Soft Calibration Method to Uncertaintyof Measurement about Nondestructive Quantitative Testing

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Abstract

By the uncertainty, the common Nondestructive quantitative testing data could not meet the needs of the basic request of Nondestructive evaluation and reliability safety analysis in actual engineering. In this article, used the uncertainty evaluation method, the regress analysis and the fuzzy theory, the soft calibration method was built for uncertainty of measurement of nondestructive quantitative testing. Base on the same accuracy of Nondestructive testing instrument, the calculation and analysis results of some engineering example displayed that the random and systematic uncertainty of testing results was lessening clearly by the soft calibration method, the quality of results was raised clearly by overcoming some lacking of the common hard calibration. By the soft calibration method, the Nondestructive quantitative testing data was capable of meeting the needs of the basic request for Nondestructive evaluation and Reliability safety analysis.

Keywords :Nondestructive testing ;Uncertainty ;Backwards regression analysis ;Soft calibration

1. Introduction

In Fracture Mechanics, Damage allowance design, Reliability safe analysis and evaluation, Risk and life-based design (RBD), Security condition evaluation, Quality control and Acceptance, The accuracy or the uncertainty question of Nondestructive testing (i.e. NDT) data becomes more and more important. But it has not always obtained the enough attention. The uncertain analysis method of testing result, the correlation standard system still is not yet established and formed. The uncertainty of Nondestructive testing data cannot satisfy the basic needs of Nondestructive evaluation and Reliability safe analysis in actual engineering. This article mainly discusses the soft calibration method of measurements uncertainty of NDT data.

2. Origin and Characteristic of Uncertainty

Many origin caused the uncertainty in ***NDT***, usually the main origin comes from following several aspects[1]: ①Imcomplete definition of measurand; ②Imperfect realization of the definition of measurand; ③Nonrepresentative sampling; ④Effects of environmental conditions; ⑤Error in reading analogue indication of instrument; ⑥Measurement performance influences of testing instrument sensitivity; ⑦Inexact values of standard body; ⑧Fiducial error of quotation data or other parameter; ⑨Inexact values for the approximations and assumptions in the measurement method and procedure;⑩Variations in repeated testing under apparently identical conditions.

In the above-mentioned influence, some factor is related each other. Usually the uncertainty should be divided into the systematic or random uncertainty, or from the testing system calibration and the testing process. ***NDT*** fuzzy theory divides the uncertainty into two kinds: the not fully examination condition brings random uncertainty and the not explicitly definition brings the fuzzy uncertainty. Under the repetition examination condition, Relative to measurand, The characteristic of fuzzy uncertainty is the mean of many times testing not tending to conformity, but the remarkable characteristic of random uncertainty is the mean value of many times testing tending to conformity. In ***NDT*** actual engineering, the influence of the fuzzy uncertainty is far more than random uncertainty.

Contrasted with the measurement engineering, The examination data in ***NDT*** actual engineering, has following several obvious characteristics: ①The influence of the fuzzy uncertainty is more than random uncertainty, there is many outliers in the testing data; ②Due to the limited of using method, the quantity of testing samples is few; ③The influence of systematic uncertainty is obvious; ④The definition is incomplete about measurand.

3. Distribution Rule of Testing Data

To any ***NDT*** system, after analyzing the massive ***NDT*** data, the following idea is believed: under repeatability conditions and the testing data $\boldsymbol{x}$ is the sum of the real function predicted value of measurand $\boldsymbol{y}$, random uncertainty $\boldsymbol{\varepsilon}$ which obeys standard normal distribution rule and the fuzzy uncertainty $\boldsymbol{\Delta}$, as follows:

$$\boldsymbol{x} = \varphi(y) + \boldsymbol{\varepsilon} + \boldsymbol{\Delta}$$

The physics meaning is that anyone value of $\boldsymbol{x}$ should come out which satisfies $\boldsymbol{y}$ in above equation. So testing data $\boldsymbol{x}$ is random and uncertain. In actual engineering, the most real functions $\varphi(\cdot)$ may be simplifues as common linearity functional relationship $\varphi(y) = \lambda_0 + \lambda_1 y$.

4. Soft Calibration Method

4.1. Outliers Elimination

Based on central utmost theorem, most testing data distributes approximate to normal distribution rule when affected by many factor. To the outliers under repeatability conditions, it is quite necessary to eliminate the outliers according to the distribution rule whether it satisfies or not. The following are common judgment and elimination method:

Cutting average method[2]: When the quantity of the testing data sequence is not enough, removes one or more maximum and the minimum values at the same time, and then carry on the parameter estimation and examination to the remaining data. The removed one cannot certainly be guaranteed as the outliers, but accuracy of the testing result can be guaranteed. If the uncertainty of the testing value does not have to be estimated, the testing value can be taken Mediam and Mode directly.

t-distribution criteria[3]: Firstly to calculate the statistics, and eliminate the suspected data $\boldsymbol{x_i}$, calculating the mean value $\bar{x}$ and the standard deviation according to the sample number ***(k-1)*** ; Then finding out the examination coefficient by the examination sample number of times k and α. If $|x_i - \bar{x}| > t_\alpha(k) \cdot S$, then $\boldsymbol{x_i}$ is the outliers, otherwise is not. It is practical to the data sample with little quantity of nondestructive inspection and normally takes ***0.1/0.05*** as $\boldsymbol{\alpha}$.

When $3 \leq k \leq 30$, Dixon method is available to one and more than one outliers. When for one outliers, Grubbs method is recommended by ***GB4883-85***. There are also other criteria including 3σ criterion for $n>10$, Slant-Peak inspection method, criterion based on the grey system theory, the criterion based on the fuzzy theory and so on.

4.2. Systematic Uncertainty Elimination

By the NDT fuzzy theory[4], when calibrating any NDT system, If testing measurand $\boldsymbol{y_i}$ in $\boldsymbol{n}$ times under the repetition examination condition, obtains $\boldsymbol{n}$ of effective testing value $\boldsymbol{x_i}$, It may expressed as the following fuzzy relationship:

$$y_i = f(x_i) + \varepsilon \qquad \varepsilon \sim N(0, \sigma^2)$$

By above equation, $\boldsymbol{y_i=f(x_i)}$ can reduces or eliminates the influence of systematic uncertainty. To most common linearity function related to the actual engineering, there is:

$$y_i = \lambda_0 + \lambda_1 x_i + \varepsilon$$

In above equation, the estimator $\hat{\lambda}_0$、$\hat{\lambda}_1$ & $\hat{\sigma}^2$ may be given after the backwards regression analysis[5]:

$$\hat{\lambda}_0 = \overline{y_i} - \hat{\lambda}_1 \overline{x_i} \qquad \hat{\lambda}_1 = \sum_{i=1}^{n}(y_i - \overline{y_i})(y_i - \overline{x_i}) \Big/ \sum_{i-1}^{n}(x_i - \overline{x_i})^2$$

$$\hat{\sigma}^2 = 1/(n-2)\sum_{i-1}^{n}(y_i - \hat{\lambda}_0 - \hat{\lambda}_1 x_i)^2$$

If $\boldsymbol{v=n-2}$, the ratio between the estimator $\hat{\sigma}^2$ and σ^2 takes the distribution as follows:

$$v\hat{\sigma}^2 / \sigma^2 \sim \chi^2(v)$$

In the actual engineering, If level of confidence takes 0.90, when $n=5/10/20$, the upper limit of one-sided confidence interval is $2.27/1.51/1.29\hat{\sigma}$.

4.3. Measurand Estimation

Under repeatability condition, when measurand is tested $\boldsymbol{m}$ times, on an independent examination, the testing data $\boldsymbol{x_i}$ is obtained, then the point estimator ***y'*** of ***y*** is its average value:

$$y' = \bar{y} = \lambda_0 + \lambda_1 \cdot \bar{x}_i \qquad \bar{x}_i = (\sum_{i=1}^{m} x_i)/m$$

By Bessel formula, the uncertainty $\boldsymbol{u}$ of the estimator ***y'*** in single testing is estimated of its standard deviation $\hat{\sigma}$. When $\boldsymbol{m}$ times independent testing, standard uncertainty $\boldsymbol{u}$ of ***y'***, the expanded uncertainty $\boldsymbol{U_\alpha}$ under $\boldsymbol{\alpha}$, then:

$$u = \hat{\sigma} / \sqrt{m} \qquad U_\alpha = t_\alpha(v) \cdot u$$

By GUM, the confidence interval of measurand may express as follows:

$$\bar{y} \pm t_{\alpha}(v) \cdot \hat{\sigma} / \sqrt{m} \qquad v = m - 1$$

In general actual engineering, when ***α=0.05*** and ***v*** is bigger, the contains factor of the two-sided confidence interval is possible to take ***2*** approximately. when it is used in the domain of reliability safe analysis, when needs higher degreess of confidence and safety, σ may be calculated according to $\chi^2(n-2)$ distribution, or referencing the other paper [6].

4.4. Data Fusion

Under reproducibility conditions, the testing data obey as the normal distribution rule with different mean and different variance. Normally, If ***q*** times independent testing is done to measurand ***y***, independent testing n_i times is carried on under the condition ***i***, the compounds uncertainty of measurements with common method, the weighing r_i, the uncertainty *u* and the degreess of freedom ***v*** of ***y'***, by the backwards regression analysis, the equation shown below [6]:

$$y' = \sum_{i=1}^{q} r_i \cdot y_i' \qquad u^2 = \left(\sum_{i=1}^{q} \frac{n_i}{u_i^2}\right)^{-1} \qquad r_i = \frac{n_i}{u_i^2} \sum_{i=1}^{q} \frac{n_i}{u_i^2}$$

$$v = u^{-4} \Big/ \sum_{i=1}^{q} \frac{n_i^2 \cdot u_i^{-4}}{v_i + n_i - 1} \qquad n_e = \sum_{i=1}^{q} \frac{n_i \cdot r}{n_{ei}(y_i)_i}$$

Contrasting to ***y_i'*** of any one kind of testing condition, the uncertainty of ***y'*** should reduce obviously greatly, when using the data fusion method of the backwards regression analysis.

5. Soft Calibration of Ultrasonic Testing System

By the point focusing slanting sensor ***Φ5P12DJK1-9***, the digital instrument ***DUT-92***, the line cutting test body, according to the standard ***JB4730*** to calibrated the testing system of ultrasonic testing system, the testing data[7] is gotten in repeatability conditions as table 1.

5.1. Hard calibration

By ***GUM***, to ***P_1&P_2*** , ***u***= **0.34mm**, ***U_{95}*=0.75mm**, ***v_{eff}=10***. By debugging the testing system (i.e. Common hard calibration), systematic uncertainty is unable to eliminate obviously, but random uncertainty is unable to eliminate.

Table 1 Testing data and calibration data statistics

Vertex		Upper-point P_1(mm)					Lower-point P_2(mm)					
Test serial		1	2	3	4	5	6	7	8	9	10	11
Measurand		5.3	9.3	13.3	17.3	21.3	4.0	8.0	12.0	16.0	20.0	24.0
Testing times	1	5.6	9.8	13.6	17.6	21.8	4.4	8.2	11.7	15.9	19.5	23.7
	2	5.6	9.8	13.6	17.6	21.8	4.4	8.2	11.7	15.9	19.5	23.9
	3	5.6	9.8	13.6	17.6	21.8	4.4	8.2	11.7	15.9	19.5	23.9
Test result		5.6	9.8	13.6	17.6	21.8	4.4	8.2	11.7	15.9	19.5	23.9
Error		0.3	0.5	0.3	0.3	0.5	0.4	0.2	-0.3	-0.1	-0.5	-0.1

Name	Hard Calibration		Soft calibration				
			Same method		Different method		
	P_1 P_2	*H*	P_1 P_2	*H*	P_1	P_2	*H*
Δ_m	*0.50*	/	*0.53*	/	*0.14*	*0.30*	/
u	*0.34*	*0.48*	*0.31*	*0.44*	*0.10*	*0.23*	*0.25*
U_{95}	*0.75*	*1.06*	*0.70*	*0.99*	*0.29*	*0.60*	*0.67*

5.2. Same Method

With the linear relation, to ***P_1&P_2***, the backwards regression analysis is carried on with the same equation:

$$P = -0.388 + 1.02P' + \varepsilon \qquad \varepsilon \sim N(0,\ 0.31^2)$$

Carries on the soft calibration computation by the above equation, the calculated result as Table 3. For P_1、P_2, range$\Delta_m \le 0.53mm$, residual error sum$\Sigma\delta=0$, u**=0.31mm,** U_{95}**=0.70mm**. After comparing the data, We know, If Soft calibration at the Same method for P_1 and P_2 , the random uncertainty should reduce slightly, but the systematic uncertainty should reduce more.

5.3. Different Method[8]

Different from common hard calibration, by using the characteristic of soft calibration which processing the data of P_1 or P_2 with different equation, the backwards regression analysis is carried on with the linear relationships:

$$P' = -0.31+1.01P_1+\varepsilon \quad \varepsilon \sim N(0, 0.10^2)$$

$$P' = -0.36+0.97P_2+\varepsilon \quad \varepsilon \sim N(0, 0.22^2)$$

By above equation, the calculated result show in Table 2. To P_1&P_2, the range$\Delta_m \le$ **0.14/0.30mm**, $\Sigma\Delta=0$, $u=0.10/0.23mm$, $U_{95}=0.29/0.60mm$. Among them, Δ_m reduces at large scale, the sum of residual error $\Sigma\Delta$ is eliminated, u&U_{95} reduces at large scale.

Then, the result quality distinct improvement, the effect is better to the vertex reflection method when the backwards regression analysis with different equation for the data of P_1 or P_2.

5.4. Uncertainty of Self-height

Self-height H and combined expanded uncertainty U of H should express as follows:

$$H= P_2'- P_1' \qquad U^2= U_{P1}^2+ U_{P2}^2$$

The calculated result show in Table 2. Then, $u=0.25mm$, $U_{95}=0.67mm$. So this result was able to satisfy the needs of Nondestructive evaluation and Reliability safe analysis.

5.5. Engineering Example

By the technics of UT quantitative testing , to typical 10 flaws on Mid-pressure vessel made of ***16Mn***&***20g/AST41***, 9 times independent testing was carried for self-height H of flaws [8]. After expression by some standard such as ***CVDA-84***、***SAPV-95 & R6,*** The Outliers of testing data was eliminated with Dixon, Grubbs and ***t***-distribution method ($\alpha = 0.10$) . The systematic uncertainty was reduced by the backwards regression analysis. Many times testing data fusion reduce the random uncertainty largely which Satisfied the reproducibility examination condition. The mean value of u of testing result reduces form ***0.37mm*** to ***0.19mm***, the data quality increase obviously, Then the degrees of freedom mean value from 7.2 rised to 50.0, namely the reliability degrees increase obviously large. So, It’s able to satisfy the general needs of ***0.07*** coefficient of variation to ***5mm*** self-height in Probabilistic Safety Evaluation, as well the other needs of Nondestructive evaluation and Reliability safe analysis in actual engineering.

6. Data Fusion Example

Table 3 Ultrasonic Testing Value

Test serial		1	2	3	4
Test times	1	~~12.00~~	7.00	11.00	12.00
	2	9.00	~~13.00~~	~~7.00~~	~~5.00~~
	3	8.00	7.00	13.00	12.00
	4	7.00	6.00	13.00	13.00
	5	5.00	4.00	11.00	13.00

Table 4 Soft calibration data contrast

Test serial		1	2	3	4	Merge	Fusion
Uncorrected	dB	8.17	7.50	11.00	11.00	/	/
	u	2.32	3.02	2.45	3.39	2.79	1.35
Corrected	dB	7.40	6.40	12.00	12.50	/	/
	u	1.52	1.52	1.15	0.58	1.2	0.5

Some Nondestructive quantitative testing data of flaw body standard show as Table 3, testing by the skilled ultrasonic wave tester in one Nondestructive examine committee. with the data of Table 3, under repeatability condition, the random uncertainty usually ignores. such the variance is close to each testing flaw, so it satisfied the reproducibility condition, Owing to ***P=0.86*** in Bartlett examination.

when ***α=0.1***, the Dixon and Grubbs examination method should not eliminate the outliers, the eliminated the outliers (deletion line data) show as Table 3 with examination method of ***T***-test. The merged and fusion testing results shown as Table 4, when used the common method of measurement uncertainty and the regression analysis method. The standard uncertainty ***u*** of amplitude value is ***2.8db*** or so. After eliminating the outliers, ***u*** is ***1.2db*** or so. But after eliminating the outliers and data-fusioning, ***u*** is only ***0.5db*** or so.

Namely, the method of variance merge in the common measurement uncertainty theory is more reasonable to evaluate the uncertainty of one ***NDT*** method. But the method of soft calibrates is able obviously to reduce the uncertainty of testing result of one flaw.

7. The conclusion

Different with common hard calibration, This method is called the soft calibration method to uncertainty of mathematical about ***NDT***, Through the analysis and the discussion in this article, some conclusions may draw following:

1）It's able to reduce obviously the systematic uncertainty and the random uncertainty of ***NDT*** system by the linear relations backwards regression analysis between the testing data and measurand, and then the lacking was overcomed about the accuracy of testing instrument and the testing method.

2）Base on the characteristic of NDT data, It's completely necessary to eliminate the outliers by the mathematical statistic method, under reproducibility standard testing condition.

3）The method of variance merge is more reasonable to evaluate the uncertainty of one NDT method. But the method of soft calibrates is able obviously to reduce the uncertainty of testing result of one flaw.

4) With carried on soft calibration separately to the different type data, the uncertainty of testing result reduces obviously, this testing result was able to satisfy the needs of Nondestructive evaluation and Reliability safe analysis in actual engineering.

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