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ANALYSIS OF ACCURACY OF IN-LINE INSPECTION RESULTS

Abstract. The paper presents a method for assessing the accuracy of in-line inspection (ILI) results. The main objective of the method is to determine whether the measurements obtained by ILI are adequate and acceptable. If too few measured dimensions of defect parameters (for example, their depths) fall within the range of values obtained using verification results, this indicates that the ILI tool incorrectly estimated the actual data. Thus, the lower (upper) limit is estimated for the number of satisfactory (unsatisfactory) ILI tool measurements.

Keywords: in-line diagnostics, pipeline systems, measurement errors, flaw detection.

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АНАЛИЗ ТОЧНОСТИ РЕЗУЛЬТАТОВ ВНУТРИТРУБНОЙ ДИАГНОСТИКИ

Аннотация. В работе представлен метод оценки точности результатов внутритрубной диагностики (ВТД) и его применение к анализу результатов инспекции реального трубопровода. Описанный метод позволяет определить, являются ли полученные в результате ВТД измерения адекватными и приемлемыми. Если слишком мало измеренных размеров параметров дефектов (например, их глубин) попадают в интервал значений, полученных с помощью результатов верификации, это свидетельствует о том, что внутритрубный инструмент (ВТИ) неправильно оценил фактические данные. Таким образом, оценивается нижняя (верхняя) граница для числа удовлетворительных (неудовлетворительных) измерений ВТИ.

Ключевые слова: внутритрубная диагностика, трубопроводные системы, погрешности измерений, дефектоскопия.

Introduction

Detection of pipelines defects mainly occurs in the course of diagnostics using various measuring instruments (MI). Information issued by an MI inevitably contains constant (systematic) and random measurement errors (MEs), which can greatly distort the actual state of the system under study.

If MI overestimates the size of defects, then this significantly worsens the perceived physical condition of the pipeline, which leads to significant economic costs due to unreasonable repair of defects. When underestimating the size of the defects, it is possible that emergencies may occur that lead to large environmental and economic losses.

Thus, it is obvious that in assessing the risk of a defect, one of the most important components of its consistency is how accurately were determined the parameters of correctly identified defects.

The diagnostics of the technical state of the linear part of a PS is performed with the use of in-line diagnostic tools – defectoscopes [1-3]. Hereinafter, unless expressly stated otherwise, they will be referred to as the ILI tools. After completion of the ILI a small percentage of detected defects is verified, i.e., a second set of measurements is performed with another, as a rule, more accurate instrument.

The results of measurements represent an approximate evaluation of the true values of defect parameters. The true values are the values ideally describing the object's properties. They are considered an absolute truth and therefore are immeasurable; they may only be evaluated with a certain degree of accuracy.

A measurement error is an unknown random value. All MI have inherent ME, since there could be no ME-free measurement instruments.

The paper contains a description of the method for assessing the allowed number of satisfactory (unsatisfactory) measurements when conducting ILI. The method is based on variance and regression analysis. The main goal of the method is to determine whether the results obtained using the ILI tool are adequate and acceptable. The case when too few defect parameter sizes (e.g., their depths) fall within the interval of values obtained as a result of verification is an evidence of poor assessment of the actual data by the ILI tool. Hence, it is necessary to assess the lower (upper) boundary for the number of successful (failed) ILI tool measurements.

Using the real data of the ILI, the application of the developed technique is demonstrated. ILI data is provided by an anonymous source.

Mathematical model of measurements

Suppose that using two tools (ILIT and VI) *n* independent measurements are made. We believe that the variance $\sigma_{\varepsilon V}^2$ of ILIT MEs is smaller than the variance $\sigma_{\varepsilon I}^2$ of VI MEs, i.e. $\sigma_{\varepsilon V}^2 \geq \sigma_{\varepsilon I}^2$ (VI is more precise than ILIT).

The mathematical model of measurements in this case will have the form [4, 5]:

$$
\begin{aligned}
p_{I,i} &= \alpha_I + p_{tr} + \varepsilon_{I,i}, \\
p_{V,i} &= \alpha_V + p_{tr} + \varepsilon_{V,i},\ i = 1, 2, .., n,
\end{aligned}
\tag{1}
$$

where p_{tr} is the true (immeasurable) value of the parameter to be measured (depth, length, width) ; $p_{I,i}, p_{V,i}$ is the ILIT and VI reading respectively; α_I, α_V is the constant systemic measurement errors of ILIT and VI respectively; $\varepsilon_{I,i}, \varepsilon_{V,i}$ is the random measurement error of ILIT and VI respectively.

A following criterion is based on following assumptions:

– measurements are made by two independent tools, one measurement by each tool;

– measurement errors are normally distributed with zero mathematical expectation and variance $\sigma_{\varepsilon I}^2, \sigma_{\varepsilon V}^2$, respectively;
– MEs are independent of each other and the true values of the measured parameter.

Assessment of the ILI Instrument Accuracy

According to the measurement model (1), because of independence of p_{tr} and $\varepsilon_I, \varepsilon_V$, the RVs p_V and p_I will have variances:

$$\begin{aligned}\sigma_I^2 &= \sigma_{tr}^2 + \sigma_{\varepsilon I}^2,\\ \sigma_V^2 &= \sigma_{tr}^2 + \sigma_{\varepsilon V}^2,\end{aligned} \tag{2}$$

where σ_{tr}^2 is the true value of the defect parameter p_{tr} variance.

From formula (2) it follows that

$$S^2 = \sigma_{\varepsilon I}^2 + \sigma_{\varepsilon V}^2 = \sigma_I^2 + \sigma_V^2 - 2\sigma_{tr}^2. \tag{3}$$

We construct an adequate physical estimate of the sum S^2 of the MEs variances of both instruments. The scatter of measurements between the two compared MIs (ILIT and VI) is calculated using the RMSD (*Root Mean Square Deviation*) of measurements made with one tool from the measurements made with another tool. RMSD is calculated by the formula [6-8]

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(p_{I,i} - p_{V,i})^2}, \tag{4}$$

where n is the number of verified measurements and $p_{I,i}, p_{V,i}$ are the measurements of defect parameter sizes.

Assessment of the relative bias *RBias* of measurements of one instrument relative to measurements of the other instrument

$$RBias = \overline{p}_I - \overline{p}_V, \tag{5}$$

where $\overline{p}_I, \overline{p}_V$ is the sample mean of ILIT and VI measurements, respectively.

Then the total scatter between the measurements *RMSD* can be split into two independent components: the square of the relative bias *RBias* and the sum *S* of MEs variances:

$$RMSD = \sqrt{RBias^2 + S^2}. \tag{6}$$

Formula (6) is easy to prove. Let $p_{I,i}, p_{V,i}$ be the *i*-th measurement of ILIT and VI, respectively. The value $d_i = p_{I,i} - p_{V,i}$ is distributed with a variance of $S^2 = \sigma_{\varepsilon I}^2 + \sigma_{\varepsilon V}^2$, and the sample estimate of this value is equal to:

$$\frac{1}{n}\sum_{i=1}^{n}(p_{I,i}-p_{V,i})^2-\left(\frac{1}{n}\sum_{i=1}^{n}(p_{I,i}-p_{V,i})\right)^2=RMSD^2-RBias^2. \tag{7}$$

The value

$$RMSD=\sqrt{RBias^2+\sigma_{\varepsilon I}^2+\sigma_{\varepsilon V}^2},$$

is the distance from the origin to the point with coordinate $(x,y,z)=(\sigma_{\varepsilon V},\sigma_{\varepsilon I},RBias)$ in the three-dimensional space.

Then the sum of the variances can be estimated by the formula

$$RMSD^2-RBias^2=\sigma_{\varepsilon I}^2+\sigma_{\varepsilon V}^2. \tag{8}$$

From the formula (3) you can find the variance of the true size of the defects

$$\sigma_{tr}^2=\frac{\sigma_I^2+\sigma_V^2-S^2}{2}. \tag{9}$$

Then by the formula (2) it is possible to estimate the MEs variation of both tools

$$\begin{aligned}\sigma_{\varepsilon I}^2&=\sigma_I^2-\sigma_{tr}^2,\\ \sigma_{\varepsilon V}^2&=\sigma_V^2-\sigma_{tr}^2,\end{aligned} \tag{10}$$

where the unbiased sample variances of the ILIT and VI measurements are determined by the formulas:

$$\sigma_I^2=\frac{1}{n-1}\left(\sum_{i=1}^{n}{p_{Ii}}^2-\frac{1}{n}\left(\sum_{i=1}^{n}p_{Ii}\right)^2\right),$$

$$\sigma_V^2=\frac{1}{n-1}\left(\sum_{i=1}^{n}{p_{Vi}}^2-\frac{1}{n}\left(\sum_{i=1}^{n}p_{Vi}\right)^2\right).$$

Criterion for the accuracy of in-line diagnostic results

This criterion is designed for assessing the allowed number of satisfactory (unsatisfactory) measurements when conducting ILI. The main goal of the method is to determine whether the results obtained using the ILI tool are adequate and acceptable. The case when too few defect parameter sizes (e.g., their depths) fall within the interval of values obtained as a result of verification is an evidence of poor assessment of the actual data by the ILI tool. Hence, it is necessary to assess the lower (upper) boundary for the number of successful (failed) ILI tool measurements.

Since the measurement process, in fact, follows the scheme of independent Bernoulli trials ("success" or "failure" of a measurement), the distribution of the number of "successes" will follow the binomial distribution pattern [3]. "Success" is the ILI tool measurement lying inside the ILI tool accuracy confidence interval. "Failure" is when the measurement lies outside the confidence interval of the ILI tool accuracy. If the number of the ILI tool measurements inside the confidence interval is too small, it means that this small number could not be accidental. Hence, the ILI tool produces unacceptable level of distortion of the true values of the measured parameters, which has to be rejected (put out of use).

Assessment of the minimum acceptable number of satisfactory and minimum acceptable number of unsatisfactory measurements, detected in the process of ILI and subsequently verified with the use of a more accurate MI, is performed using the binomial distribution law [9-11].

Binomial probability distribution is the distribution of probabilities of the number of manifestations of a certain event in the course of a series of repeated independent tests (in our case, measurements). Let the number of "successes" M in the test sequence $X_1, X_2, .., X_n$ have binomial distribution with n degrees of freedom and "success" probability p, i.e., $M \in Bin(n, p)$. Then the PDF of random value M is determined by the formula [9-11]

$$P(M = m) = f(m,n,p) = \frac{n!}{m!(n-m)!} p^m (1-p)^{n-m}.$$

Using this formula, the probability of occurrence of m successful results in a series of n tests with the "success" probability p is determined.

According to the definition of the binomial PDF the probability of the number of successful tests not exceeding k will be

$$P(M \le N) = \sum_{m=0}^{k} P(M = m) = \sum_{m=0}^{k} f(m,n,p). \tag{11}$$

This formula is a CDF of the binomial law.

Let n defects be detected during an ILI and some parameter of these defects is measured (e.g., depth). Let p be the measurement reliability ("success" probability). Then $q = 1 - p$ is the probability of occurrence of an unsatisfactory measurement ("failure" probability). Denote k as the number of satisfactory (successful) measurements. Then the probability of having at least k satisfactory measurements, when n defects are measured, equals to

$$P_k = 1 - \sum_{m=0}^{k-1} f(m,n,p) = \sum_{m=k}^{n} f(m,n,p). \tag{12}$$

For existing high-resolution MFL tools the error of defect depth measurement is ±10% of the pipe wall thickness (*wt)* with 80% certainty, i.e., their ME will stay within the interval [−10; +10%*wt*] with probability $p = 0.8$.

Thus in order to determine whether the ILI tool measurements lie within the acceptable accuracy range, it is necessary to calculate by formula (11) the probability of ILI results demonstrating at *least k satisfactory measurements.*

Overall tolerance for measurements taking into account the ME of both MI (ILI tool and the VI) is calculated by the formula

$$tol_t = \sqrt{tol_I^2 + tol_V^2}, \tag{13}$$

where tol_I is the tolerance for ILI tool measurement (measurement error), %*wt*; tol_V is the tolerance for the VI measurements, %*wt*.

For a given measurement reliability p the tolerance for the ILI tool measurement is calculated by assessing its ME variance [12]:

$$\begin{aligned} tol_I &= Q_{\frac{1+P_I}{2}} \sqrt{\sigma_{\varepsilon I}^2}, \\ tol_V &= Q_{\frac{1+P_V}{2}} \sqrt{\sigma_{\varepsilon V}^2}, \end{aligned} \tag{14}$$

where P_I, P_V is the ILI tool and VI measurement certainty, respectively; $Q_{\frac{1+p}{2}}$ is the quantile of level $(1+p)/2$ of the standard normal distribution.

In order to determine whether the *i*-th measurement lies within the overall tolerance range it is necessary to check whether it meets the condition

$$\left| p_{V,i} - p_{I,i} \right| \le tol_t, \tag{15}$$

If this condition is met, the measurement stays *within the tolerance range*, i.e., is considered satisfactory. Thus it is possible to determine the number *k* of *satisfactory* measurements.

Further, for the obtained value of *k* it is necessary to check the condition

$$P_k = \sum_{m=k}^{n} f(m,n,p) < P_c. \tag{16}$$

If it is met, the results of ILI are within the acceptable accuracy range. Otherwise, the ILI results do not meet the ILI tool specifications. In formula (4) P_c is the probability (confidence level), necessary for acceptance of the diagnostics results. This value may vary from vendor to vendor. Its determination is a separate problem.

Analysis of the accuracy of the real ILI results

An anonymous data source (working in the pipeline business) provided 50 verified depth measurements of defects, with no information given on measuring instruments.

Let us construct a scatter plot of ILI tool and VI measurements (see Fig. 1), according to which in almost all cases for several values of ILIT measurements there is one VI value. For example, a value of 2.5 mm corresponds to three ILIT readings. A similar picture is usually observed with rough verification, when the measured dimensions of defects are rounded off (usually in a big direction) and possibly even with some margin.

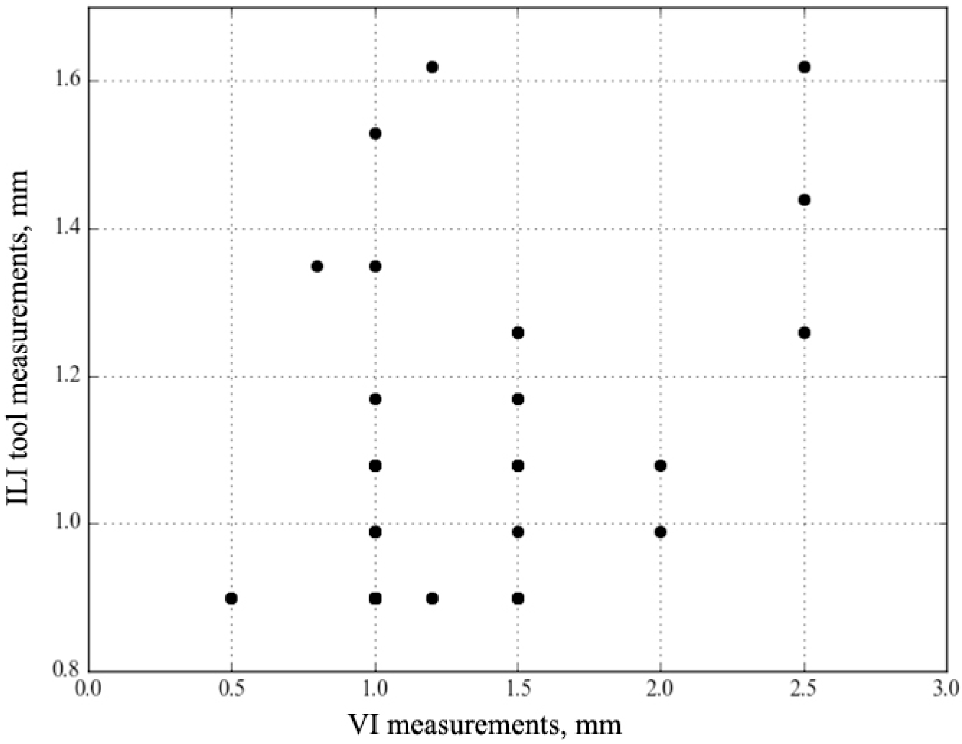

Figure 1. The scatter plot of ILI tool and VI measurements

Estimate the variance of tools MEs. The sample mean of ILIT and VI measurements and relative bias are equal to:

$$\overline{p}_I = 1.044,$$
$$\overline{p}_V = 1.258,$$
$$RBias = -0.214.$$

Thus, either ILI tool underestimates the size of defects, or VI overestimates them.

By formula (4) we calculate *RMSD*, by formula (8) – the sum of the MEs variances and the sample variances of measurements:

$$RMSD = 0.451,$$
$$S^2 = 0.158,$$
$$\sigma_I^2 = 0.040, \quad \sigma_V^2 = 0.192.$$

It should be noted that the sample variation of VI measurements is *significantly larger* than the variance of ILI tool measurements. Since in the measurement model (1) the variation of the true values of defects sizes is the same in both measurements, it is obvious that this difference between the variations of the measurements is *due to the greater variation of VI measurements, which suggests that the VI is less accurate than the ILI tool*. This conclusion will be confirmed mathematically and by formula (9) we estimate the variance of true sizes of the defects depths:

$$\sigma_{tr}^2 = 0.037.$$

Thus, the MEs variations will be equal:

$$\sigma_{\varepsilon I}^2 = 0.003,$$
$$\sigma_{\varepsilon V}^2 = 0.154.$$

We obtained that the variation of VI MEs is significantly larger than variation of ILI tool MEs. This suggests that the results of this verification need to be rejected without even applying the criterion of accuracy of ILI results.

Conclusion

A method has been developed for assessing the accuracy of in-line diagnostics results, which was used to analyze real ILI data and its subsequent verification. The analysis showed that measurements of the verification tool contain measurement errors that are larger than the measurement errors of the in-line inspection tool, which is not valid. Therefore, the results of this verification must be rejected. This situation is often encountered when verifying the ILI results, when the measured dimensions of defects are rounded off (usually in the safe direction) and possibly even with some additional margin. With such a rough verification, it is impossible to assess the actual quality of the conducted ILI.

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