shovel of same manufacturer and of same bucket capacity involved in the coal production of a reputed mine of Dhanbad, Jharkhand. Hydraulic shovel is the one of the most widely used mining machinery used for excavation purpose in coal mines. Reliability analysis helps us to ascertain maintenance intervals [1], and with correct decision making, may be even increase the length of the intervals and thus decrease maintenance costs. These lead to many studies to be performed in the field of reliability analysis of mining equipment [2-6]. In the inspiring work of Barabady [7], the time between failures (TBF) data is used and it is possible to estimate the failure patterns and hence decision making regarding timed and economic scheduling of maintenance activities. However in a mining industry or firm where data are not systematically stored but only some raw data like overall time to failure (TTF) is available. It is essential to study the failure pattern and the probability distribution that can be adopted to calculate the reliability of the machines that is taken under study of this paper (in this case, two hydraulic shovels machine - type-I and type-II). The main objectives of this paper are:

- To carry out trend analysis of the hydraulic shovel machines from the raw failure data that is collected at the interval of 8 hour and to compare its validity with TTT (time to test) graph.
- To estimate the reliabilities of the type-I and type-II shovel machines and hence to compare their reliability.
- To forecast the next failure hour by calculating MTTF (mean time to failure).

2. Methodology

The reliability of the hydraulic shovel machine involved in coal production has been developed on the basis the raw data that is collected from one of the reputed mines of Dhanbad. Data collected is at the interval of 8 hour and is unorganized, it is arranged in the increasing order and then the trend analysis is carried on the basis of available data. To confirm the result obtained from trend analysis of data collected the TTT graph plotting is done. These two methods helped in adopting the appropriate probability distribution method for calculating the reliability of type-I and type-II hydraulic shovel machine. MTTF (mean time to failure) of the two machines is also calculated and reliability of the machine is compared to approximately 400 hours.

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3. Data collection

The raw failure data of two hydraulic shovel machines are collected from the reputed area of Dhanbad coal mine for the period of one and half years from the date of commencing of hydraulic shovel machine. The time between failures (TBF) is noted down at the interval of 8 hours and is tabulated and classified as under:

4. Results and discussion

4.1 Trend Analysis

Trend analysis refers to collecting data and using the data for extracting and underlying pattern of behaviour in time series. Before fitting any data in any distribution, it is necessary to confirm that the error of one data belonging to a particular distribution is not carried to next data and also that the data belongs to certain probability distribution. For this collected data must be independent and identically distributed (or iid). To check the data for iid, trend analysis of time between failures is carried out. The grouped data of type-I machine and type-II machine is tabulated in the form of cumulative time between failure and cumulative number of failure that occurred as shown in Tables 3 and 4. The graph is plotted between cumulative time between failure and the cumulative number of failure for type-I machine and type-II machine, as shown in Figs.1 and 2.

Figs.1 and 2 show a non-linear graph i.e. it does not follow any identical distribution. Now next with the help of TBF data, a plot between (i-1)th TBF and ith TBF for type-I and type-II machines are drawn as shown in Figs.3 and 4, the graphs show a scattering plot which in combination with Figs.1 and 2 assure independent and identical (iid) characteristics sample without any trend. As there is no trend found in the collected data, the next step is to fit the data in the appropriate probability distribution.

4.2 TTT (test to time) Graph Plotting

The TTT-plot and its theoretical counterpart are introduced by Barlow and Campo [8]. Since then various applications of TTT-plotting have been presented [8]. TTT plotting of the failure data obtained for the above the hydraulic shovel machine is plotted to confirm the trend analysis in order to select the suitable distribution method.

Steps considered for plotting:

- TBF is structured as 0 <= t(0) <= t(1) <= t(2) ... ...<= t(n), i = 1,2,... ...n
- S_i is determined from S_i = nt (1) + (n-1) (t (2)-t (1)) +... + (n-i+1)(t(i)-t(i-1)), i = 1,2,... ...n
- X co-ordinate = (i/n) where i = 1,2,3... ...n
- Y co-ordinate = $U_i = S_i/S_n$

where, 'i' is the number of failure and n is the number of observations for time between failures. U_i is the ratio of S_i/S_n, where, S_i is the TTT at time t_i and S_n is the TTT at nth failure, where i=1, 2, 3... ...n. The values (i/n) and U_i will lie between 0 and 1. The graphic representation of TTT is formed by plotting i/n on the horizontal axis and U_i on the vertical axis and shown in Figs.5 and 6.

The TTT plot of the two hydraulic shovel machines reveals that there is a variation in failure rate and hence non-parametric distribution can be applied rather than going for parametric distribution such as weibull distribution, exponential distribution or lognormal distribution.

The reliability calculated by using the formula given in eqn. (1) and at different TBF tabulated and compared to approximately 400 hours. Mean time to failure (MTTF) for two machines was found to be eqns.(2) and (3). Hence reliability of machines were compared and tabulated on basis of formula as (Table 7).

$$R(t) = \pi\left(1 - \frac{i}{n}\right) \quad \text{... (1)}$$

where, $i : t_i < t$

For Type-I machine

$$MTBF = \frac{220.7 + 581.8 + 302.2 + 966.8 + 0.6 + 254.9 + 215.8 + 54.6 + 281.5 + 220.2 + 338.2 + 1437.5}{12}$$

MTBF = 406.23hrs ... (2)

For Type-II Machine

$$MTBF = \frac{258.8+972.3+5.8+123.3+106.5+1754.1+303.9+24+1797.1+71.4+74.9}{11}$$

MTBF = 499.28hrs ... (3)

$$R(0.6) = \frac{12-1}{12} = 0.916667$$

$$R(54.6) = \frac{11-1}{11} \times 0.916667 = 0.833333$$

Hence from above table it is shown that at after 0.6 hours the reliability of machine type-I is 91% approximately which decreased to 83% at 54.6 hrs. So on and similarly for machine type-II. On the basis of above calculation the graph between reliability vs. TBF is drawn and shown in Figs.7 and 8.

Now since the graph of reliability verses TBF shows a decreasing trend so for finding reliability of both machines at 400hrs (by interpolation method [9]). For machine-I, calculation at 400 hours: Let the reliability at 400 hours be x,

Table 1 TBF and Number of Failure for type-I machine

*Type-I Machine	
Number of failure (for 8 hrs)	TBF (Time between failure) in 8 hrs
1	220.7
2	581.8
3	302.2
4	966.8
5	0.6
6	254.9
7	215.8
8	54.6
9	281.5
10	220.2
11	338.2
12	1437.5

***Explanation for type-I machine:** The above data were grouped for every 8 hour failure from raw data that is available from record book of hydraulic shovel machines in mine of study. From above table it is clear that the first failure occurred after 220.7 hour operation of machines and second failure occurred after 581.8 hour operation of machine after first failure had occurred. So on, the other failures are noted down.

Table 2 TBF and Number of Failure for type-II machine

**Type-II Machine	
Number of failure (for 8 hrs)	TBF (Time between failure) in 8 hrs
1	258.8
2	972.3
3	5.8
4	123.3
5	106.5
6	1754.1
7	303.9
8	24
9	1797.1
10	71.4
11	74.9

**Explanation for type-II machine: Similarly as the type-I machine the same method is adopted for the grouping data for 8 hours failure from the raw data available for machine-II from mine of study and it is found that the first 8 hour failure occurred after 258.8 hours from the first day of operation and second failure occurred after 972.3 hours, after first failure had occurred.

and since 400 lies between 338.2 hours and 581.8 hours having reliability 0.25 and 0.166667 respectively therefore by using interpolation method we get:

$$\frac{x-0.166667}{400-581.8}=\frac{0.166667-0.25}{581.8-338.2}$$

i.e. x = 0.228858

Therefore, R (400) = 0.228858 ... (4)

For machine-II , calculation at 400 hours:

Table 3 Cumulative TBF and Cumulative number of failure for type-I machine

Type-I Machine	
TBF (Time between failures) in 8 hrs	Number of failure (for 8 hrs)
220.7	1
802.5	2
1104.7	3
2071.5	4
2072.1	5
2327	6
2542.8	7
2597.4	8
2878.9	9
3099.1	10
3437.3	11
4874.8	12

Table 4 Cumulative TBF and cumulative number of failure for type-II machine

Type-II Machine	
TBF (Time between failures) in 8 hrs	Number of failure (for 8 hrs)
258.8	1
1231.1	2
1236.9	3
1360.2	4
1466.7	5
3220.8	6
3524.7	7
3548.7	8
5345.8	9
5417.2	10
5492.1	11

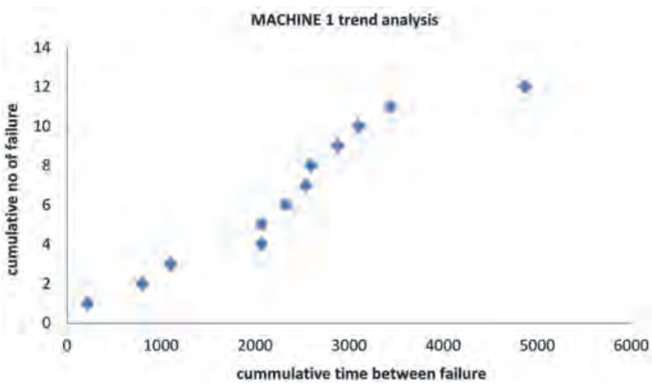

Fig.1 Plot of cumulative time between failure vs. cumulative numbers of failure for type-I machine

Let the reliability at 400 hours be x, and since 400 lies between 303.9 hours and 972.3 hours having reliability 0.272727 and 0.181815 respectively therefore by using interpolation method we get:

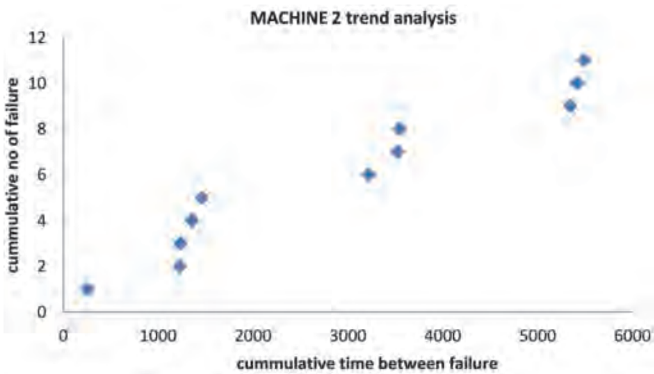

Fig.2 Plot of cumulative time between failure vs. cumulative numbers of failure for type-II machine

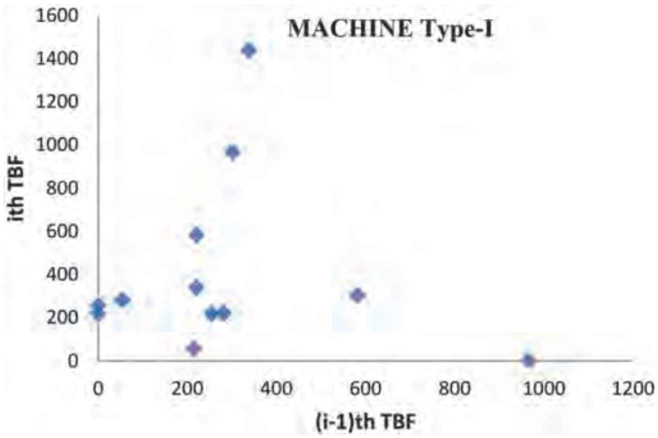

Fig.3 Test of serial correlation for TBF of hydraulic shovel machine type-I

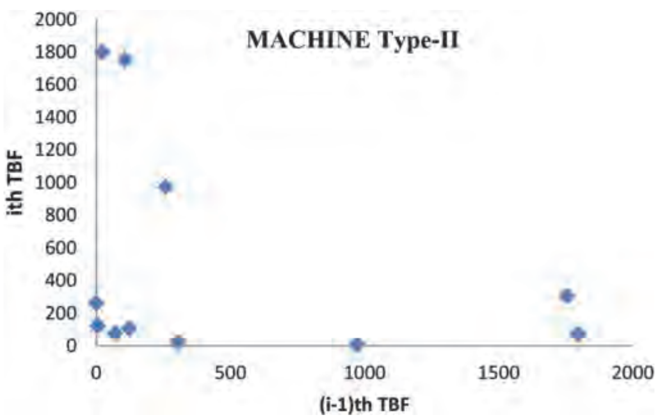

Fig.4 Test of serial correlation for TBF of hydraulic shovel machine type-II

$$\frac{x-0.181815}{400-972.3}=\frac{0.181815-0.272727}{972.3-303.9}$$

i.e. x = 0.249525.

Therefore, R (400) = 0.249525 ... (5)

Thus the reliability of the machine type-I and the machine type-II is calculated at 400 hour and it is seen that at 400 hour, reliability of the type-I machine is more than that of the type-II machine (given in eqns. (4) and (5)).

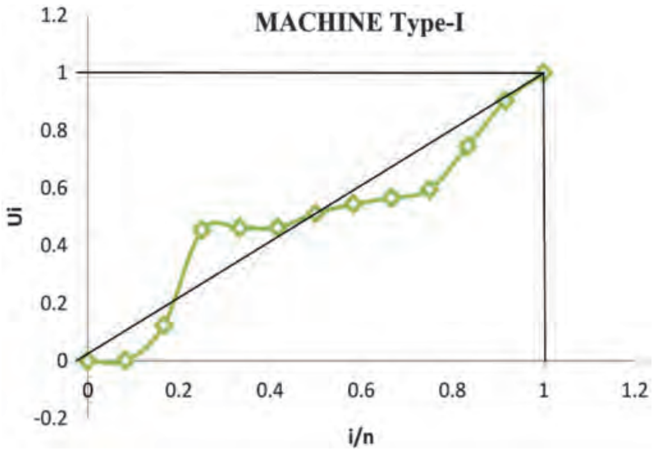

Fig. 5 TTT plot for machine type-I

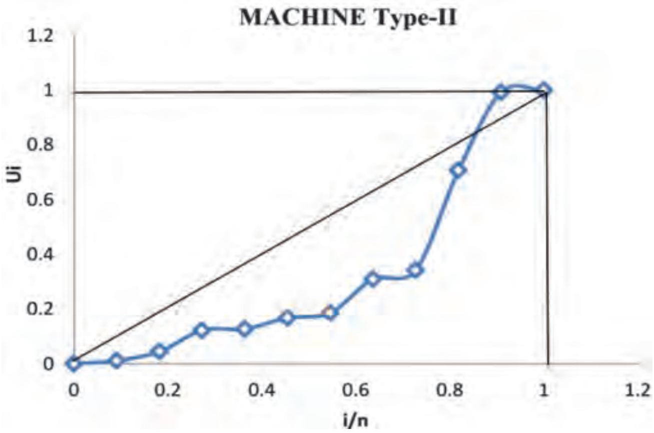

Fig. 6 TTT plot for machine type-II

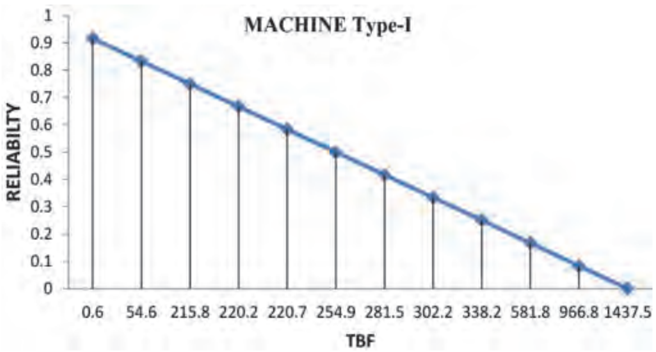

Fig.7 Reliability vs. TBF for type-I machine

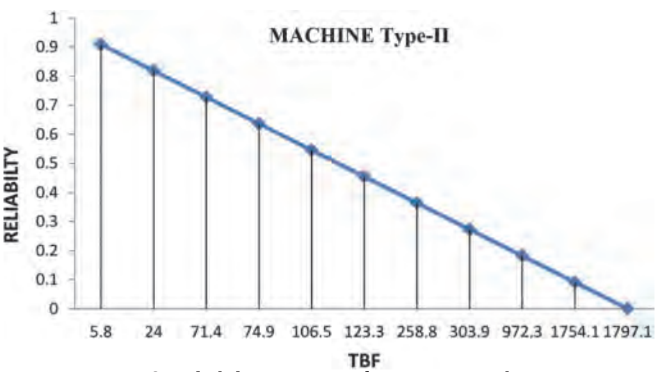

Fig.8 Reliability vs. TBF for type-II machine

Table 5 U_i and i/n for type-I machine

No. of failure (for 8 hrs)	TBF in hrs.	S_i	U_i	i/n
1	0.6	7.2	0.001477	0.083333
2	54.6	601.2	0.123328	0.166667
3	215.8	2213.2	0.454008	0.25
4	220.2	2252.8	0.462132	0.333333
5	220.7	2256.8	0.462952	0.416667
6	254.9	2496.2	0.512062	0.5
7	281.5	2655.8	0.544802	0.583333
8	302.2	2759.3	0.566033	0.666667
9	338.2	2903.3	0.595573	0.75
10	581.8	3634.1	0.745487	0.833333
11	966.8	4404.1	0.903442	0.916667
12	1437.5	4874.8	1	1

Table 6 U_i and i/n for type-II machine

No. of failure (for 8 hrs)	TBF in hrs.	S_i	U_i	i/n
1	5.8	63.8	0.011618	0.090909
2	24	245.8	0.044758	0.181818
3	71.4	672.4	0.122439	0.272727
4	74.9	700.4	0.127538	0.363636
5	106.5	921.6	0.167817	0.454545
6	123.3	1022.4	0.186172	0.545455
7	258.8	1699.9	0.30954	0.636364
8	303.9	1879.9	0.342317	0.727273
9	972.3	3885.1	0.707449	0.818182
10	1754.1	5448.7	0.99217	0.909091
11	1797.1	5491.7	1	1

Table 7 Reliability vs TBF for machine at 400

Machine	TBF (time between failure) in hrs	Reliability	Reliability at 400hrs.
Machine type-I	0.6	0.916667	
	54.6	0.833333	
	215.8	0.75	
	220.2	0.666667	
	220.7	0.583333	
	254.9	0.5	
	281.5	0.416667	
	302.2	0.333333	
	338.2	0.25	0.222886
	581.8	0.166667	
	966.8	0.083333	
	1437.5	0	
Machine type-II	5.8	0.90909	
	24	0.818181	
	71.4	0.727272	
	74.9	0.636363	
	106.5	0.545454	
	123.3	0.454545	0.249525
	258.8	0.363635	
	303.9	0.272727	
	972.3	0.181815	
	1754.1	0.090907	
	1797.1	0	

5. Conclusions

This paper concludes that machine type-II is more reliable and works for more period of time than machine type-I. The data collected after field study of hydraulic shovel reveales that it is an unorganized data at time of failure. It is observed that at some point it is increasing and decreasing so we do not know the actual trend of the data, so first the trend analysis is done to know the trend so that we can apply appropriate statistical distribution.

The trend analysis shows that time between failure data collected did not follow the linear trend for both the type-I and type-II machines hence we go for the non-parametric distribution of statistics. The use of trend analysis in determining the reliability of the machine is essential. The test of serial correlation is performed for TBF of hydraulic shovel which shows a scattering plot, which reveals that the data have no trend with any serial correlation and are totally independent.

Thus the graphs obtained in combination with trend analysis and test of serial correlation assures independent and identical characteristics sample without any trend. Hence, the interpretation from the graph obtained shows that data follows non-parametric or empirical method and the parametric distribution such as weibull distribution, normal distribution, exponential distribution etc. cannot be applied. TTT plotting is done based on the data collected and it is seen that the line shows the variation of IFR and DFR along the diagonal line from which it can be interpreted that the reliability calculation can be carried by the non-parametric distribution model. Second it is interestingly to note that the reliability of the machine that is calculated using the collected data is showing the linear line decreasing with the TBF.

Hence the mean time between failures (MTBF) is calculated for machine type-I as 406.23 hours and for type-II machine as 499.28 hrs.

The machine reliability is reduced after 406.23 hours and 499.28 hours for type-I and type-II respectively and makes them prone to failure. In this, the attempt is made to predict the next failure time that is MTTF. This value gives the forecast for the next failure. The proper maintenance after knowing its next failure at which it may occur, necessary preventive measure can be adopted to improve the performance, and increase production capacity with continuous functioning of machine.

Further comparing of reliability of the two hydraulic shovels that are done at the 400 hours and it is noted that the reliability of machine type-II is more than that of machine type-I. Hence the type-II machine can perform for longer than the type-I and requires less maintenance as compared to the type-II machine, although the maintenance of machine is the important procedure that should be carried out in order to improve the reliability of machine.

Future scope of reliability analysis: Reliability engineering, with increasing mechanization and technological development in the field of mining industry finds its wide application. The machine used is quite complex and sophisticated and needs regular maintenance but due to increased demand of productivity and tight schedule of mining companies, it is often avoided. Through reliability engineering we can predict the failure of the system and sub-system that may occur in next hours. The reliability engineering techniques can also be applied on components that are involved in the functioning of equipment so that it can provide the smooth operations of the equipment and thereby increasing the productivity and efficiency of the task performed.

References

[1] Barabady, J., & Kumar, U. (2008): Reliability analysis of mining equipment: A case study of a crushing plant at Jajarm Bauxite Mine in Iran. *Reliability engineering & system safety,* 93(4), 647-653.

[2] Kumar, U., Klefsjö, B., & Granholm, S. (1989): Reliability investigation for a fleet of load haul dump machines in a Swedish mine. *Reliability Engineering & System Safety,* 26(4), 341-361.

[3] Kumar, U., and Klefsjö, B. (1992): Reliability analysis of hydraulic systems of LHD machines using the power law process model. *Reliability Engineering and System Safety,* 35(3), 217-224.

[4] Samanta, B., Sarkar, B., and Mukherjee, S. K. (2004): Reliability modelling and performance analyses of an LHD system in mining. *Journal of the South African Institute of Mining and Metallurgy*, 104(1), 1-8.

[5] Mandal, S. K. (1996): Evaluation of reliability index of longwall equipment systems for production contingency. *Mining Technology,* 78(897), 138-140.

[6] Kumar, U., & Huang, Y. (1993): Reliability analysis of a mine production system-A case study. In *Reliability and Maintainability Symposium*, January, 1993. Proceedings. Annual (pp. 167-172). IEEE.

[7] Barabady, J. (2005): Reliability and maintainability analysis of crushing plants in Jajarm Bauxite Mine of Iran. In *Reliability and Maintainability Symposium*, January, 2005. Proceedings. Annual (pp. 109-115). IEEE.

[8] Barlow, R. E., & Campo, R. A. (1975): *Total Time on Test Processes and Applications to Failure Data Analysis* (No. ORC-75-8). California Univ. Berkelay Operations Research Centre.

[9] Dhingra, R., & Singh, S. (2013): Comparison of Various Interpolation Based Image Zooming Techniques. *International Journal,* 3(6).

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[13] Wang,N. N.,Shi, Y. B., Yin, L. and Li Y. J. (2015): "A Novel Digital Phase-Sensitive Detection Algorithm of Micro Resistivity Imaging Logging Tool. "*Measurement & Control Technology*, vol. 34, no. 7, pp. 23-26.

[14] Liu, L. Y., and Li, X. L. (2017): "Circuit Design of Weak Signal Detection Based on Phase Sensitive Detection. "*Instrumentation and Measurment*, vol. 36, no. 8, pp. 94-97.

[15] He, Q., Liu.R., Tan, T.G. (2017): "Non-uniformly periodical sampling in phase-sensitive OTDR. "*Optics Communications*, vol. 405, no. 15, pp. 201-204, DOI: 10.1016/j.optcom. 2017.07.091.

[16] Jonathan, T. (2010): "Mixed signal phase sensitive detection." IEEE Computer Society, vol. 55, no. 6, pp. 1292-1295, DOI: 10.1109/ISCAS.2010.5537264.

[17] Yang,G. Y., Fan, X. Y., Liu. Q.W. and He,,Z. Y. (2018):"Frequency Response Enhancement of Direct-Detection Phase-Sensitive OTDR by Using Frequency Division Multiplexing." *Journal of Lightwave Technology,* vol. 36, no. 4, pp. 1197-1203,DOI: 10.1109/ JLT.2017.2767086

[18] Grzegorz, D. (2016): "8-Port Homodyne Detection of EIT-Enhanced Cross-Phase Modulation Using Broadband Signal Pulse. "Pro Quest Dissertations and Theses Global, pp.134.

[19] Tang, T.. Z., Chen, T., Zhou, K. B., Jioang. Y. H., and Zhang Q. H. (2008): "Design of MIT Array Induction Weak Logging Signal Detection and Acquisition System." *Well Logging Technology*, vol. 32, no. 6, pp. 584-588.