THE ERRORS OF EQUIVALENT DIAMETER MEASURING BY USING OF DGS-DIAGRAMS

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Abstract: DGS-diagrams are conventional tool for measuring of a defect equivalent diameter. Modern digital flaw detectors contain these diagrams in the memory for evaluating the equivalent diameter automatically. In fact DGS-diagrams represent the signal amplitude A (by dB) as a function of two variables: $A = A(g, x)$, where $g = d/D$ is the equivalent defect diameter normalized to the diameter of a piezoelectric transducer and $x = \lg(r/R)$ is the distance to a defect normalized to the near-field zone size $R = D^2 f/4c$ (in the logarithmic scale). One can find equivalent diameter d by measuring working frequency f, elastic wave speed c and echo amplitude A experimentally (after respective calibration) or having f, c, D (transducer diameter) as known values. As all these values are not precisely known we obtain the value of d with an error. It is obvious that the error depends on differential characteristics of the surface $A(g, x)$ or inverse surface $g(A, x)$. These characteristics and respective errors for measuring equivalent diameter of a defect by means of DGS-diagrams are considered.
The new variable $u = 40\lg(g)$ is introduced and the area of DGS-diagrams arguments is divided into two parts: far-field zone and near-field zone. For the first of them the function $A(u, x)$ can be represented analytically as linear function, for the near-field zone polynomial approximation for "inverse DGS" is used.
Basing on such representation the errors of equivalent diameter measuring were computed for all points of DGS arguments plane (both for far and near zones of diffraction). The results of the investigation allow formulating constraints on errors of measuring echo amplitude and operating frequency.

Introduction: DGS-diagrams are conventionally used in nondestructive testing when measuring of real size of a defect is conjectural (for example in [1]). They allows estimating of equivalent scatterer diameter by immediate measuring of echo-signal amplitude (A, dB) and distance to the defect (r). Effectiveness of DGS-diagrams usage is based upon that the varying parameters (such as: working frequency f, transducer diameter D, sound speed c) are involved in the generalized arguments g, x of the function $A(g, x)$ which is invariant to these parameters. Generalized arguments are defined as follows: $g = d/D$ is relation of the equivalent diameter of a defect to the diameter of the transducer; $x = \lg(r/R)$, where $R = D^2 f/4c$ is the length of near-field zone. Errors are unavoidable when measuring amplitude, frequency and others. The matter of this investigation is estimation of equivalent diameter errors according to the measure tolerance for amplitude and working frequency.

Results: Let us consider measurement procedure in more details. Main measuring is preceded by calibration which allows disambiguating electroacoustic channel gain. Let us suppose that the bottom echo-signal is used for the calibration and A_{b1} is immediately measured value of bottom echo-signal amplitude (by dB) for the distance H. By using of the "bottom curve" $A_b(x)$ from DGS-diagrams we find normalized value of the bottom signal $A_b(x_H)$ where $x_H = 4c_1 H/D^2 f$ and c_1 is sound speed in the specimen which is used for calibration. Then normalized value of echo-signal amplitude is as follows:

$$A = A_1 - (A_{b1} - A_b(x_H)) + 2(\alpha r - \alpha_1 H)20\lg(e)$$
(1)

where α is the coefficient of sound dissipation for the specimen with the measurable defect and α_1 is the same for calibration one. By using normalized amplitude A and generalized distance to the defect one can find equivalent diameter. Inverse DGS-diagrams $g(A,x)$ are used at that in explicit or implicit form. So: $d = Dg(A,x)$.

Let us consider in which manner relationships $A(g,x)$ and $g(A,x)$ can be defined. Conventionally DGS-diagrams $A(g,x)$ are given by the sequence of curves with g as discrete parameter ($g \in (0.05,1)$). All the curves transform into straight lines with generalized distance increase. It corresponds to inverse square law for echo-signal amplitudes in far-field zone for a lossless medium. The border of far-field zone is highly conventional. It is practically acceptable to assume $x = 1$ ($r/R = 10$) as the border value. Within the region $x > 1$ energy-based concept is valid. According to this concept the amplitude is proportional to a scatterer square (hence to squared diameter). So, the surface $A(u,x)$ (where $u = 40\lg(g)$) is a plane within the above mentioned region and defined as follows: $A = B + u - 40(x-1)$. Addend B adjusts the plane to DGS-surface at $x = 1$. Correspondingly, inverse relationship is as follows: $u = A + 40(x-1) - B,\quad g = 10^{u/40}$. Inverse "bottom curve" is defined as $A_b(x) = B_b - 20(x-1)$.

In case of generalized distance decreasing (within region $x < 1$) linearity of the function $A(u,x)$ at fixed value of x is being lost gradually. But this function retains monotonicity and only gradually deviates from straight line. It allows approximating of function $A(u)$ and inverse one $u(A)$ at every fixed value of x by polynomials $P_1(u)$ and $P_2(u)$, respectively. Polynomials of five degree give good approximation. So, function $A(u,x)$ and inverse function $u(A,x)$ may be defined by tables of polynomial coefficients at sequence of values of x. Such representation occurs to be convenient for calculation of errors of equivalent diameter measuring.

Let us enlarge on the factors which are responsible for the errors. In its turn all initial values required for equivalent diameter evaluation are determined by measurement. Measuring errors for distances r, H and velocities c, c_1 are sufficiently small and may be neglected in the present investigation. They are supposed to be known exactly. Measuring errors for echo amplitudes A_1 and A_{b1} caused by instability of contact conditions are more essential and hard to remove. Uncertainty of dissipation coefficients plays also significant role. At once inaccurate determination of working frequency leads to incorrect computing of generalized distances to a defect and to a bottom and results in error for equivalent diameter determination.

Coming to quantitative relations let us suppose that the relative errors are sufficiently small so that differentials in derived below expressions may be replaced by finite increments. Using above expressions for generalized variables x and u it is easy to find relative error for equivalent diameter as follows:

$$\frac{\delta d}{d} = 0.0576\left(-\left(\frac{\partial u}{\partial A}\frac{\partial A_b}{\partial x} + \frac{\partial u}{\partial x}\right)\frac{\delta f}{f} + \frac{\partial u}{\partial A}\delta A'\right)$$
(2)

The value $\delta A' = \delta A_1 - \delta A_{b1} + (r\delta\alpha - H\delta\alpha_1)40\lg(e)$ involves combined error of normalized amplitude measuring caused by the errors of direct amplitudes measuring and by the errors of measuring of dissipation coefficients. Relative error defined by expression (2) is random value. Supposing that estimate of working frequency is unbiased, relative mean square error for estimation of equivalent diameter is defined by following expression:

$$\frac{\delta d}{d} = 0.0576\sqrt{\left(\frac{\partial u}{\partial A}\frac{\partial A_b}{\partial x} + \frac{\partial u}{\partial x}\right)^2 \frac{\left\langle \delta f^2 \right\rangle}{f^2} + \left(\frac{\partial u}{\partial A}\right)^2 \left\langle \delta A'^2 \right\rangle}$$

(3)

where triangle brackets mean statistical averaging.

The value of mean square error for measuring of the normalized amplitude $\left\langle \delta A'^2 \right\rangle$ depends on methodic of measurement. In general case, when special specimen is used for calibration and its material parameters and surface condition are distinguished to tested detail we have

$$\left\langle \delta A'^2 \right\rangle = \left(\left\langle \delta A_1 \right\rangle - \left\langle \delta A_{b1} \right\rangle + (r\left\langle \delta\alpha \right\rangle - H\left\langle \delta\alpha_1 \right\rangle)(40\lg(e))\right)^2 +$$
$$+ \sigma_{A1}^2 + \sigma_{Ab1}^2 + (r^2\sigma_\alpha^2 + H^2\sigma_{\alpha 1}^2)(40\lg(e))^2$$

(4)

where σ^2 designates variance of respective random value. Estimate biases $\left\langle \delta A_1 \right\rangle, \left\langle \delta A_{b1} \right\rangle$ are caused in particular by contact surface condition.

If it is possible to use for calibration (by means of bottom signal) the main specimen (tested detail or construction) the error may be decrease because of decreasing of remainder $\left\langle \delta A_1 \right\rangle - \left\langle \delta A_{b1} \right\rangle$ (contact surface is the same for calibration and main measurement) and due to decreasing error caused by uncertainty of dissipation coefficients. In this case

$$\left\langle \delta A'^2 \right\rangle = (\left\langle \delta A_1 \right\rangle - \left\langle \delta A_{b1} \right\rangle)^2 + \sigma_{A1}^2 + \sigma_{Ab1}^2 + \left\langle \delta\alpha^2 \right\rangle (r - H)^2 (40\lg(e))^2$$

(5)

So methodic with using main specimen for calibration is seemed to be preferable.

When computing relative error of equivalent diameter measurement we specify mean-square error of the amplitude estimate as a whole (assembling all the reasons of this error).

Discussion: Let us consider some particular situations. Let the distances for calibration H and for main measurement r belong both to far-field zone. Then: $\partial u/\partial A = 1, \partial u/\partial x = 40, \partial A_b/\partial x = -20$ and it is follows from expression (3) that:

$$\frac{\delta d}{d} = 0.0576\sqrt{400\frac{\left\langle \delta f^2 \right\rangle}{f^2} + \left\langle \delta A'^2 \right\rangle}$$

(6)

In the case of distance for calibration belongs to near zone $x_H < 0$ and distance r belongs to far zone one can specify $\partial A_b/\partial x \approx 0$. Then:

$$\frac{\delta d}{d} \approx 0.0576\sqrt{1600\frac{\langle \delta f^2 \rangle}{f^2} + \langle \delta A'^2 \rangle}$$

(7)

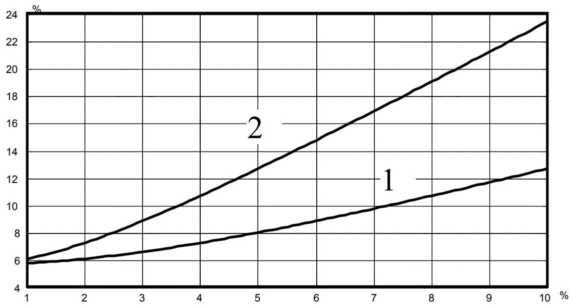

Fig. 1. Relative error of equivalent diameter measuring.
Calibration within far zone (1) and within near zone (2).

These simple expressions allow finding out substantial role of frequency estimate error. It is illustrated by plots at Fig.1, where $\sqrt{\langle \delta A'^2 \rangle}$ is supposed to be equal to 1 dB. Presented results suggest that working frequency must be measured because measurement with the use of nominal value of frequency with tolerance ±10% leads sometimes to unacceptable error.

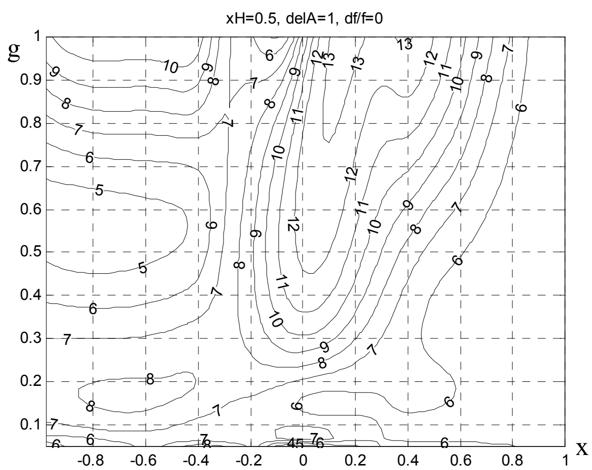

Fig. 2. Error distribution for $\sqrt{\langle \delta A'^2 \rangle}$=1 dB.

Errors by % are labeled at the level lines.

In the case when distance to the defect does not belong to far-field zone one should apply general expression (3). Derivatives $\partial u / \partial A$, $\partial u / \partial x$ and $\partial A_b / \partial x$ which appear in this expression may be computed numerically by using of above mentioned presentation of DGS-diagrams by polynomials. Some results of computation are shown below at Figs. 2 – 3. Let us consider some computation versions to estimate the different factors. Let working frequency is known precisely. Then relative error of diameter measuring does not depend on distance under calibrating and is defined as follows:

$$\frac{\delta d}{d} = 0.0576\left(\frac{\partial u}{\partial A}\right)\sqrt{\left\langle \delta A'^2 \right\rangle}$$

(8)

Error distribution over (x, g) plane is shown at Fig. 2 by contour plot. Error arises within the region near $x = 0$ (the end of near-field zone) with increasing relative defect size g.

In the hypothetic alternative case relative error of diameter measuring is proportional to relative deviation of frequency from its nominal value:

$$\frac{\delta d}{d} = 0.0576\left|\frac{\partial u}{\partial A}\frac{\partial A_b}{\partial x} + \frac{\partial u}{\partial x}\right|\frac{\sqrt{\left\langle \delta f^2 \right\rangle}}{f}$$

(9)

As is seen from expression (9) the error depends on generalized distance x_H under calibrating. Error distributions for $x_H = -0.5$ (near zone) and $x_H = 0.95$ (the end of intermediate zone) are shown at Fig. 3.

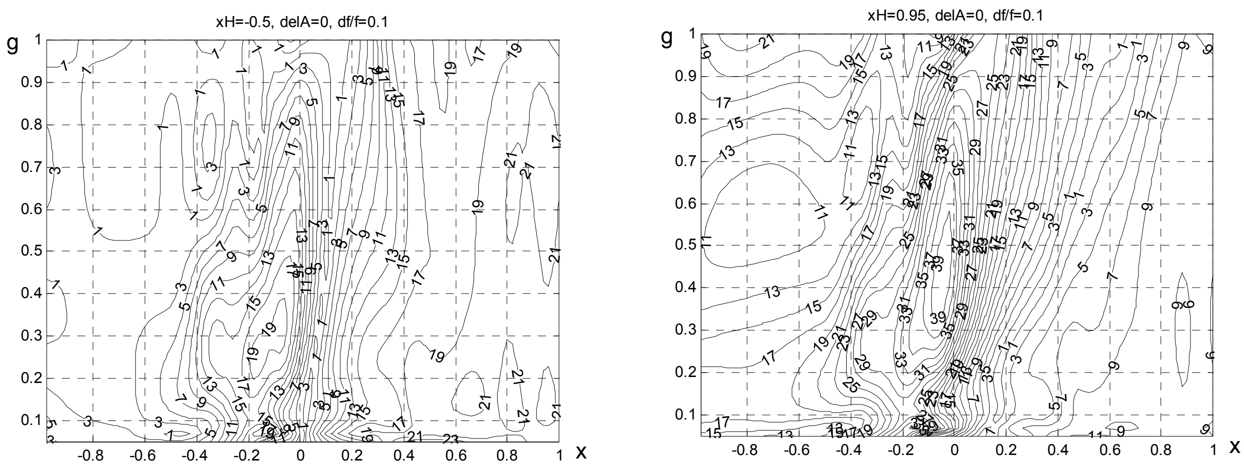

Fig. 3. Error distribution for $\sqrt{\left\langle \delta f^2 \right\rangle}\Big/ f = 0.1$

For the first case the error tends to increase with increasing of generalized distance. For the second one it increases within intermediate zone and run up inaceptable values.

When investigating the error experimentally we used standard measures of MD type, industrial transducers 1.25K20, 2.5K12, 2.5K20, 5K12 with working frequencies 1.25, 2.5 and 5 MHz and diameters 12 mm and 20 mm (10 specimens of each kind) and defectoscope UD3-71 which allows to measure working frequency and equivalent diameter automatically. Experimental results at (x, g)-plane are shown at Fig. 4.

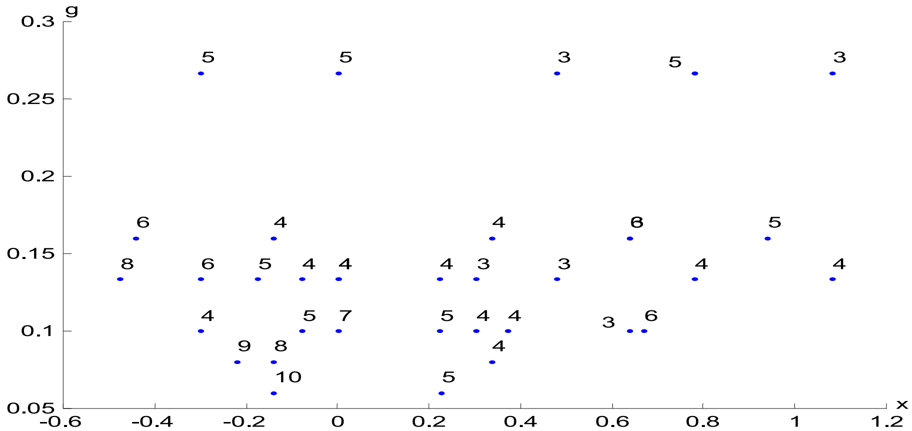

Fig. 4. Relative mean square variation of equivalent diameter by percents.

Conclusions: 1) Equivalent diameter of a defect may be measured with acceptable accuracy if working frequency was previously adjusted. 2) Accuracy depends on generalized distances to a defect and to a bottom under calibration.

References:

1. Josef Krautkramer, Herbert Krautkramer. Werkstoffprufung mit Ultraschall. Springer-Verlag, Berlin, 1986